WILLEM BACK &
HILARY CLAYTON

EQUINE LOCOMOTION

SECOND EDITION

FOREWORD BY
PETER ROSSDALE

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EQUINE LOCOMOTION

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Foreword

Scientists strive to explain the relationship between cause and effect; in the context of locomotion, structure and function. Those in practice, such as clinicians and horse trainers, are concerned with the application of scientific findings, but this requires monitoring in the spirit of evidence-based medicine (EBM).

In the foreword to the first edition of this book, Professor McNeill Alexander FRS drew attention to early studies initiated by the photography of Muybridge (1899) and of digital ligaments by Camp and Smith (1942). James Gray (1936) proposed the paradox as to how dolphins obtain high speeds and acceleration with such small muscle mass against the drag forces of water. He hypothesized that their skin must have special anti-drag properties.

This was subsequently discredited as summarized by Wei (2008), but serves to illustrate the biological need to elucidate the features of structure and function. From the viewpoint of a veterinary clinician, this is the essential contribution of locomotory science with the objective of improving performance and reducing the likelihood of injury, or improving the chances of successful treatment if injury occurs; thereby offering overall benefits in the welfare of horses.

The introduction of techniques applied to elucidate the mysteries of movement illustrates the advances reported in the present book. There is, for example, very substantial potential for telemetry involving inertial motion sensors which, especially when combined with global positioning system (GPS) technology, make possible the collection of a great deal of data about movement and limb kinematics, such as reported in the study of Pfau et al. (2006).

Viewpoints differ according to the circumstances of those involved in exercise physiology and locomotion: the scientist pursues the essential elements of knowledge. Veterinary clinicians require the means to the end of diagnosis, prophylaxis, therapy and prognosis; the owner uses knowledge to improve the return on investment; and the trainer of horses, be they for racing, competition or riding, needs to improve on methods to achieve the purpose for which the horse is kept.

The questions of practice include, why do individuals differ as to their performance or susceptibility to injury on differing track surfaces, and what in the structure or body function of the individual determines sprinting or stamina as a feature?

The modern horse is, somewhat paradoxically, the product of man's interference with the evolutionary process due to our selection for various roles, ranging from the drawing and carrying of loads to the participation in war and war-like activities, including chariot racing, and, more recently, on the racecourse, in endurance and in eventing competitions. But the relationship between the biological composition of the individual and the stresses and strains of functional challenge imposed must, in large measure, be considered unnatural as far as outcome of performance and susceptibility to injury are concerned.

Up until about the 1970s, the disciplines of locomotion and exercise physiology were largely in the hands of clinicians and horsemen, who based their diagnostic and therapeutic measures upon experience and trial and error associated with outcome. The introduction of scientific methods has not only solved problems, but also challenged those responsible for the care and well-being of horses for whatever purpose they are used. Particularly in the past two decades, science has developed the technology on which our understanding has expanded enormously, not only of the mechanical attributes of the horse's musculoskeletal system, but also of the biological and pathological processes involved in the structures on which equine 'athleticism' is based. This is a never-ending progression in keeping with scientific method and is likely to continue indefinitely in the future. The content of the present edition of *Equine Locomotion* represents a significant step in this pathway.

Consultation with two colleagues active in practice led to the following personal communications:

> ***The study of locomotion should be applied to the young racehorse to help circumvent injury or lameness developing as, for example, in the specific condition of plantar osteochondral disease (POD) or more simply a stress-related bone injury to the lower cannon. Science might guide us towards different training methods and programmes, shoeing, surfaces, tack or other unknowns to improve the soundness and welfare of the horse and reduce wastage and days lost from training.***
>
> M.C. Shepherd BVSc Massey, MRCVS

> ***Breeders of modern sport horses are currently selecting for traits that adapt the individual to the needs for a chosen discipline. With this, biomechanically specific pathologies typical of a discipline, its training and competition conditions are challenging and taxing the mental and physical limits of the animal in its artificial environment. The understanding of the changing demands each discipline exerts on the phenotypical development of the more slowly changing genotype is essential to the welfare of the horses and sustained sporting and economic success of a discipline. Learning about ground and force interaction, evolving equitation and training ideas on repetitive biomechanical stresses and their effects on skeletal, articular and muscular sustainable long term athletic health is essential for the sporting success of the current and future generations of show jumpers, eventers, dressage as well as endurance, driving, reining horses and polo ponies.***
>
> F.E. Barrelet DrVetMed Berne, MRCVS

The history of scientific progress is described eloquently in the first chapter by René van Weeren. There are then nineteen chapters devoted to the application of scientific methods and measurement techniques regarding limb and bodily function in motion. The list of 45 contributors from twelve different countries and three continents is evidence of the substantial weight of scientific input into the subject of equine locomotion; and lends emphasis to the importance of the book and the successful endeavours of the two co-editors, Wim Back and Hilary Clayton, who deserve congratulations from all concerned, contributors and readers alike.

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Foreword
to the first edition

Horse locomotion has lost most of the practical importance it had in past centuries, but a great many people remain passionately interested in horses for leisure, racing or other purposes. This, and the high value of horses, sustain veterinary interest in the species.

Horses have also attracted the interest of many research scientists. Muybridge's (1899) sequences of photographs of horses in motion, taken with multiple cameras before the cine camera had been invented, have an honored place in the history of motion pictures. Camp and Smith's (1942) study of the digital ligaments of horses was an early recognition of the importance of tendon and ligament elasticity in running; horses, people, dogs, kangaroos and many other animals save energy by bouncing along, using their tendons like the spring of a child's pogo stick. Horses were particularly good material for this study because their adaptations for elastic energy savings are surpassed only by the camel (Dimery *et al.*, 1986). Recent research provides many examples of research on horses that has wide significance for the understanding of animal and human movement. I will cite just a few of my favourites.

Most quadrupedal mammals walk, trot and gallop, but the significance of changing gaits became apparent only when Hoyt and Taylor (1981) trained ponies to change gait on command, so that they could be made (for example) to trot at speeds at which they would have preferred to walk, and vice versa. By measurements of oxygen consumption they showed that walking is the gait that needs least energy at low speeds, trotting at intermediate speeds, and galloping at high speeds, and that each gait is used in the range of speeds in which it is most economical. Bramble and Carrier (1983) depended largely on observations of horses for their demonstration that galloping mammals take one breath per stride, their breathing apparently driven by the movements of locomotion. They speculated that this might depend on the viscera functioning as an inertial piston, shifting forward and back in the trunk as the animal accelerated and decelerated in the course of each stride. Disappointingly, this seems not to be the case; the breathing of a galloping horse seems to be driven by the bending and extension of the back, functioning like a bellows (Young *et al.*, 1992). Horses gave us valuable insight into the stresses that bones have to withstand when surgically implanted strain gauges were used to record strains in the lower leg bones of running and jumping horses (Biewener *et al.*, 1983). It was in a study of horses that Rome *et al.*, (1990) showed us the remarkable range of properties that can be found within a single muscle. Some fibers in the soleus muscle of horses are capable of contracting ten times faster than others. And observations on horses were the first to show that tendons can be damaged by overheating, by heat liberated by the repeated stretching and recoil, that occurs in running (Wilson & Goodship, 1994).

Besides these studies that have wide significance, there have been others, equally fascinating, that concern horses alone. The reciprocal apparatus in the hind limb makes movements of the stifle joint drive those of the hock (van Weeren *et al.*, 1992). The hooves of horses have been shown to be designed in a remarkably sophisticated way, to withstand impact on the ground (Thomason *et al.*, 1992). The hock joint of horses has bistable properties that make it click like an electric switch from one extreme position to the other, a property which, curiously, is much more marked in domestic horses than in zebra or Przewalsky's horse (Alexander & Trestik, 1989).

These examples make it clear that horse locomotion has inspired a great deal of excellent and interesting science, much of which throws light on the biology of other animals, as well as of horses. That is one reason why this book will be so welcome. Another is that it has been written by a carefully chosen team of scientists whose research has added substantially to our knowledge of horse locomotion.

Sadly, the team has been depleted by the death of Henk Schamhardt, co-author of one of our chapters, who was preeminent among researchers in the field of equine biomechanics.

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Preface

The repercussions of societal revolutions are felt far and wide, and the equine industry is certainly not immune. The industrial revolution brought major changes in agriculture and transportation that were the impetus for a change in the predominant use of horses from work to sport and recreation. The baby boomer generation adopted a fitness craze that ultimately resulted in an increase in sport-related injuries and a growing need for sports medicine practitioners. Equestrian sports were also growing in popularity and there was a demand for scientific information about the structure, function and diseases of sport horses.

Gait analysis has always been recognized as a key element in understanding equine athletic performance but it was not until the technological revolution that the tools became available to make rapid progress in this area. Biomechanists now have at their disposal a dazzling array of equipment and techniques to analyze equine locomotion. Consequently the past decade has seen tremendous growth in the body of literature in this area. Since the first edition of *Equine Locomotion* was published in 2001, the knowledge base has expanded in the traditional areas and many new foci of investigation have emerged. Therefore, there was no shortage of new information for the second edition.

In this edition, almost every chapter has undergone substantial revision to include new information. Notable among these is the chapter on modeling of locomotion, an area that was in its infancy a decade ago but has now become much more mainstream and accessible to researchers rather than being the domain of animators and gamers. The new chapter on modeling, simulation and animation draws on the expertise of multiple authors to adequately represent this exciting area.

Considerable new information has been added to the chapters on signals from materials, genetic contributions to exercise and performance, the horse–rider interaction, locomotion ethology and welfare, and rehabilitation. These chapters present state-of-the-art information from the researchers who are at the forefront in these areas.

Production of this text was timed so that the chapter authors could include new information presented at the International Conference on Equine Exercise Physiology in November 2010. At this conference, biomechanics was the strongest subject area; there were numerous excellent presentations made at the conference and published in the proceedings book. This second edition of *Equine Locomotion* truly represents the current state of knowledge about equine locomotion and the multitude of factors that can influence locomotor performance in the horse.

As the editors of this edition we thank all our contributors for their expertise and dedication in making the information so readily available to all those who have an interest in this fascinating subject.

Willem Back (Utrecht, The Netherlands)
Hilary M. Clayton (East Lansing, Michigan, USA)
2013

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Preface
to the first edition

As a result of their diverse athletic abilities, horses have been used as beasts of burden, as vehicles of war and as partners in sports and recreation. The past century has seen an explosion in the popularity of equestrian sports with a concomitant increase in competition standards. The expectations for performance in today's competition horse require a high level of care and training, which can be achieved only through a comprehensive understanding of the anatomy and physiology of the elite equine athlete. The scientific community responded to this need for information by embracing the discipline of equine sports science, which has developed in parallel with the growth of equestrian sports. Gait analysis, which is the study of locomotion, is an area of equine sports science that has made great strides (quite literally) in the last 30 years.

By 1991, gait analysis was sufficiently established as a scientific discipline to warrant the establishment of an International Workshop on Animal Locomotion (IWAL). The idea of IWAL was conceived and brought to fruition by Henk Schamhardt and Ton van den Bogert at Utrecht University. Subsequent IWALs have been organized by Hilary Clayton in California in 1993 and by Eric Barrey in Saumur, France in 1996. By the time this book is published, Florian Buchner will have organized IWAL4 in Vienna and IWAL5 will be in the planning stages.

Each IWAL proceedings contains a collection of manuscripts that reflects the recent and on-going research projects in locomotion laboratories around the world. Although these proceedings have proven to be a valuable resource, the information they contain is not intended to cover the various aspects of the discipline completely. The need for a more comprehensive source of information on equine locomotion was recognized by Wim Back. W.B. Saunders supported the concept and Hilary Clayton was enlisted to assist in the editorial duties. Our goal in producing this book is to give the reader a complete picture of the horse in motion, as we now know it. The book begins with a history of man's association with the horse both in sports and in veterinary medicine, which sets the stage for a comprehensive description of the present state of knowledge beginning with the initiation of gait and ending with the more futuristic area of computer modeling. In areas where studies of horses are lacking, ideas from other species have been introduced. The list of authors comprises individuals who are acknowledged experts in their subject areas. We thank them for the enormous time and effort they have invested in producing this book.

Unfortunately, one of our most esteemed authors, Henk C. Schamhardt, PhD, died in an accident on June 26th 1999 during his sabattical leave in Australia. As a leading member of the Utrecht Equine Biomechanics Research Group, Henk made an enormous contribution to the development of equine biomechanics across the world. Those who did not know Henk personally are familiar with his work through his excellent conference presentations, numerous publications, and his role as co-editor of the proceedings of the first two IWALs. As a result of his generosity in sharing his skills and knowledge, Henk acted as a mentor to a new generation of researchers in equine locomotion and biomechanics. It is a fitting tribute to dedicate this book to him.

It has been an honour and a pleasure to edit this millennium book about the locomotion of our mutual friend, the horse. As our Swedish colleagues would say while standing with one boot on a chair and the other one on the table 'To the horse!'

Willem Back (Utrecht, The Netherlands)
Hilary Clayton (East Lansing, Michigan, USA)
2000

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We must also recognize the important role of our families, Wim's wife Tia and their children Niels, Floris and Milou, and Hilary's husband Richard. We appreciate their support and tolerance of the time we spent working on the book, which was usually during off duty hours.

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Glossary

Abduct, abductor, abduction: Pertaining to the movement of a body part away from the midsagittal plane.

Acceleration: The time rate change of velocity.

Acceleration due to gravity: The acceleration of a body freely falling in a vacuum, the magnitude of which varies slightly with location. Standardized value at sea level is 9.807 m/s^2.

Accelerometer, accelerometry: Pertaining to the measurement of accelerations.

Adduct, adductors, adduction: Pertaining to the movement of a body part toward the midsagittal plane.

Advanced completion/lift-off: Time elapsing between lift-off of two specified limbs.

Advanced placement: Time elapsing between ground contact of two specified limbs.

Air resistance: Drag on a body produced by the frictional effects of moving through air.

Allometry: The study of factors that change the shape and functionality of an animal with increasing size.

Angular acceleration: The time rate change of angular velocity.

Angular displacement: The change in orientation of a line segment, as the plane angle between initial and final orientation, regardless of the rotational path taken.

Angular velocity: The time rate change of angular displacement. A vector quantity.

Arthromere: One of the body segments of a jointed animal, somite.

Arthrometry: The study of joint movement range and mobility.

Articular, articulate, articulated, articulation: Pertaining to a structure constructed of segments united by joints.

Axis: A straight line about which rotation occurs.

Biokinematics: Kinematics applied to biological systems or entities.

Biokinetics: The study of the forces responsible for the movements of living organisms.

Biomechanics: The application of mechanical laws to living structures.

Biped, bipedal: Having, utilizing, or supported by two feet.

Bipedal: A portion of the stride in which two limbs support the body.

Biphasic: A movement or measurement with two distinct major amplitudes per cycle.

Canter, rotary: One of two footfall sequences of the canter gait in which a lateral pair of limbs move synchronously and the leading limbs are on opposite sides of the body for the fore and hind limb pairs.

Canter, transverse: One of two footfall sequences of the canter gait in which a diagonal pair of limbs move synchronously and the leading limbs are on the same side of the body for the fore and hind limb pairs.

Caudal, caudad: Toward the tail.

Center of mass: The point about which the total mass of a body is evenly balanced. Used to represent the mass of an object in physical calculations.

Central pattern generators: Neural networks located in the spinal cord that produce rhythmic limb movements.

Cervical: The anatomic name for the neck; horses have seven cervical vertebrae.

Contralateral: Located on opposite (left or right) sides of the body.

Cost of transport: The energy expended by an animal in moving a given distance.

Couplet: When the alternating footfalls of a pair of limbs (diagonal, lateral, fore or hind) are separated by unequal intervals of time, the two closely-spaced footfalls occur as a couplet.

Cranial, craniad: Toward the head.

Damping: A gradual reduction in the amplitude of an oscillating movement.

Density: The concentration of matter, expressed as mass per unit volume.

Diagonal dissociation: temporal dissociation at contact or lift-off of a diagonal pair of limbs that appear to move in synchrony.

Diagonal limb (pair): A forelimb of one side and the hind limb of the opposite side. Customarily, the 'right diagonal' is right fore and left hind; the 'left diagonal' is left fore and right hind.

Diagonal stance, left/right: A stride phase in which the body is supported by a diagonal pair of limbs.

Diagonal step length, left/right: The distance along the direction of motion between the diagonal fore and hind hooves during diagonal stance.

Diagonal width: The lateral distance, measured perpendicular to the direction of motion, between the placements of the diagonal fore and hind limbs during diagonal stance.

Digitize: Transform analog data, e.g. a photographic image, to digital form, e.g. an electronic file.

Displacement: Length measured along a straight line from starting point to finishing point. A vector quantity.

Distal: Away from the main mass of the body; opposite of proximal.

Distance: Length measured along the path taken by the body from starting point to finishing point. A scalar quantity.

Dorsal: Toward the dorsum (back) of the body, opposite of ventral.

Drag: Resistance to motion within a fluid.

Duration: The period of time during which a given state lasts.

Duty factor: The duration of the stance phase of a specified limb as a proportion of the total limb cycle duration or stride duration.

Dynamics: The branch of mechanics that deals with motion and the way in which forces produce motion.

Efficiency: The ratio of useful energy delivered by a dynamic system to the energy supplied to it.

Elastic energy: The potential energy stored by a body as a result of deformation.

Electrogoniometry, electrogoniometer, electrogoniometric: Pertaining to electrical signals generated by devices which monitor the change in angle of a joint.

Electromyography, electromyographer, electromyographic, EMG: Pertaining to electrical potentials generated in muscle cells during contractions.

Energetics: The study of energy, force, and efficiency.

Extend, extension, extensor (joint): Pertaining to factors that cause an increase in joint angle.

Fatigue: A reduction in power output, comfort, and/or efficiency associated with prolonged or excessive exertion.

Flex, flexion, flexor (joint): Pertaining to factors that cause a reduction in joint angle.

Flexion/extension: The movement of a joints around its transverse axis. The flexor and extensor sides of the joints are defined according to anatomical convention.

Force: The mechanical action or effect of one body on another, which causes the bodies to accelerate relative to an inertial reference frame.

Force plate: A device that measures ground reaction forces.

Frequency: The number of repetitions of a periodic event that occur within a given time interval, usually expressed in Hz (cycles per second).

Gait: Cyclic pattern of limb movements. Each complete cycle is one stride.

Gallop, rotary: One of two footfall sequences of the gallop gait in which the footfall of the leading hind limb is followed by the footfall of the ipsilateral forelimb and the leading forelimb and leading hind limb are on opposite sides of the body.

Gallop, transverse: One of two footfall sequences of the gallop gait in which the footfall of the leading hind limb is followed by the footfall of the diagonal forelimb and the leading forelimb and leading hind limb are on the same side of the body.

Ground reaction force: force exerted by the ground against a limb that is in contact with the ground. Acts in opposition to the force exerted by the limb against the ground.

Horsepower: A quantity of power equal to 735.5 watts (or joules per second) (metric unit), or 745.7 watts (imperial unit).

Hyperextension: Excessive or extreme extension of a joint; in a range that may cause injury.

Hyperflexion: Excessive or extreme flexion of a joint; in a range that may cause injury.

Ipsilateral: Located on the same (left or right) side of the body.

Jump suspension: The phase during jumping when the horse has no contact with the ground.

Kinematics: The branch of mechanics that is concerned with the description of movements.

Kinetic energy: Energy of a body associated with translational and rotational motion.

Kinesiology: The study of the mechanics of motion. Usually described with reference to human anatomy.

Kinesthesia: The perception or sensing of the motion, weight, or position of the body.

Kinetics: The study of internal and external forces, energy, power, and efficiency involved in the movement of a body.

Lateral: Pertaining to the sides, left and right.

Lateral limb (pair): A forelimb and hind limb on the same side of the body.

Lateral stance, left/right: A stride phase in which the body is supported by a lateral pair of limbs.

Lateral step length, left/right: The distance along the direction of motion between the placements of the ipsilateral hind and forelimbs.

Laterality: Asymmetry between the left and right sides of the body in motion or limb usage that occurs naturally and is not accounted for by pathology or injury, as in handedness in humans.

Levator, elevate, elevation: Pertaining to lifting a body part vertically.

Lift-off: The moment when the hoof leaves the ground. Marks the transition from stance to swing phase.

Limb, lead/leading: The second of the two hind limbs or two forelimbs to contact the ground in each stride of an asymmetrical gait.

Limb, trail/trailing: The first of the two hind limbs or two forelimbs to contact the ground in each stride of an asymmetrical gait.

Longitudinal axis: A line in the median sagittal plane extending from head to tail; craniocaudal axis.

Lumbar: The anatomic name for the loin of the horse; there are usually 6 lumbar vertebrae.

Mass: The quantity of matter contained by a body, with standardized international measurement units of kilograms.

Mass moment of inertia: The measure of a body's resistance to accelerated angular motion about an axis.

Mechanical energy: The capacity to do work, equal to the sum of potential energy and kinetic energy.

Mechanics: The branch of physics concerned with the behavior of physical bodies when subjected to forces or displacements, and the subsequent effects of the bodies on their environment.

Modeling: A theoretical, simplified mathematical construct of a physical phenomenon.

Moment of a couple: The resultant moment of two equal but oppositely directed, non-collinear parallel forces (the couple).

Moment of a force: The turning effect (torque) of a force about a point.

Morphometry, morphometric: The study of the form and dimensions of a body.

Newton: The standard unit of force, equivalent to that which will cause a mass of one kilogram to accelerate 1 m/s^2.

Normal: Perpendicular to a plane, usually the ground.

Normalize: Mathematically convert measurements to a common frame of reference to facilitate comparisons between individuals or groups.

Ontogeny: The sequential development of the individual organism.

Outliers: Values of data that are in excess of a certain cut-off point.

Overlap: Stride phase in which two or more specified limbs are simultaneously in stance.

Pedobarograph: Device for measuring the pressure distribution beneath the foot.

Phylogeny: The complete developmental history through evolution of a group of animals.

Pitch: Body rotation about the transverse (mediolateral) axis.

Placement interval: Elapsed time between the contacts of two specified limbs within a stride.

Potential energy: Energy of a body associated with position or configuration.

Power: The rate at which work is done or energy is expended.

Pressure: The force applied per unit area.

Pronate, pronator, pronation: Pertaining to axial rotation of a limb in which the lateral aspect rotates in a cranial direction.

Protract, protraction, protractor: Pertaining to moving a body part forward (cranially).

Proximal: Toward the main mass of the body; opposite of distal.

Quadruped, quadrupedal: Having, utilizing, or supported by four feet.

Quadruple or quadrupedal support: A portion of the stride in which four limbs support the body.

Retract, retraction, retractor: Pertaining to moving a body part backward (caudally).

Retrograde motion: Movement opposite to the accustomed direction, i.e. in the caudal direction.

Roll: Body rotation about the longitudinal (craniocaudal) axis.

ROM: Range of motion is the total angular change during one stride.

Sagittal plane: Plane parallel to the median plane.

Scalar quantity: A quantity that is completely expressed in terms of its magnitude.

Single support: A portion of the stride in which only one limb is in the stance phase.

Somite: Body segment.

Speed: The rate of change of distance; a scalar quantity.

Stance phase of a limb: The period of ground contact of an individual limb within a stride beginning at ground contact and ending at lift-off.

Stance phase of the stride: Summation of time periods during a stride when one or more limbs are in contact with the ground.

Statics: The branch of mechanics concerned with the analysis of loads (force, torque/moment) on physical systems in static equilibrium.

Step: The movement pattern in normal locomotion in transitioning from weight-bearing by one limb to another.

Step duration: The time between ground contacts of two specified limbs.

Step height: The height to which a specified location on a limb is raised from the ground during locomotion.

Step length: The horizontal distance in the direction of motion between the footfalls of two specified limbs.

Strain: Deformation resulting from the application of stress.

Strain rate: The rate of strain generation.

Strength: The maximal force produced by muscular contraction.

Stress: An external force that acts on a body.

Stride: A complete cycle of the repetitive series of limb movements that characterize a particular gait.

Stride duration: The time required to complete one stride.

Stride frequency: The number of repetitions of the stride per unit time.

Stride length: The horizontal distance traveled in the direction of motion during a single stride, or between consecutive hoof prints of the same hoof.

Supinate, supinator, supination: Pertaining to axial rotation of a limb in which the lateral aspect rotates in a caudal direction.

Support, bipedal or double: Ground contact and/or weight bearing by two limbs.

Support phase: phase of the stride when one or more limbs are in contact with the ground.

Support, quadrupedal or quadruple: Ground contact and/or weight bearing by four limbs.

Support, single: Ground contact and/or weight bearing by one limb.

Support, tripedal or triple: Ground contact and/or weight bearing by three limbs.

Suspension: An aerial or airborne phase of the stride in which all four limbs are simultaneously in the swing phase and free from weight bearing.

Suspension, extended: Aerial phase of the stride that occurs with between lift-off of the leading hind limb and contact of the trailing forelimb when the vertebral column is extended.

Suspension, gathered: Aerial phase of the stride that occurs between lift-off of the leading forelimb and contact of the trailing hind limb when the vertebral column is flexed.

Swing phase: The portion of the stride cycle or limb motion cycle in which a designated limb is free from contact with the ground.

Symmetrical: A movement or morphology that is substantially similar in being a mirror image on left and right sides of the body.

Symmetrical gait: A gait in which the limb coordination pattern of one side repeats that of the other side, half a stride later.

Temporal: Concerning time, duration.

Tension: The application of forces acting to stretch an object.

Tetrapod, tetrapodal: Having, utilizing, or supported by four feet.

Thoracic: The anatomic name for the chest of the horse; there are usually 18 thoracic vertebrae.

Time: Measurable quantity in the temporal domain, with standardized international units of seconds.

Toe-off: The instant at the end of the stance phase at which the toe is no longer contacting the ground. Marks the transition between stance and swing phases.

Torque: A turning or twisting force; also referred to as moment of force.

Transverse axis: A mediolateral line that is mutually perpendicular to the longitudinal and vertical axes; mediolateral axis.

Triped, tripedal: Having, utilizing, or supported by three feet.

Tripedal support: A portion of the stride in which three limbs support the body.

Ungulate: Hoofed mammal.

Uniped, unipedal: Having, utilizing, or supported by one foot.

Unipedal support: A portion of the stride in which one limb supports the body.

Units, SI: Standard international units (or their standard multiples) accepted by the International Society of Biomechanics for scientific measurement, including length in meters, mass in kilograms, time in seconds and plane angle in radians.

Vector quantity: A quantity that has both magnitude and direction.

Velocity: The time rate change of displacement. A vector quantity.

Ventral: Toward the ventrum (belly, underside) of the body; opposite of dorsal.

Weight: The force of gravity acting on a body, equal to the product of mass and the acceleration due to gravity.

Work: The result of a force acting to displace a body in a given direction.

Yaw: Body rotation about the vertical (dorsoventral) axis.

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CHAPTER 1

History

P. René van Weeren

Introduction

Man has always been fascinated by the creatures that surrounded him. Rock paintings and engravings from prehistoric times show that, apart from man himself, it was the large mammalian species that were most often depicted. Among these, the horse played a prominent role in those latitudes where this species was abundant.

After domestication interest in the species naturally deepened as the role changed from simple animals of prey to that of an important economic entity. The horse, unlike almost all other species, was domesticated for its locomotor capacities rather than as a supplier of food or clothing materials. It was this tremendous capacity to move that for millennia gave the horse its pivotal role in transport in many of the major civilizations on this planet and that also made it a most feared weapon in warfare from ancient times until very recently.

As a result of this important role in transportation combined with its proximity to man, the horse became the primary focus when veterinary science developed in the ancient societies and later as it became a flourishing branch of science during the heyday of the Greek and Roman civilizations. It is therefore not surprising that it was during Antiquity that the first scientific comments were made on gait.

The decline of the Antique culture and the subsequent fall of the Roman Empire brought science to a virtual standstill in most of Europe during the dark Middle Ages and it is not until the Renaissance that we see a renewed scientific interest that also extends to veterinary medicine. First directed at the legacy of Antiquity, science took a step forward in the 18th century when the modern approach of making observations and drawing conclusions, later followed by the conjunction of hypotheses with subsequent experimental testing, was adopted. Then we also see the founding of the first veterinary colleges. These focused almost exclusively on the horse, which, throughout this entire period, had maintained its primary role in transport and warfare. It was France that took the lead and it was also French scientists that published the first scientific study completely dedicated to the locomotion of the horse.

France retained the lead in veterinary medicine, and in equine gait analysis, for almost a century until the end of the 19th century. Then, with one notable exception in the United States, German scientists took over and explored with their characteristic thoroughness the possibilities of novel techniques like cine film.

The outbreak of World War II brought this thriving research to a halt. There was no recovery after the end of the war because the mechanical revolution, which had already started during World War I, made horse power redundant and brought to a definitive end the traditional role the horse had played for millennia in transport and warfare. In fact, it looked as if the species would become entirely marginalized.

However, interest in the species was revived at the end of the sixties and in the early seventies of the 20th century when equestrian sports enjoyed an immense popularity that continues to increase today. This popularity has again made the horse into an important economic factor, worthy of serious investment. At the same time, interest in locomotion analysis has revived. This time first in Sweden, but soon followed by other countries and regions where the horse has gained importance as a sports and leisure animal like in North America and North-western Europe. This renewed interest in equine locomotion coincided with the electronic revolution, which made computer-aided analysis a reality, thus creating the possibility for much more advanced and profound studies of equine locomotion than ever before.

The science of equine locomotion is thriving. This book aims to present the state of the art in this branch of science. In the first chapter an attempt is made to give an overview of how this science developed over time against the background of evolving veterinary science, but more so against the background of the evolving relationship of mankind with what has been called our closest ally; the horse.

Prehistoric times

The oldest known art to be produced by man is the rock art found in various caves in the Franco-Cantabrian region, covering what is nowadays South-western France and North-western Spain. Here, about 30 000 years ago the Cro-Magnon race of people began depicting their environment by means of large and impressive paintings on the walls of rock caves. At first still somewhat crude, artistic heights were reached about 15 000 years ago in the Magdalenian period, so called after the rock shelter of La Madeleine, near present-day Montauban. In those days of the last Ice Age, South-western Europe must have known abundant wildlife. In the paintings two classes of animals prevail: ruminants such as cattle, bison, deer and ibex, and horses. The way horses were represented does not reveal a profound knowledge of equine locomotion. In most cases the animals were painted standing with all four legs on the ground, or in an unnatural jump-like action with the forelimbs extended forward and the hind limbs backward, in much the same way as horses were still erroneously depicted in many 18th century and early 19th century paintings (Fig. 1.1). Species like rhinoceros, mammoth, bear and the felidae are present, but to a much lesser extent. Perhaps the plains, which covered that part of Europe in this period, looked much like the great plains of East Africa, such as the Serengeti, nowadays. Here too, ruminants like buffalo and

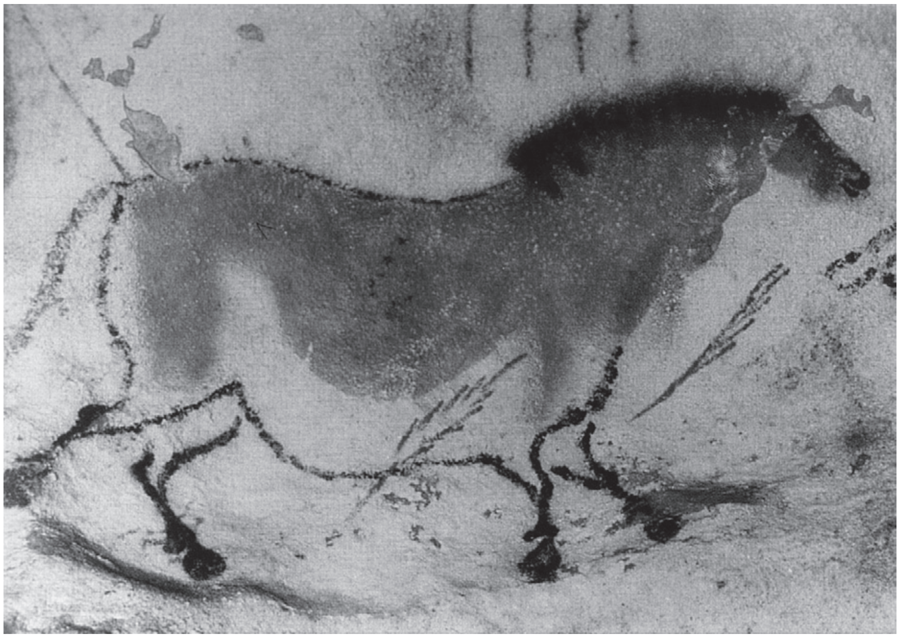

Fig 1.1 Przewalski-type horse as depicted in the cave at Lascaux (about 15 000 BC).

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wildebeest are abundant together with equids (zebras), while other species such as rhinoceros and the large cats occur in significantly smaller numbers.

Man was still a hunter-gatherer in those days and, for this reason, the wild animals comprised an essential part of his diet. Remains of large mammals eaten by man, including horses, have been found at many sites. It is interesting to note that the vast majority of rock paintings concerned animals, most of them large mammals, whereas man himself was depicted rarely and other parts of the environment such as the vegetation or topographical peculiarities were never shown. Also non-mammalian species such as birds, reptiles, fish or insects were virtually unrepresented. The rock art found in various parts of Zimbabwe and other parts of Southern Africa was somewhat different. These paintings were made by the Bushmen from 13 000–2000 years ago. Here again, the large mammalian species prevailed, with the zebra representing the equids, but man was depicted more often and there were some paintings of fish and reptiles (Adams & Handiseni, 1991). The Bushmen culture has survived until the present day, though in a much diminished and nowadays heavily endangered form, and it is known that these people, who were hunter-gatherers, lived in a very close relationship with their environment, forming an integral part of the entire ecosystem. It is easy to imagine that under such circumstances the large mammals, which were the most impressive fellow-creatures giving rise to mixed feelings of awe, admiration and a certain form of solidarity, inspired the creation of works of art.

The world changed dramatically when, at the beginning of the Neolithic period about 10 000–12 000 years ago, man changed from being a hunter-gatherer to primitive forms of agriculture and pastoralism. The capacity of most natural savanna habitats to support fixed human nutritional requirements is estimated at only one or two persons per square mile (Dunlop & Williams, 1996). The advent of agriculture and pastoralism meant that the nutritional constraints on population growth were lifted and an unprecedented population growth followed. It also meant that man definitively and irreversibly placed himself apart from his fellow-creatures and outside the existing ecosystems where the numbers of species were determined by the unmanipulated carrying capacity of the environment.

These changes in human society were to a large extent possible thanks to a new phenomenon: the domestication of animal species. It is widely believed that the dog was the first animal to be domesticated about 12 000 years ago. Like most early domestications, this event took place in Western Asia's Fertile Crescent (the area of fertile land from the Mediterranean coast around the Syrian Desert to Iraq), which was the cradle of human civilization. There also the next domestication took place: small ruminants were domesticated approximately 10 000 years ago, sheep and goats in about the same period. Cattle were domesticated 2000 years later in Anatolia (Western Turkey). Cats were domesticated (or adopted man as some people state) as early as 9000 years ago. The first camelids to be domesticated were llamas in South America, perhaps as early as 7500 years ago. The horse arrived rather late on the scene. There is evidence that the first horses were domesticated in what is now Southern Russia approximately 5000 years ago. However, the domestication of the horse dramatically influenced the history of mankind, mainly because of its enormous potency in warfare.

The horse was definitely the most revolutionary innovation in warfare before the invention of gunpowder. First, the animals were used to draw heavy war chariots which, used against traditional infantry, could provoke enormous massacres while being themselves rather invulnerable. Later, with the development of the skill of horse riding and increasing horsemanship, a real cavalry of mounted soldiers was developed which, with their greater agility, replaced the chariots. This development enabled rapid conquests of vast territories. The Hittites conquered Asia Minor (present-day Turkey) in 2000 BC with their horse drawn chariots. A thousand years later the Scythians, originally a Eurasian nomadic tribe settled in the area north of the Black Sea. The Scythians were excellent horse riders and they became masters in the tactics of cavalry-based steppe warfare, enslaving agricultural peoples and plundering what came in their way. Later, other tribes that were mostly of Eastern origin, succeeded. The Huns overran the Roman Empire from the 4th to the 6th century AD, and in the 13th century AD, Genghis Khan reached the gates of Western Europe. For those peoples the horse was more than just a domesticated animal; it was central in their culture, as a weapon, food, drink, a friend and a god. The warriors were capable of staying in the saddle for an entire day. They ate horsemeat, drank mare's milk and intoxicated themselves during their feasts with the fermented form of it. It is even said that soldiers, traveling without rations, opened the veins of their horses, drank the blood, closed the wounds, and remounted (Simpson, 1951).

The changes in attitude towards animals by man, including domestication and changes in the use of domestic animals that were partly dictated by changing environmental conditions are magnificently demonstrated by the North African rock art found, for instance, in the Hoggar and Air mountain ranges in what is now the central Sahara Desert. Several thousands of years ago, North Africa was not covered to such a large extent by the extremely arid and inhospitable Sahara Desert as it is now. The oldest art dates to about 7000 years ago and depicts wild animals such as buffalo, giraffe, elephant, ostriches, etc., suggesting that the area must have looked like large parts of Eastern Africa do now. About 4000 BC cattle and fat-tailed sheep appeared as first representations of domestic species. Horses appeared around 1200 BC, first drawing chariots. These chariots are believed to have belonged to Cretan invaders because they are similar to pictures of chariots from this island (Lhote, 1988). In those days there was a Trans-saharan route running from Tripoli and probably also Egypt to Gao on the Niger River, thus connecting the Mediterranean, Egyptian and Nubian cultures to the Bantu cultures of the Niger River valley. More recent rock art shows riders instead of chariots. With the increasing aridity of the Sahara, the horse became unsuitable for traveling large distances with ever diminishing water resources, and was supplemented by camels around 100 BC.

The ancient cultures

The first human civilizations, characterized by urbanization and the invention of a script, developed in Mesopotamia, the area around the Euphrates and Tigris Rivers, about 3000 years BC. The first report on hippiatry dates from the 14th century BC from the Assyrian culture. In those days the city of Hethiter was famous for the procurement and training of horses. Also, donkeys were already crossbred with horses to produce the sturdier, but infertile mules. There is even evidence that horses were crossbred with the then abundant wild onagers.

After the decline of the Assyrian empire in the 8th century BC the Medean and Persian cultures took over. These were, to a large extent, horse-based societies where horsemanship was developed to great heights. In fact, the word 'Persia' is derived from the word for horseman. It was the forceful Persian cavalry that created the largest empire the world had ever seen until then under Darius I. An empire that was only to be conquered by another horse-based army, that of Alexander the Great in 322 BC.

One of the other great ancient cultures, that of Egypt, lived its first periods of glory (the Old Kingdom from 2620–2170 BC and the Middle Kingdom from 2080–1760 BC) before the arrival of (horse-borne) invaders. During this period the horse was an unknown animal to the Egyptians who were surrounded by many domesticated species like dogs, cattle and cats, the last of which gradually obtained a divine status during the later periods of Egyptian culture. The horse was introduced in the New Kingdom when invaders from the Palestinian region, who used chariots drawn by swift Arabian horses, began to challenge Egyptian sovereignty. The only way to refute them was by using the same weapon: the horse. In the New Kingdom (1539–1078 BC) the Egyptians became masters in horsemanship and horse breeding, producing the finest Arabian horses. The horse even allowed them to expand their empire as far as the Euphrates River.

In China, where some think that a separate domestication of the horse had taken place, independent of the site in Southern Russia alluded to earlier (Simpson, 1951), the oldest reports of domesticated horses are from the Shung dynasty (1766–1027 BC). Like everywhere else, the horse was used first to draw chariots, then for a mounted cavalry. From the latter period dates the famous 'army' of terra cotta figures (including large numbers of horses) that was excavated at the burial site of Shih Hunagdi (259–210 BC). He is also called the first emperor as the formerly divided China was united by then. The horse gained great importance in China during the Han dynasty when emperor Wu sent out a military expedition to capture 3000 horses of a heavier and sturdier breed, which he called the 'Horses of Heaven'. They were probably related to the Tarpan breed that still roamed the steppes of Southern Russia. Only 50 of them survived the 2000-mile journey home. By the middle of the 7th century AD, during the Tang dynasty, horse breeding in China reached unprecedented heights when numbers increased from 5000 to over 700 000. The Chinese were excellent in designing saddlery and harnesses. They invented the trace harness, in which the power of the horse is transmitted by a belt around the chest, long before it was used in Europe where a collar-type of harness was common. This latter type of harness compresses the trachea and jugular veins when force is applied and therefore permits the exertion of a force only one sixth that of using a trace harness. Also stirrups are a Chinese invention, dating from the 3rd century AD.

A few reports on equine veterinary medicine have survived from these cultures, some of which are quite extensive and methodical, like some Egyptian works. However, no specific studies on equine locomotion are known. Horses in general were depicted as they had been in prehistoric times and would remain until quite recently: either in a rather natural pose at a slow gait or in the characteristic unnatural pose that was used to indicate the gallop: forelimbs extended forward and hind limbs backward.

The Antique world

There is perhaps no revolution that has changed the course of human history more than the revolutionary change in thinking that originated in the Greek port towns of Asia Minor (Western Turkey) and nearby islands around 600 BC. Leaving ordained preconceptions and supernatural speculations or dogmas behind as explanations for natural phenomena, nature was now studied in a rigorous, rational way. The proponents of this new way of thinking were called natural scientists or philosopher scientists (Dunlop & Williams, 1996). Here, the foundations were laid for the great Greek schools of philosophy, like the Athenian Academy. This institution became the intellectual center of the world a couple of centuries later, producing the great philosophers Socrates, Plato and Aristotle. It can be stated without any hesitation that with the onset of the great Greek philosophical era science was born. Nature in all its aspects was studied for the first time by theoretical speculation (proposing hypotheses), followed by critical reappraisal and revision. What was still missing was the experimental testing of hypotheses, which is essential to modern science. The Greek philosophical schools tried to resolve all problems by logical reasoning, so the balance was far to the intellectual side. Nowadays it is not uncommon to see a reversed tendency with strong emphasis on strictly controlled experimental testing, but with sometimes hardly any evidence of critical thinking.

Aristotle was a teacher of Alexander the Great who, seated on his black stallion Bucephalus, conquered most of the then known world. Alexander was a skillful rider who is said to have been the only one able to ride the horse. Bucephalus had been given to him by his father when he was 12 years old and served Alexander for 17 years (Fig. 1.2). Alexander greatly favored the development of science and created a center of learning in the city that was named

Fig 1.2 Alexander the Great attacking Persian horsemen on Bucephalus. From the sarcophage of Alexander, Syria.

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after him: Alexandria. This city on the mouth of the Nile would remain the intellectual center of the world from 300 BC to 500 AD. In the vast library 700 000 scrolls were housed compiling all knowledge that had been gained in the preceding millennium. The burning of the library on the orders of Caliph Omar in AD 642 was an act of barbarism, narrow-mindedness and, in its deepest meaning, of fear for the unknown. It resembles the burning of books that took place in more recent history and is still taking place on the instigation of totalitarian regimes and intolerant sectarian cults.

The first extensive work on equine conformation was performed by Xenophon (430–354 BC). Apparently a man of great experience, he described in full detail the desirable and undesirable traits of horses. Many of his criteria were equal to those used today. Though his work was more of a hippiatric caliber than a scientific work, he already recognized the role of the hindquarters as the motor of locomotion.

It is not surprising that the first documented study on animal locomotion originated from one of the great Greek philosophers, Aristotle (384–322 BC). In his youth, Aristotle was intrigued by natural history, and he wrote various volumes on biological and medical matters. In his works *De motu animalium* and *De incessu animalium* (*On the movements of animals* and *On the progression of animals*) he accurately described quadrupedal locomotion, at least in the slower gaits. In *De incessu animalium* (Aristotle, 1961) he states that:

Αἵ μὲν οὖν κάμψεις τῶν σκελῶν τοῦτόν τε τὸν τρόπον ἔχουσι καὶ διὰ τὰς ἀἰτίας τας εἰρμένας, κινεῖται δὲ τὰ ὀπίσθια πρὸς τὰ ἔμπροσθεν κατὰ διαμετρον· μετὰ γὰρ τὸ δεξιὸν τῶν ἔμπροσθεν τὸ ἀριστερὸν τῶν ὅπισθεν κινοῦσιν, εἶτα τὸ ἀριστερὸν τῶν ἔμπροσθεν, μετὰ δὲ

> ***(The bendings, then, of the limbs take place in this manner and for the reasons stated. But the hind limbs move diagonally in relation to the forelimbs; for after the right forelimb animals move the left hind limb, then the left forelimb, and after it the right hind limb.)***

The Romans were more doers than thinkers and lacked the intellectual drive that characterized the Greeks. Throughout the whole period of the Roman Empire, the intellectual center remained in Greece, Asia Minor and, of course, Alexandria. However, the Romans were excellent in organizing and implementing the scientific and technical advances of others. Consequently, they created one of the vastest empires the world has ever known and which still influences many aspects of daily life.

Horses played a pivotal role in the Roman army, which employed large numbers of veterinarians to care for them. These were first called 'mulomedici', but after an overhaul of the military regulations under Commodus (180–192 AD) the term 'veterinarii' appears. Thanks to the enormous popularity of horse racing (chariots drawn by 2 or 4 horses), there was also employment for a category of veterinary specialists not unknown today: the racetrack veterinarian of which Pelagonius in the 4th century was a famous example. However, these veterinarians were mainly engaged in the treatment of diseases and healing of the many wounds. Empiricists, they relied heavily on their Greek and Hellenistic counterparts for some theoretical basis. A noteworthy exception was the physician Galenus. Galenus was born in Pergamon, Asia Minor, in 130 AD, but he worked for decades in Rome. He conducted large numbers of experiments on animals to advance medical knowledge and can be seen as the founder of the experimental basis of comparative medicine. He produced vast numbers of treatises of which about 20% have survived the ages. None of those is dedicated to the study of animal or human locomotion.

Emperor Diocletianus (284–306 AD) had divided the Roman Empire into an eastern and a western half. Constantine the Great reunited the empire in 324, but it was divided again in 395. The western part fell with the abdication of Romulus Augustus in 476; the eastern part was to survive for an additional 1000 years as the Byzantine Empire with Constantinople (Istanbul) as capital. The veterinary profession was at a high level as can be judged from the compilation of all that was known in this field under the name *Corpus Hippiatricorum Graecorum* or *Hippiatrika*. Though published in the 9th or 10th century, most of the contents date back to the 4th century. The contributions of Apsyrtos (300–360), the chief military veterinarian in the army of Constantine the Great, are of outstanding quality. Though the care and treatment of the locomotor system have a prominent position in this work, no specific comments on locomotion itself or gait analysis are made.

Through the Dark Ages to the Renaissance

After the fall of the Western Roman Empire, the existing administrative structures collapsed and much of the knowledge that had been gained over the centuries was lost. For centuries most of Europe became an incoherent assembly of tribes and mini-states where insecurity and ignorance reigned. During this period the impressive Arab conquest started from Mecca in the Arabian Peninsula where the prophet Muhammad had died in 632. Within a century, the Arabs conquered millions of square miles of land from Northern India to Spain. This could be accomplished thanks to their aggressive light cavalry, which was based on the swift and enduring Arab horses, and their great horsemanship. They were halted by the troops of the Frankish king Charles Martel at Poitiers in 752. The Franks were only able to withstand them because they employed a heavily armored cavalry, which was rather invulnerable to the light cavalry of the Arabs, not unlike the use of the first tanks in World War I.

While Europe was in cultural decline, the Arab culture flourished. It is thanks to many Arab scientists that at least a part of what had been written in Antiquity has survived to the present day. They translated the works into Arabic and in the later Middle Ages these Arabic versions were translated again into Latin to lay the foundation for the scientific revival in the Renaissance. The Arabs also contributed to veterinary medicine with original works. Akhi Hizam al-Furusiyah wa al-Khayl wrote the first book on the characteristics, behavior and diseases of horses in 860. Abu Bakr ibn el-bedr al Baytar (1309–1340) wrote an excellent work on veterinary medicine, the *Kamil as Sina'atayn*. This book features aspects of equine management and care including the tricks of horse-dealers(!), together with remarks on appearance, conformation and gait (Dunlop & Williams, 1996). The horse had a very high standing in the Arab world. Abu Bakr held the opinion that the horse was so important to an Arab man that it would be reunited with him in paradise, together with his wives. There is also an Arab maxim stating that:

> ***Every grain of barley given to a horse is entered by God in the register of Good Works.***
>
> Simpson, 1951

In the first part of the Middle Ages the medical and veterinary professions stood at a low level in most of Europe. The link with Antiquity had been broken and the Christian church, which saw diseases as a divine punishment to be cured with the help of supernatural power, had a hostile attitude towards the few rational natural scientists. In medieval matters mystics and superstition played an important role. It was not until the late Middle Ages that, mainly through the translation of Arab texts (originals and translations of classical works), the tide changed. The emperor Frederick II was a man ahead of his time. He formed a bridge between the Christian Western world and the Islamic East. He was a great proponent of science and had a special interest in animals. It was his chief marshal, Jordanus Ruffus, who, supported by the emperor, published the first new work on equine medicine *De Medicina Equorum* in 1250. Fredrick II was a great, but ruthless, innovator. At first supported by Pope Innocent III, he fell into disgrace with his successors who deprived him of his kingdoms in 1245. This enlightened man can be seen as a very early protagonist of the wave of renewal that was to blow over Europe and which would mean an end to the Middle Ages: the Renaissance.

From the Renaissance to the 18th century

In Italy a change in scientific attitude developed; this involved a change from the concept of life as the product of supernatural and mystical powers towards a more rational, naturalistic approach. Perhaps no one was as closely associated with this revolutionary process as the genial artist and scientist Leonardo da Vinci (1452–1519). Leonardo himself is known to have been interested in the movements of animals and he even projected to:

> ***… write a separate treatise describing the movement of animals with four feet, among which is man, who likewise in its infancy crawls on all fours.***
>
> Clayton, 1996

Da Vinci was intrigued by the flexibility of the equine spine and produced a series of fine drawings, now in the British Royal Collection at Windsor Castle, with horses in a number of exceptional, but not impossible poses.

It has been stated that the renaissance in veterinary medicine started with the publication of the first great textbook on veterinary anatomy *Dell Anatomia et dell'Infirmita del Cavallo* (*On the Anatomy and Diseases of the Horse*) by Carlo Ruini in 1598. The anatomical part presented the first real new work since Antiquity. However, the part on diseases did not pass the standards of Jordanus Ruffus, *De Medicina Equorum* that had been published 350 years earlier.

It may not be surprising that this ambiance of emerging science fostered the first contribution to the science of equine locomotion since Aristotle. Giovanni Alphonso Borelli (1608–1679) was a professor of mathematics at Pisa University and applied physical theory to the study of animal locomotion. He calculated the force of muscle action and recognized that the muscles were under nervous control (Fig. 1.3). In his book *De motu Animalium* (*On the movement of animals*), he describes the center of gravity and also makes observations about limb placement in the various gaits (Borelli, 1681).

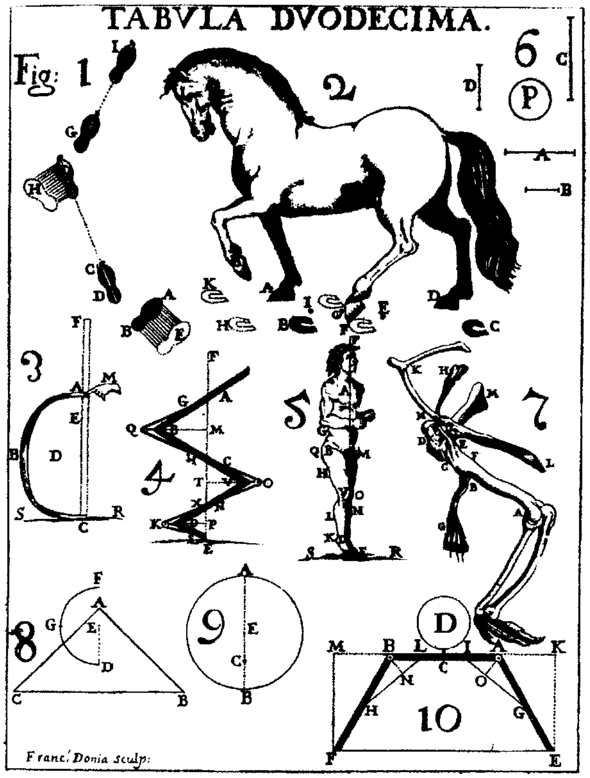


Fig 1.3 Page from *De motu animalium* by Giovanni Borelli comparing equine and human locomotion.

Reproduced from Dunlop, R.H., Williams, D.J. (Eds.), 1996. Veterinary Medicine. An illustrated history. Mosby, St. Louis, with permission from Elsevier.

He was obviously ahead of his time; this line of investigation would not be further pursued until the end of the 18th century.

The 17th century was the age of the great horse marshals. One of these was William Cavendysh, the first Duke of Newcastle (1592–1676). He was one of the most famous horse trainers of his days but was, as a royalist, forced to leave Britain when Charles I's army was defeated by Cromwell's troops. In exile in Antwerp he wrote an extensive work on all aspects of the horse, which first appeared in French. It includes a chapter on the gaits, which he studied with help of the sounds that the hooves make when they strike the ground (Cavendysh, 1674). Another great marshal of this era was Jacques de Solleysel from France. His great work *Le Parfait Maréschal qui enseigne a connoistre la beauté, la bonté, et les défauts des chevaux* (*The perfect marshal who teaches how to know the beauty, the virtue and the defects of horses*) consists of two volumes. The first one is dedicated to horse management, the second to equine diseases. De Solleysel makes some remarks on limb placement in various gaits, but appears not to really have made a study of the subject (De Solleysel, 1733).

The start of veterinary education

Notwithstanding some progress in the preceding centuries, the veterinary profession was still far from any scientific status in the middle of the 18th century. George Leclerc, Comte de Buffon (1707–1778), who was the dominant personality in zoology during the second half of the 18th century, wrote at the end of his zoological description of the horse:

> ***I cannot end the story of the horse without writing with regret that the health of this useful and precious animal has been up to now surrendered to the care and practice, often blind, of people without knowledge and without qualification.***
>
> Dunlop & Williams, 1996

However, the chances for the veterinary profession were to change for the better, mainly because of two reasons. On the one hand the need for better veterinary care became dramatically evident in this period by the huge losses of horses on the many battlefields of those days, and by the incredible losses of livestock caused by various waves of cattle plagues, mostly rinderpest, that swept over Europe. It has been estimated that more than 200 000 000 cattle died in Europe in the years between 1711 and 1780 because of this disease which had a profound demoralizing effect on the rural areas. On the other hand, a new intellectual movement, which came to be known as the Enlightenment, was spreading through Europe from its origins in France. Philosophers such as Montesquieu, Rousseau and Voltaire rejected the idea of mere authority as the source of truth and emphasized the role of reason. These two concurrent circumstances created an optimal starting point for veterinary education. It was Claude Bourgelat, director of the Academy of Equitation in Lyon and, himself, one of the authors of the great work, *The Enlightenment*, a highly controversial and unorthodox encyclopedia that trampled the toes of many established authorities, who finally obtained royal permission to transform the riding school into the first veterinary school in 1761. A few years later he would establish a second one in the center of the French empire; Paris. Other European countries followed the French example with the Austro-Hungarian Empire as the first (1766).

The newly established veterinary center at Alfort near Paris did not fail to produce results. In 1779 the first modern work that focuses entirely on equine gait was published. The authors were the late Mr Goiffon and his deputy Vincent, who was employed by the school and later became one of the first pupils of the Alfort School. The book of Goiffon and Vincent was primarily intended to help artists depict their horses in a more natural way, which had been a problem throughout the ages, but it was considered equally interesting for everybody dedicated to the art of horse-riding. The work is of extreme importance in the history of equine gait analysis. Though not entirely correct with respect to limb placement in the faster gaits, the study is well done and enters into great detail. Gaits of horses are represented by a 'piste' (a graphical representation of the footfall pattern), a kind of schematic stick diagram, an elaborate table, and by what we now call a gait diagram (Fig. 1.4). This latter representation of equine gait was invented by Goiffon and Vincent and has proved so useful that it is used in many present-day publications in an essentially unaltered form. Goiffon and Vincent called it an 'échelle odochronométrique'. Regarding the origin of the word, they state:

> ***Cette denomination est composée de trois mots grecs, dont l'un signifie chemin, l'autre temps & le troisieme mesure. C'est la définition exacte de notre échelle; elle est la mesure du temps & du chemin fait pendant ce temps.***
>
> ***(This name is composed of three Greek words: one means distance, one means time and the third means measurement. This is the exact definition of our scale, which in fact measures time and the distance covered in that time.)***
>
> Goiffon & Vincent, 1779

The 19th century

By the end of the first half of the 19th century veterinary schools had been founded in practically all countries that belonged to the then developed world, which did not yet include the United States. There, the first (private) veterinary school was the Veterinary College of Philadelphia, founded in 1852. However, progress was relatively slow and some of these institutions, an example being the Royal Veterinary College in London under Coleman, even had a questionable academic level. The profession still had a low status and the interest in the courses sometimes was marginal. In Holland, where veterinary education had started in 1821 with 24 first-year students, only 8 first-year students entered during the 7(!) years from 1848 until 1855 (Kroon et al., 1921). In the second half of the century, things would change dramatically thanks to decisive breakthroughs in microbiology, especially in bacteriology. Scientists such as Pasteur and Koch provided the clues for many diseases that so far had been of mysterious origin. The brilliant pathologist Virchow laid the basis for a cell-based pathology that broke with the old humoral theories. These discoveries had enormous implications, not only for human medicine, but also for the veterinary sciences. It was the time that the great cattle plagues rinderpest and contagious pleuropneumonia came under control. In the horse the causative agent of glanders, then the greatest plague of this species and, as a zoonosis, a potential threat to man, was isolated by Schütz and Löffler in 1886. All these developments boosted the interest in veterinary medicine and stressed the importance of the profession.

Throughout the 19th century the horse retained its primary position in society. On the battlefields the cavalry remained as decisive as ever though heavier losses of horses were inflicted because of the increasing artillery firepower. Napoleon lost more than 30 000 horses (and over 300 000 men) during his Russian expedition. In the Boer war of 1899–1902, 326 073 horses perished. Over the entire century, millions more must have lost their lives in battle. The horse remained equally important in the transport sector though in the second half of the century they were increasingly replaced by the rapidly expanding rail network for long-distance transport. In Britain, travel by mail coach peaked in the 1830s and then declined because of the increasing rail services. The extension of the railroad network in Great Britain tripled between the years 1850–1875 from 5000–14 500 miles. However, horse-drawn transport remained important at a local level and in the rural areas until well into the 20th century.

In the field of locomotion analysis some progress was made in the first three quarters of the 19th century. In Switzerland, Conrad von Hochstätter published, from 1821–1824, his *Theoretisch-praktisches Handbuch der äussern Pferdekenntniß, und der Wartung und Pflege der Pferde* (*Theoretical and practical handbook of the conformation of the horse and of horse grooming and care*), which includes the first considerations of the mechanisms underlying equine gait, based on his own observations. He also discusses the consequences of a number of faulty conformations for performance. Unfortunately, this work remained largely unnoticed by the veterinary profession (Schauder, 1923a). In Germany, there was an increasing interest in the explanation of locomotion by specific muscle action. This culminated in the classical work *Die topographische Myologie des Pferdes mit besonderer Berücksichtigung der lokomotorischen Wirkung der Muskeln* (*Topographical myology of the horse with special attention to the locomotor effect of muscles*) by Karl Günther in 1866. In Austria, Bayer (1882) did some experimental work on the hoof mechanism using an electrical device (Fig. 1.5) while in Germany Peters (1879) also dedicated himself to the hoof.

In the meantime, in France, attention remained focused on gait analysis as initiated by Goiffon and Vincent. In his book on the conformation of the horse, Lecoq (1843) introduced a different gait diagram from that of Goiffon and Vincent (Fig. 1.6). It did not find general acceptance because, although it was unequivocal regarding limb placement, it did not give temporal information.

In his book *Locomotion du cheval* (*Locomotion of the horse*, 1883), Captain Raabe presented an ingenious system consisting of two discs, a fixed one and a rotating one, with which the sequence of limb placement in all symmetrical gaits can be determined (Fig. 1.7). Raabe, who first published his work in 1857, divided the stride cycle of a limb into six periods. This was a simplification of the system used by Goiffon and Vincent who had used 12 time intervals. Raabe's division was also used by Lenoble du Teil (1873). In his 1893 publication, when he had a leading position at the famous national stud Haras du Pin, Lenoble du Teil used his studies and similar works of others to take a strong stand against the classical Italian school of riding.

In the Anglo-Saxon world there was not much research on the topic. However, the problem of gait analysis was a point of discussion from time to time as exemplified by a scientific quarrel between Joseph Gamgee (Edinburgh) and Neville Goodman (Cambridge) in the *Journal of Anatomy and Physiology* in the early 1870s. Discussing the canter, Gamgee stated that:

> ***The horse in the fast paces, as in the slowest movement, has never less than two of his feet acting on the ground.***

This statement was (correctly) attacked by Goodman. However, there was, as yet, no means to prove this (Gamgee, 1869, 1870; Goodman, 1870, 1871). In 1873, Pettigrew published a book on animal locomotion in which he put forward some ideas that were later taken by Marey from France, who was to become much more famous.

Muybridge and Marey: revolution in gait analysis

About a century after the French Revolution, which meant the end of an era and changed world politics forever, a revolution took place

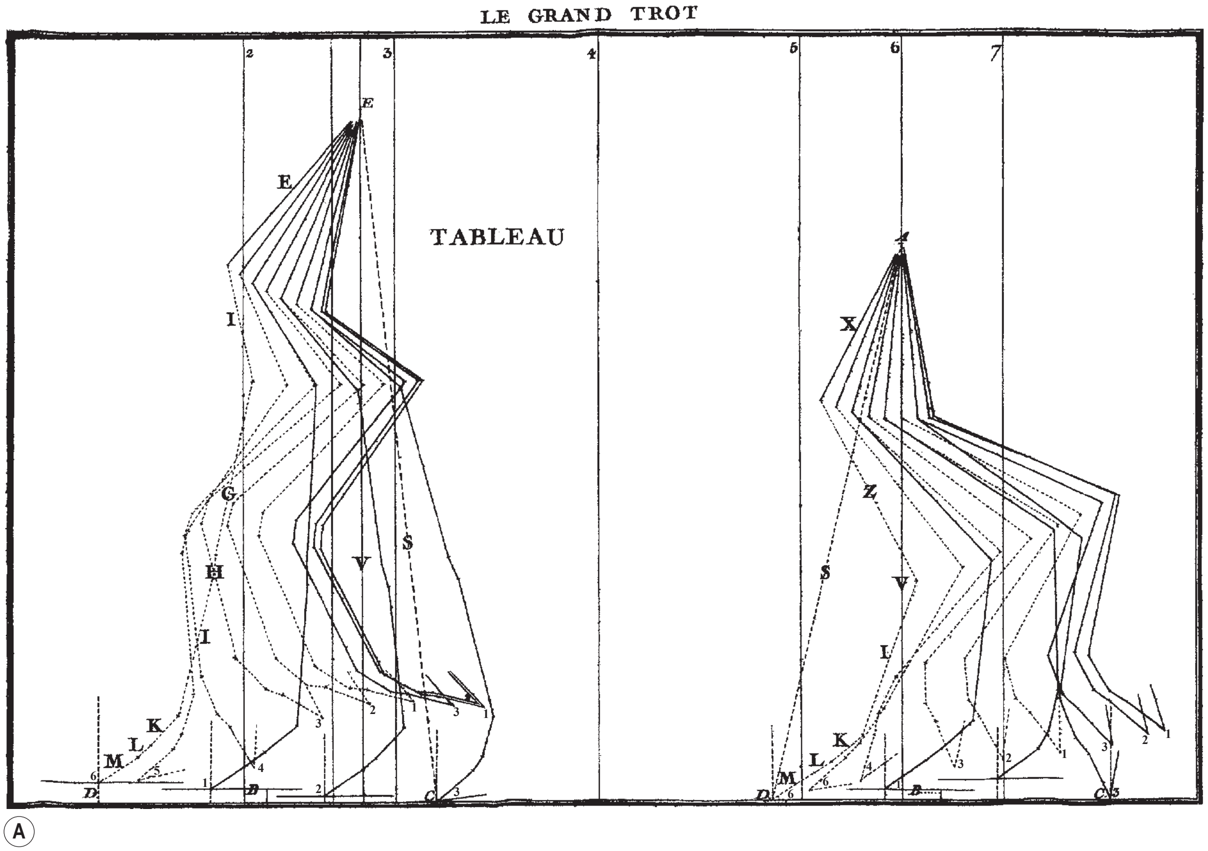
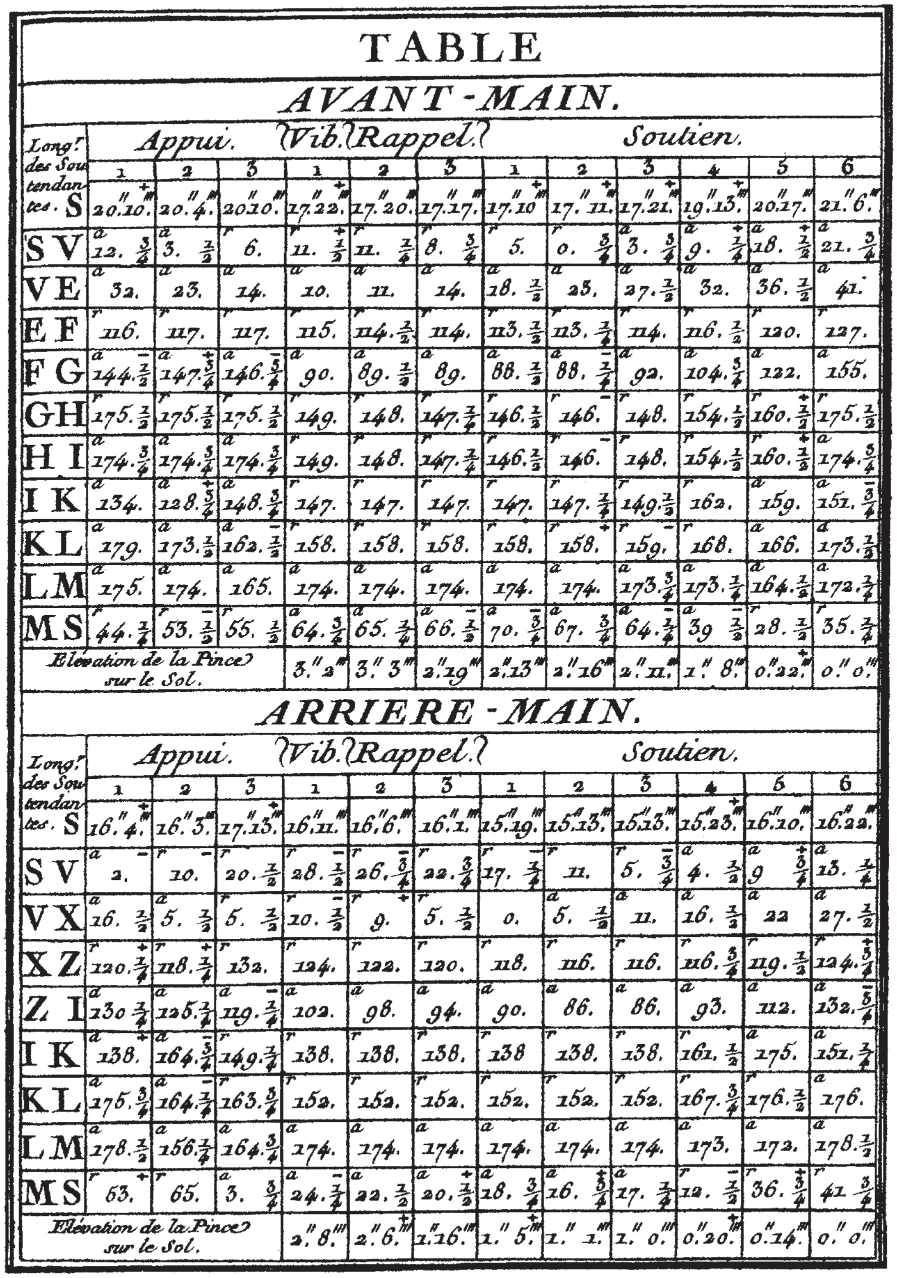


Fig 1.4 Forms in which equine gait was represented by Goiffon and Vincent in the first work that was entirely dedicated to the subject: (A) stick diagram; (B) table; (C) footfall pattern; (D) *'échelle odochronométrique'* or the precursor of the present day gait diagram.

Reproduced from Goiffon & Vincent, 1779. Mémoire artificielle des principes relatifs à la fidelle répresentation des animaux tant en peinture, qu'en sculpture. Ecole Royale Vétérinaire, Alfort.



TABLE

AVANT-MAIN.

Long.^{r} des Soustendantes.	Appui.			Vib. Rappel.			Soutien.					
	1	2	3	1	2	3	1	2	3	4	5	6
S	20″.10‴ $^{+}$	20″.4‴	20″.10‴	17″.22‴ $^{+}$	17″.20‴	17″.17‴	17″.10‴ $^{+}$	17″.11‴ $^{+}$	17″.21‴ $^{+}$	19″.13‴ $^{+}$	20″.17‴	21″.6‴
S V	^{a} 12. ¾	^{a} 3. ½	^{r} 6.	^{r} 11. ½ $^{+}$	^{r} 11. ¼	^{r} 8. ¾	^{r} 5.	^{r} 0. ¾	^{a} 3. ¾	^{a} 9. ¼ $^{+}$	^{a} 18. ½ $^{+}$	^{a} 21. ¾
V E	^{a} 32.	^{a} 23.	^{a} 14.	^{a} 10.	^{a} 11.	^{a} 14.	^{a} 18. ½	^{a} 23.	^{a} 27. ½	^{a} 32.	^{a} 36. ½	^{a} 41.
E F	^{r} 116.	^{r} 117.	^{r} 117.	^{r} 115.	^{r} 114. ½	^{r} 114.	^{r} 113. ½	^{r} 113. ¼	^{r} 114.	^{r} 116. ½	^{r} 120.	^{r} 127.
F G	^{a} 144. ½ $^{-}$	^{a} 147. ¾ $^{+}$	^{a} 146. ¾ $^{-}$	^{a} 90.	^{a} 89. ½	^{a} 89.	^{a} 88. ½	^{a} 88. ¼ $^{-}$	^{a} 92.	^{a} 104. ¾	^{a} 122.	^{a} 155.
G H	^{r} 175. ½	^{r} 175. ½	^{r} 175. ½	^{r} 149.	^{r} 148.	^{r} 147. ¼	^{r} 146. ½	^{r} 146. $^{-}$	^{r} 148.	^{r} 154. ½	^{r} 160. ½ $^{+}$	^{r} 175. ½
H I	^{a} 174. ¾	^{a} 174. ¾	^{a} 174. ¾	^{r} 149.	^{r} 148.	^{r} 147. ¼	^{r} 146. ½	^{r} 146. $^{-}$	^{r} 148.	^{r} 154. ½	^{r} 160. ½ $^{+}$	^{a} 174. ¾
I K	^{a} 134.	^{a} 128. ¾ $^{+}$	^{a} 148. ¾	^{r} 147.	^{r} 147.	^{r} 147.	^{r} 147.	^{r} 147. ¼	^{r} 149. ½	^{r} 162.	^{a} 159.	^{a} 151. ¾ $^{-}$
K L	^{a} 179.	^{a} 173. ½	^{a} 162. ½ $^{-}$	^{r} 158.	^{r} 158.	^{r} 158.	^{r} 158.	^{r} 158. $^{+}$	^{r} 159. $^{-}$	^{r} 168.	^{a} 166.	^{a} 173. ½
L M	^{a} 175.	^{a} 174.	^{a} 165.	^{a} 174.	^{a} 174.	^{a} 174.	^{a} 174.	^{a} 174.	^{a} 173. ¾	^{a} 173. ¼	^{a} 164. ½	^{a} 172. ¼
M S	^{r} 44. ¼	^{r} 53. ½ $^{-}$	^{r} 55. ½	^{a} 64. ¾	^{a} 65. ¼	^{a} 66. ½ $^{-}$	^{a} 70. ¾ $^{-}$	^{a} 67. ¾	^{a} 64. ¼ $^{-}$	^{a} 39 ½ $^{-}$	^{r} 28. ½	^{r} 35. ¼
Elévation de la Pince sur le Sol.				3″.2‴	3″.3‴	2″.19‴	2″.13‴	2″.16‴	2″.11‴	1″.8‴	0″.22‴ $^{+}$	0″.0‴

ARRIERE-MAIN.

Long.^{r} des Soustendantes.	Appui.			Vib. Rappel.			Soutien.					
	1	2	3	1	2	3	1	2	3	4	5	6
S	16″.4‴ $^{+}$	16″.3‴	17″.13‴ $^{+}$	16″.11‴	16″.6‴	16″.1‴	15″.19‴	15″.13‴	15″.13‴	15″.23‴ $^{+}$	16″.10‴	16″.22‴
S V	^{a} 2. $^{-}$	^{r} 10. $^{-}$	^{r} 20. ½	^{r} 28. ½ $^{-}$	^{r} 26. ¾ $^{-}$	^{r} 22. ¾	^{r} 17. ¼ $^{-}$	^{r} 11.	^{r} 5. ¾ $^{-}$	^{a} 4. ½	^{a} 9 ¾ $^{+}$	^{a} 13. ¼
V X	^{a} 16. ½	^{a} 5. ½	^{r} 5. ½	^{r} 20. ½ $^{-}$	^{r} 9. $^{+}$	^{r} 5. ½	0.	^{a} 5. ½	^{a} 11.	^{a} 16. ½	^{a} 22	^{a} 27. ½
X Z	^{r} 120. ¼ $^{+}$	^{r} 118. ¼ $^{+}$	^{r} 132.	^{r} 124.	^{r} 122.	^{r} 120.	^{r} 118.	^{r} 116.	^{r} 116.	^{r} 116. ¾	^{r} 119. ½	^{r} 124. ¾ $^{+}$
Z I	^{a} 130 ¼	^{a} 125. ¼	^{a} 119. ¼ $^{-}$	^{a} 102.	^{a} 98.	^{a} 94.	^{a} 90.	^{a} 86.	^{a} 86.	^{a} 93.	^{a} 112.	^{a} 132. ¾ $^{-}$
I K	^{a} 138. $^{+}$	^{a} 164. ¾ $^{-}$	^{r} 149. ¼	^{r} 138.	^{r} 138.	^{r} 138.	^{r} 138	^{r} 138.	^{r} 138.	^{r} 161. ½	^{a} 175.	^{a} 151. ¼
K L	^{a} 175. ¾	^{a} 164. ¼ $^{-}$	^{r} 163. ¾	^{r} 152.	^{r} 152.	^{r} 152.	^{r} 152.	^{r} 152.	^{r} 152.	^{r} 167. ¾	^{r} 176. ½	^{a} 176.
L M	^{a} 178. ½	^{a} 156. ¼	^{a} 164. ¾	^{a} 174.	^{a} 174.	^{a} 174.	^{a} 174.	^{a} 174.	^{a} 174.	^{a} 173.	^{a} 172.	^{a} 178. ½
M S	^{r} 63. $^{+}$	^{r} 65.	^{a} 3. ¾	^{a} 24. ¼ $^{-}$	^{a} 22. ½	^{a} 20. ½ $^{+}$	^{a} 18. ¾	^{a} 16. ¾ $^{+}$	^{a} 17. ¼	^{r} 12. ½ $^{-}$	^{r} 36. ¾ $^{+}$	^{r} 41 ¾
Elévation de la Pince sur le Sol.				2″.8‴	2″.6‴ $^{+}$	1″.16‴	1″.5‴ $^{+}$	1″.1‴	1″.0‴	0″.20‴ $^{+}$	0″.14‴	0″.0‴

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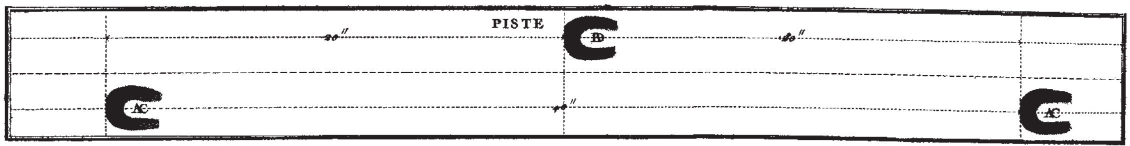

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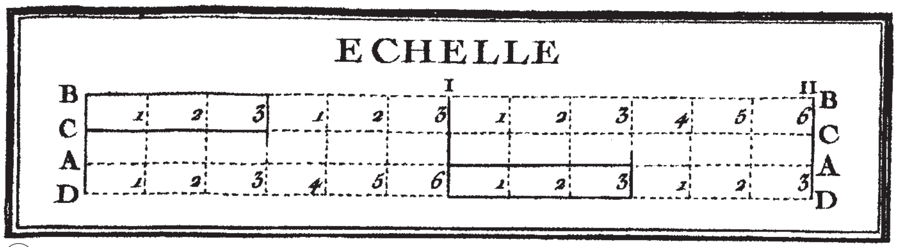

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Fig 1.4 *Continued*

in the field of equine gait analysis. So far, treatises on gait analysis had largely consisted of theoretical considerations while conclusions based on experimental data were scarce. This was mainly due to the limitations of the human eye when observing the faster gaits. In the middle of the 19th century it was still contentious whether the faster gaits had moments when all limbs were in suspension or not, as illustrated by the dispute between Gamgee and Goodman alluded to above.

It is thanks to the efforts of two men that decisive breakthroughs were made. The English-born American photographer Eadweard Muybridge and the French physiologist Etienne Jules Marey used the technology of their time to study equine gait.

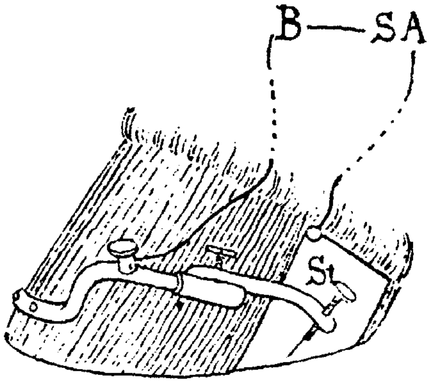


Fig 1.5 Electrical device as developed by Bayer to measure the movement of the lateral hoof wall. St, needle; B, wire to battery; SA, wire to electric bell.

Reproduced from Bayer, J., 1882. Experimentelles über Hufmechanismus. Oesterr. Monatsschr. Thierheilk. 7, 72–74.

It has been argued that 'the invention of motion pictures can be traced to an argument among the ancient Egyptians whether a trotting horse ever had all four feet off the ground at once' (Simpson, 1951). Though this certainly is a bit of an overstatement, it was this still unresolved question that led to Muybridge's first photographic

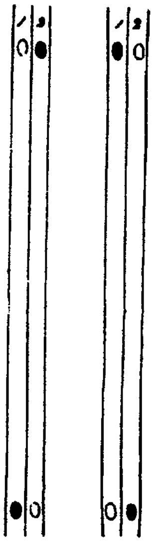


Fig 1.6 Gait diagram as introduced by Lecoq (trot). Though later used by celebrities such as Muybridge, it did not find general acceptance because it provided information about the spatial position of the limbs only, but not about temporal aspects. This in contrast to the original *'échelle odochronométrique'* invented by Goiffon and Vincent which, after modification by Marey, became the world standard.

Reproduced from Lecoq, F., 1843. Traité de l'extérieur du cheval, et des principaux animaux domestiques. Savy, Lyon.

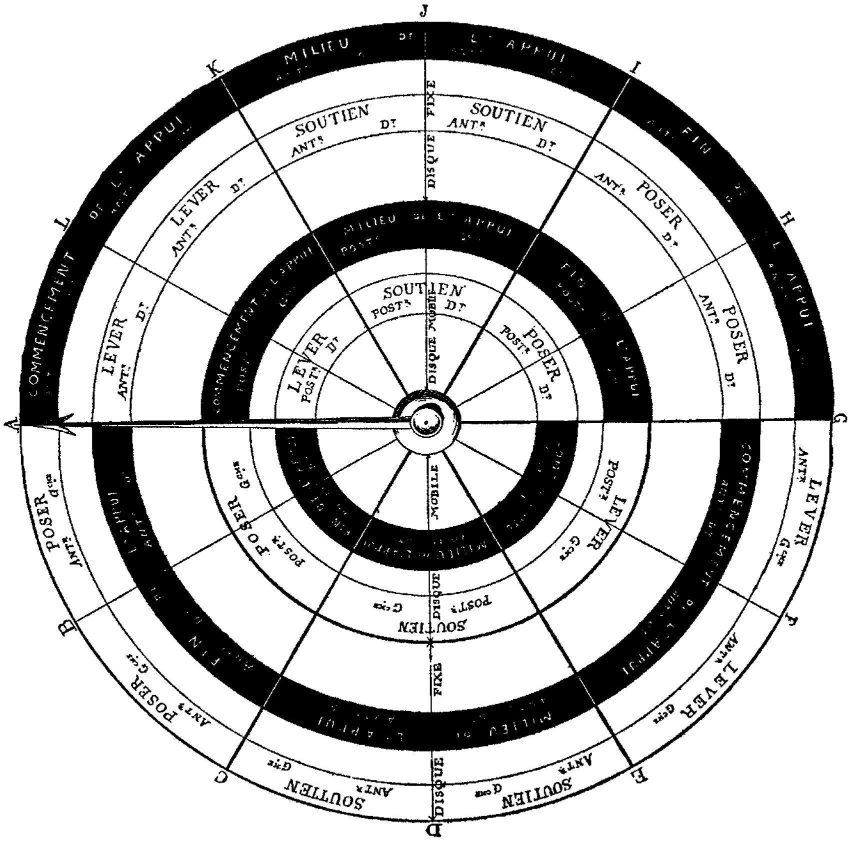


Fig 1.7 System consisting of a fixed and a rotating disc to determine the sequence of limb placement in the symmetrical gaits.

Reproduced from Raabe, 1883. Locomotion du cheval. Cadran hippique des allures marchées. T. Symonds, Paris.

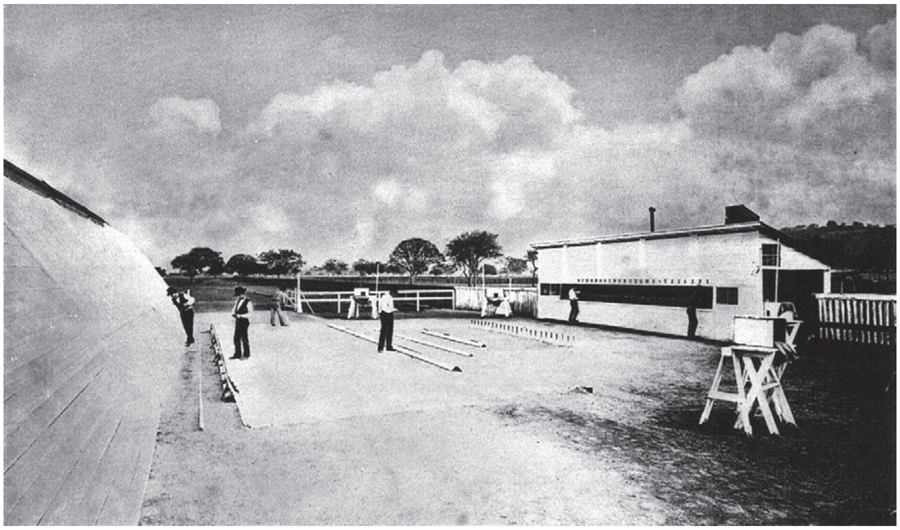


Fig 1.8 The set-up at Palo Alto in California as used by Muybridge during his research on the locomotion of the horse for Leland Stanford with 24 cameras in a linear array.

Reproduced from Stillman, J.D.B., 1882. The horse in motion as shown by instantaneous photography with a study on animal mechanics founded on anatomy and the revelations of the camera in which is demonstrated the theory of quadrupedal locomotion. James R. Osgood & Co., Boston.

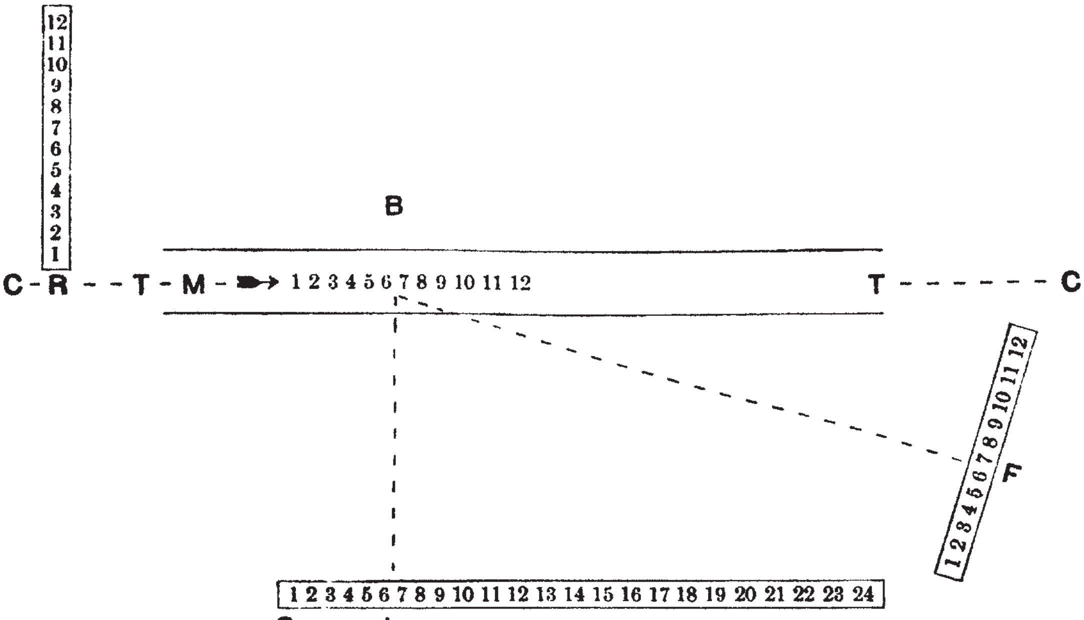


Fig 1.9 Position of cameras and track as used in the studies conducted by Muybridge during his period at the University of Pennsylvania. B, lateral background; C, transverse backgrounds; F, R, batteries of 12 automatic photo-electric cameras; L, lateral battery of 24 automatic photo-electric cameras; O, position of operator; T, track.

Reproduced from Muybridge, E., 1957. Animals in motion. Original edition 1899. Republished: Brown, L.S. (Ed.), Dover Publications, New York.

experiments. The railroad magnate Leland Stanford, the founder of Stanford University, was intrigued by this question with respect to his trotter 'Occident' and it was at his farm in Palo Alto, California, that Muybridge commenced his experiments in 1872 (Fig. 1.8).

His first efforts were unsuccessful because his camera lacked a fast shutter. Then the project was interrupted because Muybridge was being tried for the murder of his wife's lover. Though acquitted, he found it expedient to travel for a number of years in Mexico and Central America taking publicity photographs for the Union Pacific railroad, owned by Stanford. In 1877, he returned to California and later pursued his work at the University of Pennsylvania (Fig. 1.9). Muybridge placed 24 single-lens cameras on a row. The cameras were triggered in sequence by a series of thin threads that were stretched across the path of the animal. The thrust against each thread completed an electric circuit and effectuated a photographic exposure. He managed to get pictures of an excellent quality as, through an ingenious combination of clockworks and electro-magnetic circuits, he had finally succeeded in bringing exposure time down to one six-thousandth second (in a time when an exposure of half a second was considered instantaneous!).

Muybridge did not only study equine locomotion, though it formed the major part of his work. He also focused on other domesticated species, wild animals and man. His book *Animal Locomotion*, first published in 1887, has been republished several times. Muybridge also invented the 'zoöpraxiscope', a device that consisted of a large glass disc on which successive pictures were printed. By projecting these in rapid succession on a screen, it gave an

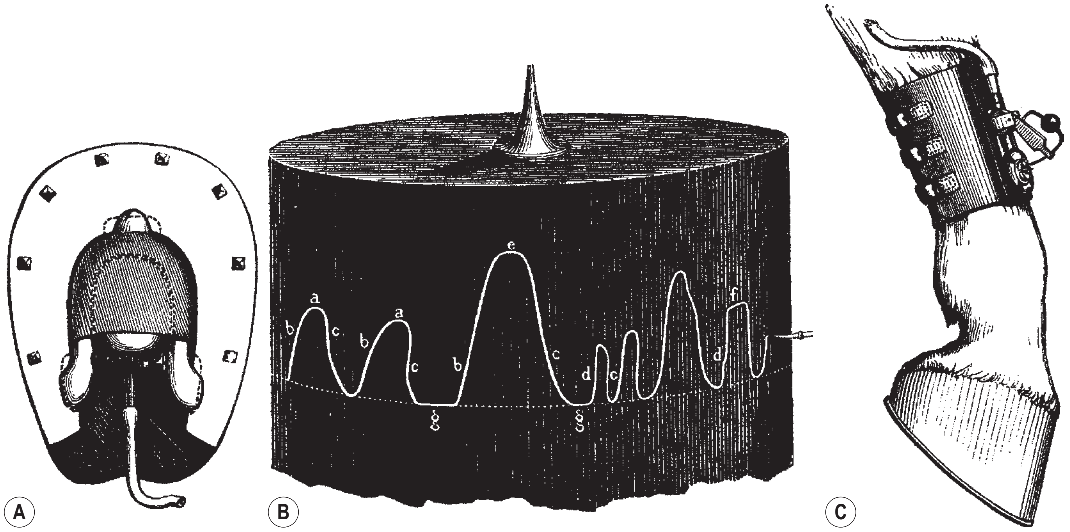


Fig 1.10 Devices developed by Marey to quantify equine locomotion. (A) *'Chaussure exploratrice'* or exploratory shoe; (B) the recorder indicating limb placement of the horse; (C) air-filled bracelet for the discrimination between stance and swing phase on hard surfaces where the *'chaussure exploratrice'* could not be used. *Reproduced from Marey, E.J., 1882. La machine animale. Locomotion terestre et aérienne. Germer Baillière et Cie, Paris.*

impression of a moving picture. In fact, this was a forerunner of present-day cine film, the invention of which is usually credited to Thomas Edison, though it is known that Edison derived some of his basic ideas from Muybridge. Early in 1888 Muybridge even discussed with Edison the possibility of producing talking pictures by synchronizing a zoöpraxiscope with a phonograph. As the phonograph at the time was not loud enough to be heard by an audience, the idea was abandoned (Muybridge, 1957). It would take another 40 years before the talking picture would conquer the world.

Though originally a photographer, Muybridge was also something of a scientist. His book *Animals in motion* has a better scientific base than the book *The horse in motion as shown by instantaneous photography with a study on animal mechanisms founded on anatomy and the revelation of the camera in which is demonstrated the theory of quadrupedal locomotion* by the physician J.D.B. Stillman (1882). Stanford provided many of Muybridge's photographs to Stillman without giving credit to the original photographer. Muybridge also suggested in a letter to *Nature* in 1883 that the photographic technique could be used to identify the winner of horse races when the finish was very close (Leach & Dagg, 1983). Indeed, in 1888, the world's first photo finish was made in New Jersey.

In the meantime, in France, the physiologist and university professor E.J. Marey investigated equine gait with equally inventive, but somewhat different techniques. Marey was intrigued by the similarity of natural mechanisms and mechanical machinery and was convinced that a more profound study of the former, especially in the area of locomotion, would lead to substantial progress in mechanical engineering. In the preface of his book *La machine animale, locomotion terrestre et aérienne* (Marey, 1882a) he writes:

> ***Quant à la locomotion aérienne, elle a toujours eu le privilège d'exciter vivement la curiosité chez l'homme. Que de fois ne s'est-il pas demandé s'il devrait toujours envier à l'oiseau et à l'insecte leurs ailes, et s'il ne pourrait aussi voyager à travers les airs, comme il voyage à travers les océans? A différentes époques, des hommes qui faisaient autorité dans la science ont proclamé, à la suite de longs calculs, que c'était là un rêve chimérique. Mais que d'inventions n'avons-nous pas vu réaliser qui avaient été pareillement déclarées impossibles?***
>
> ***(Aerial locomotion has always provoked a vivid curiosity in man. How many times did man wonder whether he would have to for ever envy the birds and insects for their wings or whether it would be possible some day for him to travel through the skies as he travels the oceans? At various times scientific authorities have declared, after having made elaborate calculations, that this was an idle dream. But how many inventions did we not see that had been declared equally impossible beforehand?)***

Twenty years later the Wright brothers would make their first flight and 80 years later long-distance maritime passenger transport would have been almost totally replaced by air travel.

In his book, Marey studied both terrestrial and aerial locomotion. The studies on terrestrial gait focused on the horse. Three ingenious devices were used to study the equine gaits in a relatively accurate way. To discriminate between stance and swing phase Marey used a 'chaussure exploratrice' or 'exploratory shoe' (Fig. 1.10A). This was essentially an India rubber ball filled with horsehair that was attached to the horse's foot. At hoof placement the ball was compressed. The increase in pressure, transmitted by airtight rubber tubing, was registered by a recorder in the rider's hand (Fig. 1.10B). The recorder consisted of a charcoal-blackened rotating cylinder on which traces were made by a needle that reacted to changes in air pressure. As this device wore rapidly on hard surfaces, a second instrument was made (Fig. 1.10C). It consisted of a kind of bracelet that was fastened to the distal limb just above the fetlock joint and that functioned according to the same principle. A third device consisted of two collapsible drums that were fastened to the withers and the croup, with levers attached to record vertical movements in the gaits.

Marey discussed various notations of gaits and concluded that the notation by Goiffon and Vincent was by far superior. He adapted this method somewhat and his notation, depicting limb placement by sequential open and filled bars, is still in common use today. Marey worked out the exact sequence of foot contacts, but his calculation of how long each foot remained on the ground was too short. Like Muybridge, he demonstrated the short suspension phase of the trot and he also correctly deduced that the hindquarters gave the main propulsion whereas the forequarters provided support (Leach & Dagg, 1983).

Though the techniques used in *La machine animale* are mainly of a mechanical nature and not photographic, Marey in fact is also one of the pioneers in photography (Marey, 1882b, 1883). At first he used multiple exposures on the same photographic plate, later he made a rotating plate not unlike Muybridge's 'zoöpraxiscope'. He also produced flight arcs of several segments of the body by repeated exposure of black objects with reflecting markers at anatomically defined points moving against a black background. Most of these techniques were applied to study human locomotion, but photographs of horses were also made. In the latter the superposition of hind limb markers over forelimb markers using the repeated exposure technique made interpretation of the data a difficult job. He and his coworkers, Pagès and Le Hello, published a fine series of articles on the subject in the *Comptes Rendus Hebdomodaires des Séances de l'Academie des Sciences* (Le Hello, 1896, 1897, 1899; Marey & Pagès, 1886, 1887; Pagès, 1885, 1889).

Coincidentally, these two great men of equine gait analysis, Muybridge and Marey, were born 1 month apart in 1830 and died within 1 week from each other in 1904. They met in Marey's laboratory, in the presence of a large number of scientists from all over the world who attended the Electrical Congress in Paris in 1881. This was when Muybridge gave the first demonstration of his 'zoöpraxiscope' in Europe (Muybridge, 1957).

German supremacy until World War II

A nice synopsis of late 19th century state of the art in the field of equine gait analysis is given in the book by Goubaux and Barrier *De l'extérieur du cheval* (*On the conformation of the horse*, 1884). They describe both Marey's techniques and Muybridge's work. They cite Marey as saying that, if he had to do his experiments again, he would use an electric circuit instead of a pneumatic system. In fact, it appears that Barrier repeated his measurements in 1899 using an electrical device to improve accuracy (Schauder, 1923b). Goubaux and Barrier also described some other means to represent equine gait such as a kind of adjustable rattle that would reproduce the sounds made by the hoof beats in the various gaits, and a wooden table that was over 8 feet high through which limb placement in various gaits could be visualized (Fig. 1.11).

Following Goubaux and Barrier, the period of French supremacy in gait analysis ended. The French were very ingenious inventors, but there is little work by French authors on gait analysis dating from after 1900 and it was essentially the Germans who chose to follow the path indicated by Marey and Muybridge. It was only through sequential photography, soon followed by cine film, which is essentially the same, that the faster equine gaits could be fully explored.

After laying the foundations in the late 19th century, German veterinary science had its golden age in the first half of the 20th century. Many disciplines flourished, but perhaps none so abundantly as the discipline of veterinary anatomy. Wilhelm Ellenberger (1848–1928) and Hermann Baum (1864–1932) published many editions of their *Handbuch der vergleichenden Anatomie der Haustiere* (*Handbook of comparative anatomy of domestic animals*). This work was so complete that a facsimile version of the 1943 edition was still in print in the 1970s. Another excellent anatomist was Paul Martin who moved from Zurich to Giessen in the first years of the 20th century. Two of his pupils were to become famous anatomists themselves: Wilhelm Schauder at Giessen University and Reinhold Schmaltz in Berlin. In Germany, the study of muscle function and locomotion was in the hands of the anatomists. It is therefore not surprising that many of these individuals became involved in equine gait analysis and/or biomechanical studies. It has been reported that Ellenberger studied the gallop by attaching 4 different-sounding bells to the feet of the horses (Schauder, 1923b). Schmaltz was among the first to extensively use cine film for equine gait analysis, and Schauder published on equine gait and related topics throughout a long career that extended until after World War II.

Chief veterinary officer in the first Dragoon Regiment at Berlin, Werner Borcherdt, used the pictures by Muybridge and the German photographer Otoman Anschütz for his largely theoretical treatise on the jumping horse (1912). In the proceedings of the *Kaiserlich-Königliche Botanische Gesellschaft* in Vienna in early 1917 professor Keller showed the results of own kinematic experiments. Keller had constructed a turntable, which was moved by the horse itself, in the center of which was a camera. This system ensured a strictly lateral view although the horse was not walking along a straight line. Keller filmed at a rate of 32–50 fps (frames per second), and showed the film at the standard rate of 16 fps, thus creating a slow motion effect. Schmaltz (1922a,b) used essentially the same technique, but used the film mainly to produce a photographic series that shows the characteristics of each gait. It is Walter (1925) who, under the guidance of Schmaltz, extensively used the turntable in his study of limb placement sequence and changes in joint angles during walk, trot and gallop. Walter admits the disadvantage of the circular movement and indicates that the clinical department of the Berlin Veterinary High School made use of a linear rail over which a camera could be moved by mechanical power in order to keep up with a horse moving on a parallel path.

In a publication from 1923, A.O. Stoss from Munich used photographic methods to study the anatomy and kinematics of the equine limbs. In the section on the shoulder he remarked that it was a pity he could not use Muybridge's pictures as for the exact location of the skeletal parts that make up the shoulder, because only skinny horses could be used for this purpose. Apparently, Muybridge's horses were too fat!

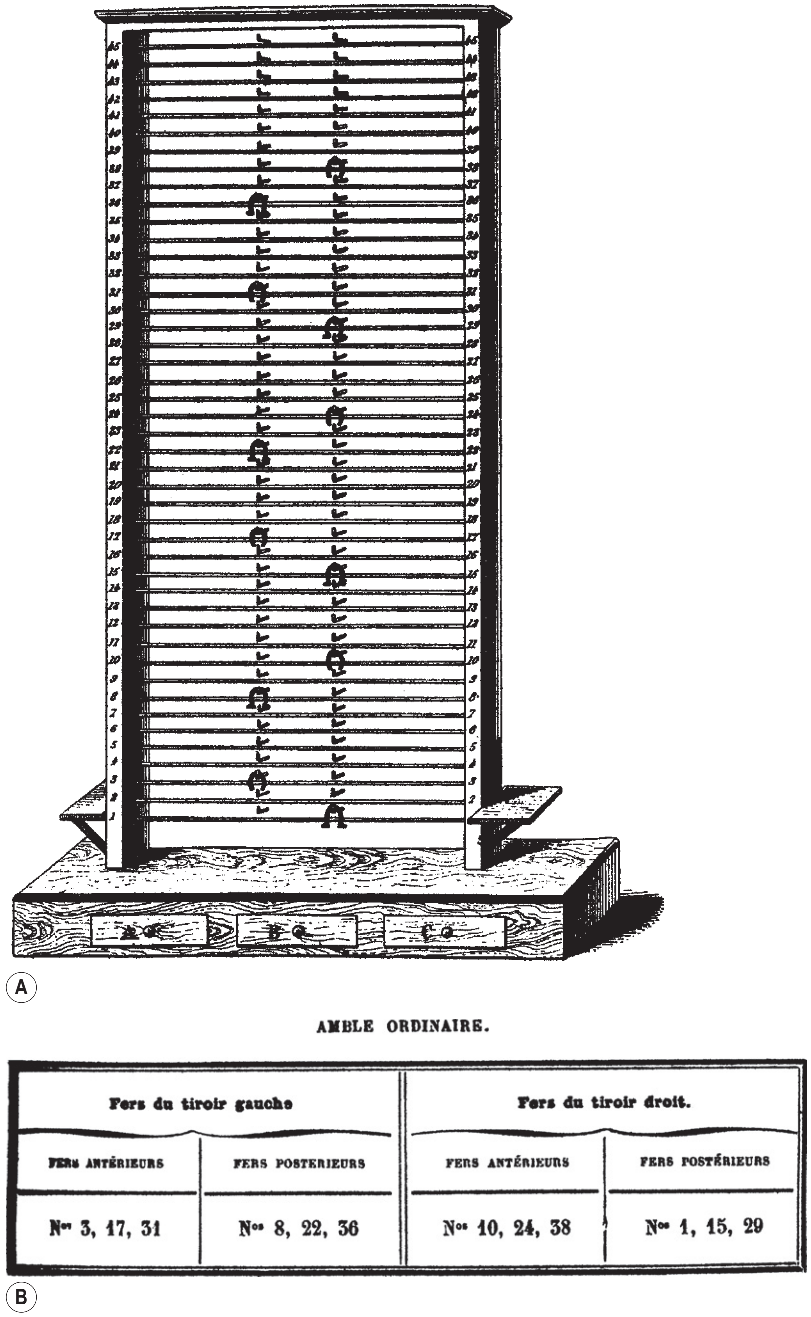
Also, studies using techniques other than photography were being performed, again mainly by anatomists. Dörrer (1911), working at the Königliche Tierärztliche Hochschule in Dresden, wrote a thesis on the tension in the flexor tendons and the suspensory ligament during various phases of the stride cycle. For his *in vitro* work he used a device that had originally been designed by Moser (Fig. 1.12). Strubelt (1928), who worked in Hanover, found that transecting either the lacertus fibrosus or the peroneus tertius muscle did not affect locomotion in the living animal, or the anatomical relations in a specimen of the hind limb that was brought under tension.

Bethcke (1930) focused on the relationship between morphometric data and performance in the trotter. Earlier studies on the subject had been performed by Bantoiu (1922) in Berlin and Birger Rösiö (1927) who performed measurements on Standardbreds in Sweden, Germany and the United States. Bantoiu was one of a series of Rumanian vets who, under the guidance of professor Schöttler in Berlin studied the relationship between conformation and performance in various breeds. His colleagues Stratul (1922), Nicolescu (1923) and Radescu (1923) studied this relationship in Thoroughbreds and Hanoverian horses. Though Bethcke is able to give some data on anatomical differences between various breeds of horses, he has to conclude that he could not predict performance, stating that:

> ***Wenn uns so auch die Maße für die Beurteilung eines Trabers gewisse Anhaltspunkte geben, so sind für seine Leistungsfähigkeit letzten Endes doch noch andere Faktoren wie Training, Temperament, Abstammung, Ausdauer, Beschaffenheit der inneren Organe usw. mit ausschlaggebend.***
>
> ***(Though the measurements may give us some clues for the judgement of a trotter, performance is in the end more determined by other factors such as training, character, descent, endurance and condition of the internal organs.)***

This conclusion has not changed in the past 80 years.

The relationship of conformation and locomotion was heavily studied in pre-war Germany. Wiechert (1927) studied East-Prussian cavalry horses to find morphometric criteria for performance potential. Though he finds some biometric differences between horses selected for specific purposes, the study lacks any statistical elaboration of the data. Buchmann (1929) focused mainly on stride length



AMBLE ORDINAIRE.

Fers du tiroir gauche		Fers du tiroir droit.	
FERS ANTÉRIEURS	FERS POSTERIEURS	FERS ANTÉRIEURS	FERS POSTÉRIEURS
Nos 3, 17, 31	Nos 8, 22, 36	Nos 10, 24, 38	Nos 1, 15, 29

Fig 1.11 Wooden table (A) invented by Goubaux and Barrier to represent the footfall pattern in various gaits. Drawers A and B contain nickel-plated shoes for fore and hind limbs. Drawer C contains a series of cards (B) on which the correct position of the feet in a certain gait are described.

Reproduced from Goubaux, A., Barrier, G., 1884. De l'extérieur du cheval. Asselin et Cie, Paris.

in various breeds. Kronacher and Ogrizek (1931) published a comprehensive study using 60 Brandenburger mares. A follow-up to this study was performed by Horst Franke (1935) who studied 186 mares from the famous stud in Trakehnen (East-Prussia). A positive relationship between the length of some limb segments and stride length was found, but results on the influence of joint angulation were not consistent. While Kronacher and Ogrizek report a clear positive relationship between stride length and shoulder and elbow angles, Franke is more cautious stating that joint angles are much less important in determining stride length than the dimensions of limb segments. The study of Schmidt (1939) is even less conclusive. He studied 100 cavalry horses with the aim of determining conformational characteristics that were indicative of a long stride, which was a desirable trait of cavalry horses that often had to cover more than 30 miles a day, and concluded that no unequivocal conformational indications could be found. Therefore, it was better to accurately measure the actual stride length when buying cavalry horses! In 1934 Wagener published a comprehensive study on jumping horses and in 1944 Wehner wrote on the relation of bone axes and joint angles and stride length in the German Coldblood.

In Munich research was more biomechanically oriented. Moskovits (1930) studied statical-mechanical aspects of the equine metacarpus. Max Kadletz studied the biomechanical behavior of the small tarsal joints in detail in relation to the pathogenesis of bone spavin (Kadletz, 1937). He also paid attention to the movements of fore and hind limbs, and addressed the age-old problem of how artists should depict horses, inventing some makeshifts for this purpose (Kadletz, 1926, 1932, 1933).

Possibly the most prolific of the pre-war German scientists was Wilhelm Krüger from Berlin. He published a very elaborate and

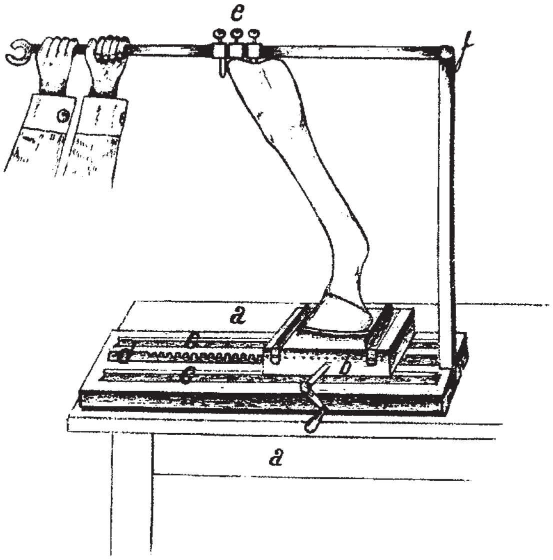


Fig 1.12 Device to (semi-quantitatively) determine the tension in the flexor tendons and the suspensory ligament in various positions of the limb as designed by Moser and used by Dörrer.

Reproduced from Dörrer, H., 1911. Über die Anspannung der Beugesehnen des Pferdefußes während der verschiedenen Bewegungsstadien derselben. Inauguraldissertation, Dresden.

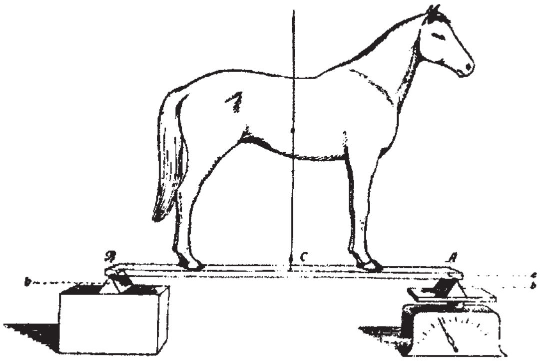


Abb. 1. Borelli'ſche Schwerpunktswaage (Schema).
Erläuterungen im Text.

Fig 1.13 The so-called 'Balance of Borelli' as used by Krüger to determine the center of gravity of the horse.

Reproduced from Krüger, W., 1939. Die Fortbewegung des Pferdes. Paul Parey, Berlin.

authoritative study on the kinematics of both fore- and hind limbs (Krüger, 1937, 1938). Krüger did not use a turntable like his predecessors Schmaltz and Walter, but made use of a vehicle that moved alongside and at the same speed as the horse, probably the same installation that had already been described by Walter. He was well aware of the artifact introduced by the use of skin markers, which had already been noted by Fick (1910) who had stated:

> ***Vor allem ist es schwierig, an den bewegten Gliedern bestimmte Punkte sicher zu markieren die ihre Lage auf der Körperoberfläche während der Bewegung nicht ändern, da sich ja auch die Haut in der Nähe der Gelenke beträchtlich verschiebt.***
>
> ***(In the first place it is difficult on the moving limbs to mark sites that do not alter their positions on the body surface during movement, as the skin near the joints shifts considerably.)***

Krüger avoided the problem by oiling the skin and using oblique lighting, thus visualizing the position of the bones directly. Though the skin displacement artifact is taken into account in most pre-war research (in contrast to many much more recent studies), this was not always the case and Krüger does not hesitate to blame this artifact for the discrepancies of his findings with those by Aepli (1937) who, in his cinematographic measurements of joint angles during locomotion, failed to correct for the artifact (Krüger, 1938). Krüger was a dedicated scientist and a prolific writer. Apart from his cinematographic work on gait analysis, which he summarized in a treatise on the movement of the horse (1939a) (Fig. 1.13), he wrote on the oscillations of the vertebral column (1939b), specific limb placement during the gallop and while jumping (1939c,d), the position of the center of gravity during locomotion (1941a), and the effect of hauling heavy loads on the tendons in the forelimb (1941b).

Though German scientists were dominant in the era between the turn of the century and World War II, this was not the only site of activity. The work of Aepli (1937), which has been referred to already, was performed in Zurich. Before World War II, there were also scientists in South America who focused on equine gait analysis. When asked to write a series of articles for a sports magazine on the gaits of the horse, Magne de la Croix from Argentina started to study photographic material, including the series made by Muybridge, and became so interested in the subject that he wrote an article on the evolution of the gallop in which he stated that, in evolutionary terms, the rotatory gallop was more advanced than the transverse gallop (Magne de la Croix, 1928). He can be seen as a forerunner of the great American zoologist Milton Hildebrand, who four decades later stated that the various gaits are not that distinct as hitherto presumed but in fact form a continuum that may gradually change into each other, when he writes:

> ***Un hecho en el cual nunca me había fijado, resaltó de repente a mis ojos, y es que el galope de carrera de los varios animales, en vez de presentarse sólo bajo dos formas: transverse gallop y rotatory gallop, como los llama Muybridge, ofrece, en realidad, una infinidad de variantes que constituyen una cadena insensible y continua.***
>
> ***(A fact that so far had never occurred to me became suddenly clear. This is that the racing gallop of the various species, instead of presenting in only two forms: transverse and rotatory gallop as Muybridge calls them, in fact presents as an infinite number of variations that form a continuous, imperceptibly changing chain.)***

He developed the idea further and included all gaits and many different animals in his extensive paper on the phylogeny of quadrupedal and bipedal locomotion in vertebrates (Magne de la Croix, 1929) (Fig. 1.14). He continued publishing on the subject until the mid-1930s (Magne de la Croix, 1932, 1936). Armando Chieffi in Brazil started his investigations of locomotion with a large study of the position of the center of gravity (Chieffi & de Mello, 1939). He continued with papers on the 'marcha' (an artificial gait) in the Mangalarga horse (1943) and with studies comparing the stance phases of different gaits and the change of gallop (Chieffi, 1945, 1946). Finally he wrote a thesis (1949) on the subject of the transition of gaits, a subject on which little scientific work had been done as he concluded from his review of the literature:

> ***O exame de literatura a respeito…… revelou que pouco ou nade existe sôbre transição de andamentos.***
>
> ***(The literature search showed that there was very little if anything on the subject of changes of gait.)***

It still is a relatively unexplored area.

In Belgium, Zwaenepoel published the same study on the impulse of gait in the horse twice in different journals (Zwaenepoel, 1910a,b, 1911a,b). In Holland, Kroon (1922, 1929) and van der Plank

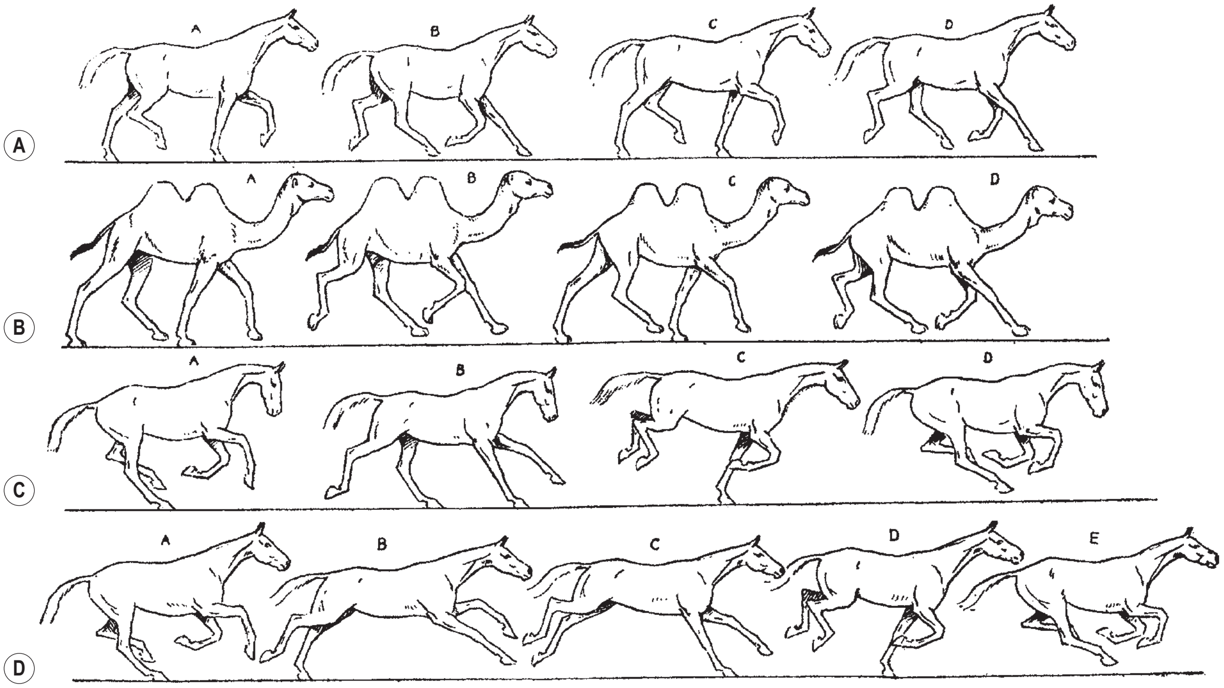


Fig 1.14 Depiction of various gaits by Magne de la Croix. (A) Trotting horse; (B) pacing camel; (C) 3-beat gallop; (D) horse featuring 4-beat racing gallop.
Reproduced from Magne de la Croix, P., 1929. Filogenia de las locomociones cuadripedal y bipedal en los vertebrados y evolución de la forma consecutiva de la evolución de la locomoción. Anal. Soc. Argent. 108, 383–406.

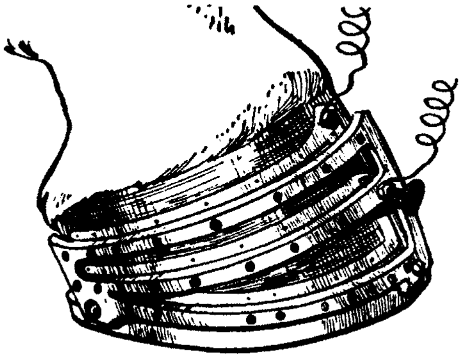


Fig 1.15 Electric device to measure deformation of the hoof wall, adapted by Kroon (1922) from the original by Bayer (1882).
Reproduced from Kroon, H.M., 1922. Een bijdrage tot de studie van het hoefmechanisme. Tijdschr. Dierg. 49 (11), 399–406.

(1929) performed some detailed studies on the hoof mechanism using electric devices, not photography or cine film (Fig. 1.15). Captain Carnus from the military training school at Saumur was one of the few French authors of the era who wrote on the subject. His was a largely theoretical study on the role of the muscles of the neck in forelimb motion (Carnus, 1935). From an earlier date is the work by another cavalry officer, who wrote a book on equine motion that contains experimental cinematographic parts on show jumping and the racing gallop (De Sévy, 1918). In Sweden, the well-known veterinarian Forssell investigated the effect of the transection of various tendons and ligaments (Forssell, 1915) and Palmgren (1929) studied the angulation pattern of the elbow joint in relation to muscle use and muscle conformation ('feathering' of certain muscle groups) in Swedish Standardbreds using high-speed cine film. In Czechoslovakia, Kolda (1937) published on the functional anatomy of the equine shoulder joint.

In the United States work in this area of research was scarce. In 1912, Gregory published a largely theoretical treatise on quadrupedal locomotion and Chubb of the American Museum of Natural History used photographs of horses as aids in the preparation of accurate specimens for the Museum (Berger, 1923). In 1934, Harry H. Laughlin, from the Carnegie Institution's Department of Genetics, published a study in which he developed a formula based on age, weight carried, distance run and time taken that quantified Thoroughbred performance in a given race. These figures were meant to serve as a 'mathematical yardstick' to be used in the search to find the natural laws governing the transmission of inborn racing capacity (Laughlin, 1934a,b). Less specific to the horse was the work of John T. Manter of South Dakota who wrote on the dynamics of quadrupedal walking (1938). The same applies to the book on speed of animals by A. Brazier Howell (1944). Also in 1944, J. Gray from Cambridge (UK) published a comprehensive study on the mechanics of the tetrapod skeleton. Even in Bolshevik Russia, research was performed. Ivanov and Borissov (1935) continued the line set by Forssell (1915) and Strubelt (1928); studying the importance of the *Lacertus fibrosus* in the standing and moving horse. Schtserbakow (1935) tried to use kinematic data for the determination of the optimal amount of work a horse should be given during training. Afanasieff (1930) claimed that he found correlations between some morphometric variables and maximal speed. He did not fail to mention that, whereas before the Russian Revolution there was a great interest in the American trotter and many crossings were made with the Russian Orlow trotter, the present breeding goal was to develop the pure Orlow trotter breed and to cut out any American influence.

The horse in decline

World War II left large parts of Europe in ruins. Apart from the tragic loss of life for millions of people, the war had a devastating effect on many aspects of pre-war society. In Germany, where research on equine gait analysis and biomechanics had flourished as nowhere else, Bernhard Grzimek was still performing research on handedness in horses, parrots and monkeys in Frankfurt Zoo in the summer of 1944 when the Allied Forces already were fighting their way to Paris through the heavily defended French province of Normandy. He submitted the paper on October 5th 1944, about at the time Montgomery's troops were defeated in the Battle of Arnhem, which would prolong the war for about half a year. However, after the capitulation of the Third Reich in May 1945, science in Germany, like practically all aspects of public life, came to a grinding halt. Grzimek's paper finally was published in 1949.

Although public life regained its vitality earlier in the formerly occupied and now liberated parts of Europe, the situation was not essentially different. Attention was focused on repairing the enormous damage caused by the war, rather than on developing new scientific approaches.

Apart from the direct consequences of the war, there were other developments that failed to stimulate new research in the field of equine locomotion. In World War I horses had been used extensively. The British expeditionary force in France in 1914 began with 53 000 horses, but it is estimated that in 1917 the army had more than 1 000 000 horses in active service over all fronts (Dunlop & Williams, 1996). On the German side the number of horses was reported to be 1 236 000 in the same year, not counting those belonging to the army contingents employed at home or in the occupied territories (von den Driesch, 1989). In German East Africa (Tanzania), the commander of the relatively weak forces, First Lieutenant von Lettow-Vorbeck, developed a 'veterinary strategy' to combat an overwhelmingly more numerous army, consisting of British, South African, Belgian and Portuguese forces. Using his superior knowledge of the local situation of tropical diseases, especially trypanosomiasis, and giving better prophylactic care to his own animals, he consistently retreated through the tsetse infested areas, inflicting heavy losses in animals on the Imperial Forces. On Armistice Day in 1918, he still was at large with his last 1323 troops, pursued by an army of 120 000.

At the start of World War II, in September 1939, Polish lancers tried to stop the invading German tanks. Not surprisingly, they suffered heavy losses and were not able to slacken the advance of the enemy. Though the German army still used horses extensively for transportation (a mean population of about 1 350 000 has been estimated of which an average of 59% was lost), it became clear that the role of the horse in warfare finally had come to an end after 5000 years. There is no modern army in which the horse plays a prominent role, except perhaps for some ceremonial duties.

The increasing mechanization not only influenced the military role of the horse. Numbers of horses in the United States reached their peak in 1918 at 21 000 000. After that year, which is also the year that automobile production first passed the 1 million mark, the population more than halved to an estimated 8 million horses and 2 million mules in 1947 (Simpson, 1951). In Britain, the agricultural horse population in 1913 was 1 324 400; in 1956 it was only 233 500 (Brayley Reynolds, 1957). It was to be expected that the day would not be far away that the last commercially used horse could be turned out to pasture after retirement. Of course, this trend affected the numbers of patients presented for treatment to the veterinary schools. In the pre-war period, the Utrecht Clinic of Large Animal Surgery received more equine than bovine patients. This ratio changed to 1 : 1 in the early post-war period and remained so through the early 1960s, followed by an increase in equine patients again from 1964 onwards, now in the form of sports and leisure animals (Offringa, 1981).

In view of the declining role of the horse in society, it is not surprising that research on equine locomotion received less priority than in the years before the war. Nevertheless, some activity remained. In Germany the old tradition had not completely been broken by the war, though the relative number of publications decreased considerably. Of the pre-war scientists, Schauder, at Giessen University, continued publishing. He was principally interested in the functional development of the musculoskeletal system. In his pre-war publications he had focused on the development of various parts of the equine musculoskeletal system (Schauder, 1924a, 1924b, 1932). After the war he continued with this subject when quoting Goethe to express his basic presumption: 'Gestaltenlehre ist Verwandlungslehre' (Morphology is the science of change, Schauder, 1949). In the early 1950s, he concentrated on shock-absorbing structures in the equine limbs and rump (Schauder, 1951, 1952, 1954), which he discussed on a theoretical basis.

The tradition at Giessen was continued by L. Krüger (not to be confused with Wilhelm Krüger from Berlin), who published on the hauling capacity of horses (and cattle) in order to determine performance capacity (Krüger, 1957). At the Institute of Animal Physiology of the University of Bonn (which features no veterinary faculty), Kaemmerer (1960) used photography to study the flight arcs of various parts of the equine limbs. He concluded that these flight arcs cannot be seen as parts of a circle, as had been stated before, but in fact are complicated cycloids which change their form when the horse is more heavily loaded. He stated, not without surprise, that the work by Walter (1925) had not received the recognition it merited. He had come across Walter's work only after finishing his own experiments, and concluded that both investigations, performed using different techniques, generally confirmed each other.

Equine gait analysis still formed a topic for a few of the many veterinary doctorate theses at the German universities. Richter (1953) in Berlin, continued the tradition of the Rumanian veterinarians from the early 1920s when he studied the American-bred trotter in order to correlate morphometric data with performance. In Giessen, Maennicke (1961) and Genieser (1962) were among the first to work with (Shetland) ponies and not with horses. The Turkish veterinarian, Ihsan Aysan (1964), analyzed the gait of lame horses during his years in Giessen in which he prepared his thesis. He worked with a 3-m long track and with a fixed camera using a film speed of 132 fps. As the distance of the horse to the camera was not constant, complicated mathematical procedures were necessary to calculate the exact locations of certain anatomical sites. Though the principle of this mathematical data processing is the same in the modern video-based systems, one should be aware of the fact that this study was undertaken before the advent of the computer. As Aysan could not statistically process the data, his work basically consists of extended case reports of various types of lameness.

Though the interest in equine locomotion certainly was at a low in the period between the end of World War II and the early 1970s, some seeds were sown of what in later decades would become rich fruit-bearing trees. In Sweden, Björck (1958) was the first to use a force-shoe to analyze the ground reaction forces exerted by the horse. In Vienna, the opening of the reconstructed lecture hall of the anatomy department in 1950 was celebrated with a lecture by Schreiber on the old theme of the anatomically (in)correct depiction of horses in art.

The then young assistant Peter Knezevic used strain gauges and cinematography to study the hoof mechanism. With a 4-channel recorder he was able to make synchronous ungulographic recordings at walk, trot and gallop (Knezevic, 1962). In Holland, Slijper had already published an extensive study on the vertebral column and spinal musculature of mammals in 1946. However, the tradition of biomechanical research and gait analysis at Utrecht University, which is maintained to the present day, can be said to have started with the publication by Dick Badoux in *Nature* on the friction between feet and ground (1964). Many publications were to follow, all focusing on the biomechanics of specific parts of the musculoskeletal system (Badoux, 1966, 1970a, 1970b). There was also a start of the input of biomechanics in essentially clinical work, as shown by the thesis of Rathor (1968) on disorders of the equine and bovine femoropatellar articulation.

Elsewhere, activity was very limited in this field of research. In France, a thesis was published by Marcel André (1949) on static, dynamic and cinematic aspects of equine locomotion. In Switzerland some work was performed on the biomechanics of the equine elbow joint in the late 1960s (Mosimann & Micheluzzi, 1969). In Eastern Europe, there was some interest in the relation between conformation and performance. Fehér focused principally on biometric data concerning the horse with a normal configuration (Fehér, 1957, 1958). From the early 1960s, Dušek from Czechoslovakia started a series of publications on the relation of a number of conformational parameters and performance like jumping ability and how to correctly evaluate these parameters. Unfortunately, some of this work was published in the Czech language, which is not accessible to many scientists (Dušek & Dušek, 1963, Dušek et al., 1970). In the German Democratic Republic, some work was done on the conformation of trotters by von Lengerken and Werner (1969). However, the breed was not very important in socialist days as there was no more than one racetrack in the whole country. In the Soviet Union, Sukhanov (1963) focused in a more general sense on the evolution of gait. In Japan Nomura published a series of reports on the mechanics of a number of equine joints in the early 1950s (Nomura, 1953a,b,c).

In the Anglo-Saxon world, the interest in equine gait analysis and biomechanics was still limited. In 1951 Grogan published a general descriptive article about gaits in horses which ominously opens with the words: 'With the drop in the number of working horses, the study of the horse has held less interest for most veterinarians and received less attention in the schools'. In England, H.W. Dawes (1957) published a paper on the relationship between conformation and soundness, giving detailed descriptions of some more or less desirable traits. The same topic is discussed by Pritchard in the United States nearly a decade later (1965). Though interesting, both papers are based on clinical impressions rather than scientific research. This is different with the work of the great American zoologist Milton Hildebrand who studied, using film among other techniques, the gaits of tetrapods. Though he used the horse frequently as a study object, his interests were broader. The analysis and interpretation of the gaits of tetrapods, including the energetics of oscillating legs in relation to conformation and gait were his main targets, not the horse itself (Hildebrand, 1959, 1960, 1965, 1966). However, in the late 1960s some horse-specific research was published in the United States (Taylor et al., 1966; Rooney, 1968, 1969; Solá, 1969; Cheney et al., 1970), indicating that we are in the wake of what may be called revolutionary changes in the science of equine biomechanical research and gait analysis.

The revival in equine locomotion research

In most countries in the world the era directly after World War II had been a period of hardship in which the damage caused by the war, either materially or economically, had to be repaired. In large parts of the world it was a period of lack of resources in which people were forced to work hard while leading a life deprived of any luxury. Gradually this picture changed since, from the late 1950s and early 1960s, economies began to boom. The mid 1960s onwards marked the start of a period of unprecedented economic growth and increasing prosperity in the developed world. While old sources of richness, such as the former colonial empires, disappeared new technological developments enabled manifold increases in human production capacity, leading to a large increase in cheap consumer goods. This development led to a period of wealth and prosperity in the industrial world.

The horse had lost its role in the military completely and in agriculture and transport to a large extent. However, it had, after 5000 years of close alliance, not lost its appeal to man. The horse had always been a very useful instrument for the satisfaction of one of the most fundamental drives of mankind, the need for competition. The official history of horse racing tells us that this sport started in 648 BC in Olympia in Greece (Simpson, 1951), but it is highly improbable that horse races were not common in the few thousand years between domestication of the horse and that date. Apart from its role in competition, the horse, unlike any other animal with the possible exception of the dog, has always had man's affection. This special bond between man and the horse is already evident in the earliest human writings on the species in Antiquity and remains so, through the great horse marshals of the 17th century and many others in the course of time, to the present day.

With the booming economy in the 1960s, popular interest in the horse could be materialized. Equestrian sports had existed for thousands of years, but had always been restricted to the lucky few. Now they became within reach of the general public. From the end of the 1960s and beginning of the 1970s equestrian sports flourished as never before. This was evident in very old and well-known branches of the equestrian sports such as flat racing and harness racing all over the world, the Western style activities in the United States, and dressage and jumping in Europe. Popular interest also increased in other, less-known, areas such as three-day-eventing, vaulting, four-in-hand driving and endurance competitions. New competitions were created in several of these disciplines and the time was ripe for the organization of large events like the World Equestrian Games, the first of which was held in Stockholm in 1990.

The increased interest in the horse was the trigger for the revival in equine locomotion research that started in the early 1970s. Though the economic role of the horse had disappeared (except for the increasing economic significance of the horse industry itself), the need for research into equine locomotion was now even greater than before. While in earlier times the horse had to be able to do its job properly which required a functional, but not necessarily superior, locomotor system, the horse now had become an athlete upon which high demands were made. This prompted the need for a highly accurate analysis of normal and abnormal gait and of the ways in which equine locomotion could be influenced or improved. Rapid developments in computer technology enabled the production of both hardware and software that facilitated capture and analysis of the faster movements of the horse in intricate detail. These were the main factors that determined the explosion in equine locomotion research that started in the late 1970s and continues today.

Thus far, an attempt has been made in this chapter to provide a comprehensive and, to the author's knowledge, as complete as possible overview of the literature on equine gait analysis because many of the older works can not be found with help of the currently used electronic databases. However, from this point on this is no longer the case. It is far beyond the scope of this chapter to provide an exhaustive bibliography of the vast amount of work that has been done in recent decades. These references can easily be found in modern databases and most of them will be mentioned in the other chapters of this book, which are dedicated to virtually all aspects of equine locomotion. In the following section a brief overview will be given of the development of the main centers of equine locomotion research in order to provide a link from the rich history of this area of research to the practice of today. References will be restricted to some key publications, but make no pretense of completeness.

Equine locomotion research centers and activities

Europe

Stockholm/Uppsala

Ingvar Fredricson and coworkers may be credited for the initiation of the revival of research on equine locomotion. In 1970, they published a report about the quantitative analysis of hoof motion patterns of harness horses using high-speed film in the proceedings of a congress on high-speed photography (Fredricson et al., 1970). Shortly after that, the new method of investigating equine locomotion was published in the then recently founded Equine Veterinary Journal (Fredricson & Drevemo, 1971). Fredricson used high-speed film (with frame rates up to 500 fps) and analysis methods derived from the aviation industry to process his data. This approach enabled him to analyze in 3 dimensions the very fast movements of the distal limbs of Standardbreds trotting at high speed (Fig. 1.16). These investigations resulted in his thesis, which may be seen as the starting point of the modern era of equine locomotion research (Fredricson, 1972).

The Swedish group, the nucleus of which was formed by Ingvar Fredricson and Stig Drevemo, later joined by Gøran Dalín and Gunnar Hjertén, focused on kinematic analysis of the Swedish Standardbred. In Sweden, harness racing had always been a popular sport, but the industry boomed in the 1970s and 1980s with Sweden and France becoming the most important countries for harness racing in Europe. This increase in popularity of the sport was partly due to the very generous fiscal legislation for horse owners. The interest in harness racing was also evident in the extensive research this group has performed on the design of racetracks, signaling deleterious effects of poor racetrack design and giving possible solutions for improvement (Fredricson et al., 1975a, b). Indeed, their work resulted in considerable improvements with respect to banking and curve geometry of many racetracks. The Swedish group may also be credited for being the first to use a treadmill for equine locomotion analysis (Fredricson et al., 1983), an example that was soon to be followed by many research centers all over the world.

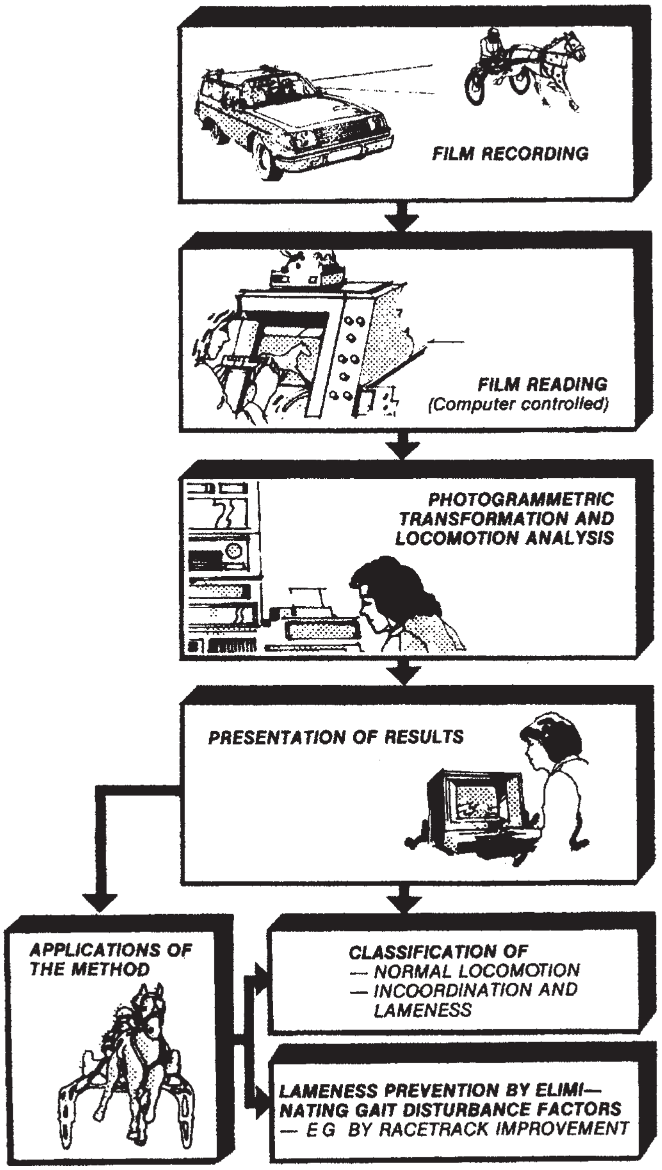


Fig 1.16 Diagrammatic representation of the data capture and data analysis procedure as used by the Swedish group in the 1970s when they worked with high-speed film.

Reproduced Fredricson, I., Drevemo, S., Dalín, G., Hjertén, G., Björne, K., 1980. The application of high-speed cinematography for the quantitative analysis of equine locomotion. Equine vet. J. 12 (2), 54–59.

After Fredricson left the group to head the national stud at Flyinge, Stig Drevemo took the helm. He became a professor of Anatomy at the Faculty of Veterinary Medicine of the Uppsala University of Agricultural Sciences into which the formerly independent Royal Veterinary College had been converted. His series of papers on equine locomotion that appeared in the Equine Veterinary Journal in 1980 can be considered as classic (Drevemo et al., 1980a–c). Drevemo was a strong protagonist of international cooperation in the field of equine locomotion research. Together with Doug Leach from Saskatoon, Canada, he published the first (and last) edition of a *Bibliography of research in equine locomotion and biomechanics* in 1988.

The almost exclusive emphasis on kinematics of the Standardbred was broken by the arrival in Uppsala of the English-born globetrotter Leo Jeffcott. His broad interest in the field of equine orthopedics included problems related to the back. With the exception of the 1939 paper by Wilhem Krüger, little attention had been paid so far to the equine back. There is little doubt that this apparent lack in interest was partly caused by the inaccessibility of this structure. Jeffcott worked with Dalín and other members of the Swedish team on normal biomechanics of the back and on various back-related disorders (Jeffcott & Dalín, 1980; Jeffcott et al., 1982, 1985).

After Jeffcott left for Australia, the Swedish group continued to perform equine locomotion research using high-speed cinematography. Though very reliable and accurate, the technique has a major drawback in that data analysis is extremely labor-intensive. The Swedes tried to overcome this problem by automating as far as possible this analysis using advanced and expensive techniques such as the Trackeye® system (Drevemo et al., 1993). In the 1990s they finally opted for the video-based Proreflex® system. Though older members of the group left or became absorbed in administrative functions, the Swedish group succeeded in maintaining momentum by attracting young researchers such as Holmström, Johnston and Roepstorff. Of these, Holmström focused on the kinematic analysis of top-level dressage horses (Holmström, et al. 1995), while Roepstorff and Johnston were engaged in the development of a force shoe suitable for use on the treadmill, in fact continuing the tradition begun by Björck in the late 1950s (Roepstorff & Drevemo, 1993).

In 1990, Uppsala housed the International Conference on Equine Exercise Physiology (ICEEP), a four-yearly conference that had started in 1982. Although the major part of this conference is dedicated to exercise physiology in a more strict sense, and thus is more cardiovascular and respiratory system oriented, the conference has always featured a part on biomechanical musculoskeletal system oriented research.

Energetically directed by Chris Johnston and Lars Roepstorff (with Stig Drevemo still in the background as Head of Department) locomotion research in Uppsala has remained strong. Around the turn of the century collaboration with the group from Utrecht was intensified in a project focusing at the kinematics of the equine back. With the results of that study it became possible to develop, together with the manufacturer of the Proreflex® system Qualisys AB, a reliable and accurate program (Backin®) for the analysis of non-invasively captured kinematic data from the equine thoracolumbar spine. Back motion had always been a very difficult area because of the difficult accessibility of the back, the relatively small ranges of motion of the components of the back and the fact that, unlike the limbs, movements out of the sagittal plane contribute significantly to overall motion. Work from Uppsala has made a substantial contribution to the knowledge about equine back motion in normal and clinically affected horses (Johnston et al., 2004; Roethlisberger-Holm et al., 2006; Rhodin et al., 2005; Wennerstrand et al., 2004). Other lines pursued in Uppsala included work on shoeing (Roepstorff et al., 2001; Johnston & Back, 2006) and on modeling and the more technical analytical aspects of equine motion (Halvorsen et al., 2008). The Uppsala group was, together with researchers from Zurich and Utrecht, one of the founders of the so-called SDS (Swiss-Dutch-Swedish) consortium that initiated a groundbreaking research project on the influence of head and neck position on dressage horses that managed to bring science closer to the equestrian sports than it ever had been (see the paragraph about the Zurich group) and later on started an FEI-backed project on the influence of the surface on the orthopedic health of the distal limb (Hernlund et al., 2010).

Vienna

Another center where research on equine locomotion was initiated in the 1970s was Vienna. Peter Knezevic had written a thesis on the biomechanics of the hoof using strain gauges when he was an assistant at the Veterinary High School. After he became head of the Department of Orthopaedics of Even and Uneven-hoofed Animals of the Faculty of Veterinary Medicine of the University of Vienna, he strongly promoted further research in this field. From the late 1970s, the Vienna group started to publish regularly on both kinematic (using high-speed cinematography and later also the Selspot® system) and kinetic studies (using force plates) in the horse (Knezevic et al., 1978; Knezevic & Floss, 1984). The historical interest of Knezevic is shown by his 1985 paper in the *Wiener Tierärztliche Monatsschrift* (where many of the papers from the first Golden Age of equine locomotion research had been published). However, this paper is principally a German copy of the Equine Veterinary Journal paper published on the same topic by Leach and Dagg in 1983. Knezevic's coworker Girtler wrote an excellent and elaborate thesis on the temporal stride characteristics of lame horses at the walk and trot which, again, appeared in the *Wiener Tierärztliche Monatsschrift* (Girtler, 1988). Also after the retirement of Knezevic locomotion research remained a priority topic in Vienna. The research facilities greatly improved when the Faculty was moved to the vast new premises at the end of the 1990s. The group was substantially reinforced by the arrival of Florian Buchner in 1996, who had spent 4 years with the Utrecht Equine Biomechanics Research group working on his PhD thesis. The growing importance of the Austrian group was recognized and in 2000 the 4th International Workshop on Animal Locomotion (IWAL-4) was organized in Vienna.

The new facilities, which included a treadmill and a Motion Analysis® kinematic gait analysis system, were not left unused. The research effort was boosted by the arrival of the vet Theresia Licka, who had graduated in Vienna but had spent a couple of years afterwards in Scotland, and the engineer Christian Peham, who became the technical figure of the group. Here too, equine back motion was studied extensively using a variety of techniques including electromyography (Licka et al., 2001). The Vienna group focused on a number of practical applications of clinical research, such as studies into saddle pressure under various circumstances (Fruehwirth et al., 2004), the influence of other tack (Kicker et al., 2004), and the effect of skill of the rider on the way a horse moves (Licka et al., 2004; Peham et al., 2004). However, more fundamental work on modeling was performed as well (Peham & Schobesberger, 2004).

Utrecht

In Holland, the foundation for the line on biomechanical research had been laid in the 1960s by Dick Badoux from the Department of Anatomy at the University of Utrecht. One of the products of this line was the still authoritative study by Wentink on the biomechanics of the hind limb of horse and dog (Wentink, 1978a,b). However, it was the strategic alliance between the Departments of Anatomy and of General and Large Animal Surgery that really boosted this kind of research from the end of the 1970s onwards. For this strategic alliance, the vision of the department heads, Professors W. Hartman and A.W. Kersjes respectively, should be given full credit.

First, Schamhardt and Merkens focused on the analysis of the ground reaction forces in sound and lame horses using a force plate (Merkens et al., 1986; Schamhardt & Merkens, 1987). Later, kinematic analysis was added. The Dutch group did not opt for high-speed film or the then recently introduced first video-based systems such as Selspot® or Vicon®, but chose a new invention from England: the CODA-3® system. This optoelectronic system used a concept that was basically different from any video-based system and thus avoided a number of disadvantages inherent to these systems. However, when the prototype with serial number 007 was delivered, it proved to be not exactly ready-to-use. In fact, it took about 4 years and a considerable amount of manpower before the machine was working well under the conditions encountered when performing gait analysis in the horse. It proved to have a high spatial and temporal (300 fps) resolution. Van Weeren, who was intended to be the first user of the newly purchased system, was forced to redirect his line of research. He started an investigation into a topic in equine kinematic gait analysis that had been correctly identified by most pre-war researchers, but which had been largely ignored so far in more recent research: the problem of skin displacement. Together with van den Bogert, Schamhardt and Barneveld, he developed techniques using intra-osseous LEDs, which shone through the skin, and transcutaneous pins to produce correction factors for skin displacement (Van Weeren & Barneveld, 1986; Van Weeren et al., 1992). In his study on the coupling between stifle and hock joint by the reciprocal apparatus, he was finally able to use the CODA-3® system for the first time (van Weeren et al., 1990). The first person using the CODA-3® system extensively was Willem Back who, in a long-term project, studied the longitudinal development of gait from 4-month-old foal to adult horse (Back et al., 1994a), concluding that the gait pattern of the individual horse does not essentially alter during this development. He also made comparisons between hard data from kinematic gait analysis and the subjective evaluation of horses as is done at horseshows and during sire selection procedures, identifying kinematic parameters that determine the judgment of quality of equine gait (Back et al., 1994b). The German veterinarian Florian Buchner used his time in Utrecht to study the kinematics of lame horses, and the symmetry of gait (Buchner et al., 1996). Besides, he performed some important work on determining the centers of gravity of various body segments (Buchner et al., 1997). Van den Bogert mathematically modeled equine gait (Van den Bogert et al., 1989). This excellent scientist included a floppy disc in his thesis with an animation of equine gait, which was a novelty at the end of the 1980s.

Apart from the kinematic and kinetic studies, other lines of research were followed as well. Some work on bone strain in the tibia was performed (Hartman et al., 1984; Schamhardt et al., 1984). Riemersma started a line on tendon research using many techniques, including kinetic and kinematic analyses (Riemersma et al., 1988a,b). This line was continued by Jansen who made use of mercury in-silastic strain gauges (Jansen et al., 1993) and by Becker who focused on the inferior check ligament (Becker et al., 1994).

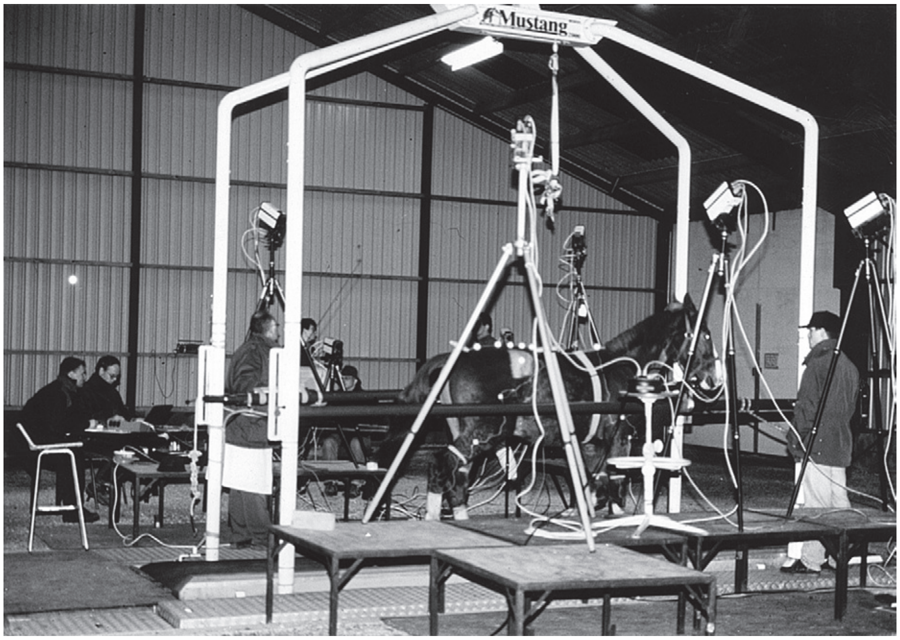


Fig 1.17 Investigations on the kinematics of the equine spine at the Utrecht Biomechanics Research Lab at the end of the 1990s by a combined Dutch and Swedish team. A total of 7 Proreflex® cameras are used.

Photograph courtesy of Utrecht Equine Biomechanics Research Group.

In 1992, a specially constructed equine biomechanics research lab was opened in Utrecht, featuring a treadmill and a force plate track. This building greatly facilitated research. In the late 1990s, the CODA-3® system was replaced by a ProReflex® system (Fig. 1.17). By the early 1990s, the Utrecht Equine Biomechanics research group had become one of the world's leading centers for equine locomotion research. This had been possible in somewhat more than a decade because of the vision of the heads of department (after the retirement of Kersjes as head of the Department of General and Large Animal Surgery, he had been succeeded by Ab Barneveld who strongly supported this line of research and, in fact, was the driving force behind many of the research projects), and the willingness to cooperate. This involved collaboration between departments, and between people with different scientific backgrounds. Henk Schamhardt, a driving force behind a large number of the research projects who unfortunately died as a consequence of a tragic accident in 1999, was a physicist not a veterinarian; as is Ton van den Bogert, who later left for Canada and the United States, changing horses for humans.

Just before the turn of the century, the Dutch group initiated a research project on the quantification of back kinematics that would, to a large extent, be carried out together with the group from Uppsala. An invasive experiment in which Steinmann pins were implanted in the spinous processes of various thoracic and lumbar vertebrae was performed that enabled the accurate quantification of back motion (Faber et al., 1999, 2001, 2002), but also served as the basis from which the skin marker-based, hence non-invasive, Backin® program was developed. Once established and validated, this technique was extensively used, among other things to study the effects of induced lameness on back motion (Gómez Álvarez et al., 2007), the effect of manual manipulation or chiropractic treatment of the equine spine (Faber et al., 2003; Gómez Álvarez et al. 2008), and the influence of various head and neck positions on equine kinematics in the SDS collaborative project alluded to earlier (Gómez Álvarez et al., 2006). Other topics of research included a five-year study into the effect of early training on jumping capacity and the predictive value of foal jumping technique for later athletic performance (Santamaría et al., 2005; Bobbert et al., 2005), saddle – related studies (De Cocq et al., 2004) and various studies on the effects of shoeing techniques and shoe types on equine locomotion (van Heel et al., 2006a). An interesting observation in the last project was that many of today's long-legged Warmblood foals tend to continually protract the same limb when they spread their front limbs in order to reach the ground for grazing, which leads to the development of uneven feet with possible clinical consequences in the long term (van Heel et al., 2006b). Maarten Bobbert of the Department of Human Movement Sciences of the Free University of Amsterdam, filled the vacuum caused by the death of Henk Schamhardt, providing invaluable scientific input. The extensive reconstruction of the entire Equine Clinic, which had been concluded in 2008, enabled the incorporation of the formerly separately housed biomechanics lab in the clinic, opening possibilities for a better integration of the lab with clinical work. A new player in the field in the Netherlands is Wageningen University, where the Department of Experimental Zoology has expanded into equine biomechanical research, focusing on the interaction of horse and rider (De Cocq et al., 2009).

Alfort

In France, the cradle of modern equine locomotion research, work on the topic had been extremely limited after the turn of the century. However, here too interest in this kind of research regained momentum at the end of the 1970s, which led to the re-emergence of France as one of the leading nations in equine locomotion research from the mid-1980s onwards. The new work originated in part from the veterinary faculties of the French universities, but also from institutions such as the Institut National de Recherches Agronomiques (INRA, National Institute for Agronomic Research) and the national Stud Services (Haras Nationaux) as is the case with the work by Langlois and co-workers (1978) relating conformation with ability in trotting, galloping and jumping. In these institutions research work of a more applied rather than fundamental character has been carried out in various fields of equestrian sports, including jumping and harness racing, which is an important discipline in France.

Alfort took the lead among the veterinary schools. Eric Barrey studied the biomechanics of the equine foot extensively (Barrey, 1987), while Jean-Marie Denoix started his very active career by studying contact areas in the fetlock joint (Denoix, 1987a) and the kinematics of the thoracolumbar spine (Denoix, 1987b). Originally an anatomist, Denoix's interest in clinical orthopedic disorders would later broaden considerably. His special interest in the biomechanics of the back, however, remained.

Fig 1.18 Trotter performing at high speed, equipped with force shoe and device for the non-invasive measurement of tendon force (A). The metal case on the sulky contains equipment for data storage. (B): non-invasive tendon force measuring device.

Photographs courtesy of Unité Mixte de Recherche Biomécanique et Pathologie Locomotrice du Cheval.

The Alfort crew aligned with INRA to form the Unité Mixte de Recherche Biomécanique et Pathologie Locomotrice du Cheval, which has been proven to be extremely productive and innovative in the past decade, led by Nathalie Crevier-Denoix. Henry Chateau made a very detailed and well-performed study into the three-dimensional motion of the equine distal limb using an invasive technique and sound-based system to capture motion (Chateau et al., 2004). Philippe Pourcelot, an engineer, was instrumental to the development of a device that could non-invasively quantify tendon force in the living and moving animal through the measurement of (changes in) speed of transmission of ultrasound signals through the tissue (Pourcelot et al., 2005) (Fig. 1.18). The group introduced more innovative technology such as a new lightweight force shoe and miniaturized accelerometers, both to be used at high speed in the performance horse (Chateau et al., 2009, Robin et al., 2009). Another example of the innovative technology produced by the group from Alfort is the video-based analysis system for the quantification of conformation that can easily be used at various horse events, such as stallion selection shows, as it requires only a single run of a horse over a defined track without any need for markers (Pourcelot et al., 2002; Crevier-Denoix et al., 2004). In 2008, the French group hosted the 6th International Conference on Equine Locomotion (ICEL-6). The French group focuses on fundamental (technological) research, as well as on more applied investigations (Vergari et al., 2012).

Zurich

In Zurich, some work was done in the 1970s and 1980s using a (Swiss-built) Kistler force plate (Koch, 1973; Hugelshofer, 1982), but it was not until the late 1990s that the vet school in Zurich seriously took up locomotor research by the development of a very special tool: a treadmill with inbuilt force plate. Through a very ingenious construction, Mike Weishaupt and colleagues, among which technician Thomas Wiestner played an important role, succeeded in combining a force plate (that can measure the vertical ground reaction force) with a Mustang® treadmill, thus avoiding the great nuisance of conventional force plates that require many runs to be made, especially at faster gaits, to get sufficient good hits (Weishaupt et al., 2002, 2004). The instrument proved crucial in the collaborative study that was performed by the SDS consortium in February 2005, which looked into the effect of various head and neck positions on equine biomechanics (Fig. 1.19). In that study, hardware from all three research groups was combined, and measurements were performed using the instrumented treadmill, a 12-camera ProReflex® system and a Novel® saddle pressure mat, simultaneously. This research project turned out to have been very timely, as shortly afterwards a fierce debate started in the equestrian lay press about the use of the so-called Rollkur (Meyer, 1992) or hyperflexion (an extremely low and flexed position of head and neck that used to be practiced by some (obviously successful) trainers and riders). The debate was highly emotional and the Zurich project provided some of the very little hard data of the effects of head and neck position. This made the outcome of the project (Gómez Álvarez et al., 2006; Weishaupt et al., 2006) play an important role in the eventual decision of the FEI (Fédération Equestre Internatonale) not to ban the practice after round table meetings held in Lausanne in 2006 and 2010, although admittedly the evidence was not conclusive, as the experiment concerned biomechanical effects only and did not look into possible behavioral consequences of the method.

United Kingdom

In the UK, where research in equine biomechanics and gait analysis had never been a strong area, a group interested in equine biomechanics emerged around Lance Lanyon and Allen Goodship. While Lanyon focused on biomechanics of bone (Lanyon, 1971; Lanyon & Rubin, 1980), Goodship dedicated himself and his group to the study of the equine tendon using force plate techniques (Goodship et al., 1983). The latter technique was also used in the extensive evaluation of various treatments of tendon injury as

Fig 1.19 Horse and rider on the instrumented treadmill at the Zurich lab during the investigations into the effect of head and neck position on equine biomechanics. Both rider and horse are equipped with reflective markers; two ProReflex® cameras can be seen in the background. The small threads running to the hooves of the horses serve to determine the exact position of each limb, which is necessary input for the analysis of the force plate data. *Photograph courtesy of Equine Hospital, University of Zurich.*

documented in the first Supplement of the Equine Veterinary Journal, the famous Silver report (Silver et al., 1983). Also from Britain, R. McNeill Alexander should be mentioned as the author of several studies on quadrupedal gait. Like the American zoologist Milton Hildebrand, Alexander regarded the horse as an example rather than a goal in itself (Alexander, 1980; Alexander & Jayes, 1983). At the Royal Veterinary College, Alan Wilson followed in his foot steps. Whereas his earlier work concerned specific equine items (Wilson et al., 1998), he later focused more on general mechanisms in equine locomotion (Wilson et al., 2001) and developed a more comparative approach (Wilson et al., 2003; Williams et al., 2007), a strategy that reduced clinical applicability, but certainly was better appreciated by the scientific community at large. Thilo Pfau has taken the lead in pursuing the clinical applications of gait analysis. His work has focused on the use of inertial measurement units to characterize movement asymmetries of the axial skeleton associated with lameness when horses move on the straight and on circles (Pfau et al., 2012). Whereas locomotion research in the UK does not have a strong historical basis, as stated before, the increase in this type of research in the past decade is remarkable, as is the diversity of institutions involved. Equine locomotion research is performed at vet schools, with the Royal Veterinary College and Bristol (Burn 2006; Parsons et al., 2008; Pfau et al., 2007; Thorpe et al., 2009) as the best examples, but certainly not limited to them. Work is done at engineering departments of universities not featuring a vet school, such as the University of Central Lancashire (Hobbs et al., 2006) and Newcastle University (Lawson et al., 2007), but is also commonplace in polytechnic type institutions such as Hartpury College (Lovett et al., 2005) and Myerscough College (Forsyth et al., 2006).

Belgium

In Belgium two main centers have been developed: in Liege the exercise physiology group (Art & Lekeux, 1988) and in Ghent (Oosterlinck et al., 2010) the focus was put on the use of pressure plate in the orthopedic examination of the horse.

Other places in Europe

In the rest of Europe there were few developments. In Germany some isolated investigations were performed (Wilsdorf, 1971; Bayer, 1973; Preuschoft & Fritz, 1977), but no new centers of research emerged. In Spain, some kinematic work has been done on Andalusian horses (Cano et al., 2001) and in Eastern Europe there are other priorities for the time being. However, some of the states in Eastern Europe have a strong tradition in horse breeding and other horse-related activities and a start with some activities in the field of equine locomotion has been made in Hungary and the Czech Republic.

North America

In North America work on equine biomechanics and gait analysis had been very limited after the great advances brought to this area of science by Eadweard Muybridge. Publications from the period that in Europe can be designated as the first Golden Age of equine locomotion research, the period between World Wars I and II, are virtually non-existent. After World War II this did not really change with only a few isolated publications on rather heterogeneous topics. However, the scene changed dramatically after the revolution started by the Swedes. In just a few years a number of research groups were founded which would become very prolific.

Saskatoon

At the Western College of Veterinary Medicine in Saskatoon, Canada, Doug Leach founded a school of equine biomechanical research that was to foster a number of excellent scientists. Leach himself published on a variety of topics including the effects of fatigue (Leach & Sprigings, 1979) and temporal stride characteristics (Leach et al., 1987). He was also interested in the history of equine locomotion research (Leach & Dagg, 1983) and was heavily involved in the definition of correct terminology (Leach et al., 1984). Another researcher from Saskatoon was Hugh Townsend who dedicated his thesis to thoracolumbar kinematics and the relationships between vertebral morphology and pathologic changes, which led to some important papers on this difficult subject (Townsend et al., 1983, 1986; Townsend & Leach, 1984).

Michigan

Leach's coworker and later chair of the Department of Veterinary Anatomy in Saskatoon, Hilary Clayton, was to become an even greater authority in the field. At first she focused on the kinematic analysis of various causes of lameness using high-speed film (Clayton, 1986, 1987). Later her research developed a more fundamental character when it was directed towards the kinematic analysis of elite sport horses (Clayton, 1993, 1994, 1997). Collaboration between Clayton and Bob Colborne, a human kinesiologist, and Joel Lanovaz, a mechanical engineer, broadened the scope of the work in Saskatoon to the calculation of net joint moments and joint powers at all joints of the equine limbs during both the stance and swing phases of the stride (Colborne et al., 1998; Clayton et al., 1998). In 1997, Clayton left Canada to become the first incumbent of the Mary Anne McPhail Dressage Chair in Equine Sports Medicine at Michigan State University in East Lansing (Fig. 1.20). The large research endowment that founded this unique chair and the construction of the new Mary Anne McPhail Equine Performance Center made equine locomotion research at Michigan State University flourish over the past decade. The excellent facilities have enabled research into a great many areas of fundamental, clinical and sport-related research (Clayton & Sha, 2006; Clayton et al., 2008; Geutjens et al., 2008), offering the possibility to many young researchers to become acquainted with equine locomotion research.

Fig 1.20 Kinematic research conducted at the Equine Sports Medicine Center of Michigan State University, East Lansing.

Photograph courtesy of Mary Anne McPhail, Dressage Chair in Equine Sports Medicine.

In 2004 the Center hosted the 5th International Conference on Equine Locomotion (succeeding the 4th International Workshop on Animal Locomotion, the name change indicating that from then on it was a single-species conference). A selection of the papers describing the research presented at the conference was published in a special issue of Equine Veterinary Journal in December 2004. In 2009 the facilities were improved by the installation of an array of six force plates designed to provide data simultaneously from all supporting limbs during locomotion on the straight and on circles and to facilitate postural sway analysis with each hoof positioned on a separate force plate (Clayton & Nauwelaerts, 2012).

Missouri

At Missouri State University, an endowed chair was installed for locomotor research related to lameness. It was Kevin Keegan who took the lead there and produced many lameness-related studies (Keegan, 2007; Keegan et al., 2008). His mathematical background drove him into new approaches, such as the fuzzy clustering technique to describe the motion of horses suspected of ataxia (Keegan et al., 2004). This research led to the development of a commercially marketed lameness detection system, the Lameness Locator™ (Equinosis® LLC, Columbia, Missouri, USA).

Other places in North America

There have been several places in the United States where work on equine locomotion has been or is performed, but thus far, apart from the groups in Michigan and Missouri mentioned above, no lasting research lines with a strong tradition have developed.

As an early researcher in equine biomechanics Jim Rooney, a pathologist in the Mecca of the American Thoroughbred industry, Kentucky, should be mentioned. In 1969 he published a book on the Biomechanics of Lameness in horses. After that, a long series of papers on a wide variety of biomechanical subjects followed. Rooney can to a certain extent be compared with the old scientists of the pre-World War II generation. The vast majority of his papers are single-authored and it sometimes is hard to tell which of his statements are personal opinions based on deductions from observations, and which are real facts based on hard, statistically sound, scientific data.

From the mid 1970s, Marc Ratzlaff and his group at Washington State University in Pullman were one of the few who extensively used electrogoniometry for gait analysis in the horse, in addition to other techniques such as cinematography (Ratzlaff, 1974; Ratzlaff et al., 1979). The gallop was the gait most intensively studied by this group (Ratzlaff et al., 1995). The start of the work by George Pratt Jr. dates from about the same period. He used the force plate and concentrated on the Thoroughbred and the interaction with the racetrack (Pratt & O'Connor, 1976; Pratt, 1984).

Nancy Deuel, who spent part of her career at the University of Maryland in College Park, wrote her thesis on the kinematic analysis of the gallop in Quarter Horses (Deuel, 1985). She later became interested in top-level performance horses and obtained permission to make recordings during the World Equestrian Games in 1990 and the Olympic Games in 1988, 1992 and 1996 (Deuel & Park, 1990, 1991). Calvin Kobluk performed equine kinematic research, first using cinematography at Guelph University, then the video-based Motion Analysis® system at the University of Minnesota (Kobluk et al., 1989).

Apart from the fundamental research, more applied investigations were also being carried out. At Texas A&M University, Gingerich et al. (1979) used the force plate to study the effect of pharmaceuticals on joint function. In the same university, Swiss-born Jörg Auer experimented with the so-called Kaegi-Straße, a 5-m long track of rubber matting consisting of a large number of tiny liquid-filled chambers, which in fact were electrical circuits. The pressure of the hoof changed the electric resistance and thus resulted in a change in the shape of the signal (Auer & Butler, 1985). This 'diagnostic street' was intended to aid in diagnosing specific lameness causes. After the first enthusiastic reports, it died a silent death as things turned out not to be as simple as that. At Tufts University, Howard Seeherman constructed his Equine Performance Lab, which, among many other tests for equine performance, featured gait analysis techniques. Apart from the detection of gait irregularities, these were mainly used to correctly balance the hooves of the patients (Seeherman et al., 1987; Seeherman et al., 1996).

At Cornell University, Kevin Haussler, a vet and qualified chiropractor, conducted research on the effects of chiropractic treatment on spinal kinematics (Haussler et al., 2001, 2007), but later moved to the orthopedic research center of Colorado State University in Fort Collins, where the research climate was more welcoming for this type of investigations. For several years the team of Don Hoyt, Steve Wickler, Ed Cogger and Darren Dutto had an active equine biomechanics and exercise physiology lab at the California State Polytechnic University Pomona. This group performed a number of fundamental studies on the relationships between gait and energetics and the effects of moving at different speeds and on an incline or decline (Hoyt et al., 2006).

Elsewhere in the world

Elsewhere in the world, research remained limited. In Australia, Leo Jeffcott began investigations into the non-invasive measurement of bone quality and the influence of exercise thereon (Jeffcott et al., 1987), while Wilson et al. (1988a,b) did some work on the kinematics of trotters. However, the only long-lasting research line was set up by Helen Davies at the University of Melbourne, where she focused on bone strain in Thoroughbred racehorses, both under *in vivo* and *ex vivo* conditions (Davies, 2006; Davies et al., 1993). In New Zealand, Chris Rogers introduced kinematic research at Massey University. He did a lot of work in collaboration with the group in Utrecht (Rogers & Back, 2007) and aims, as is the case with the SDS consortium mentioned earlier, to bridge the gap between the scientist and the end-user in the equestrian sports (Rogers et al., 1999). In Japan, Tokuriki and coworkers made advances in electromyography in the horse (Aoki et al., 1984), while Niki and colleagues used the force plate for the study of equine biomechanics (Niki et al., 1982).

In the second decade of the 21st century, the second Golden Age of equine biomechanical and locomotion research has certainly surpassed the first in researchers involved and in what had been accomplished. This type of research is now well established with various centers where high-quality research is being performed in North Western Europe and North America. Besides these major research groups, smaller scale projects are undertaken in many other places, the number of which is growing and starts to include places where no real tradition existed.

Concluding remarks

After its domestication 5000 years ago, the horse has had a close relationship with man. There is no doubt that, from a historical viewpoint, the horse's most important role has been that of a machine of war, followed by its economic significance as a draft animal. However, from the very early days after domestication, the horse has had other roles also: as a sports and competition animal and as an animal with which man formed a bond of affection. It was the latter two aspects that ensured the horse's survival when mechanization relieved the horse of its former strongholds of military and economic importance and, at the end of the 1940s, a total eclipse of the species threatened. Despite its retreat from many areas in society, the horse has remained within the public domain and is now more popular than ever.

The interest in the species from the veterinary perspective has kept pace with public appreciation of the horse. The same applies to equine locomotion research, though another factor should be mentioned too: the state of technology. The development of technology in general, and photography in particular, made possible the great breakthroughs accomplished by Muybridge and Marey at the end of the 19th century, which were the prelude to the first Golden Age of equine locomotion research. It was also the combination of the renewed interest in the horse and the rapidly developing computer technology, which led to the second Golden Age of this branch of research.

What about the future? The bond between man and the horse has proved to be strong enough to survive the disappearance of what seemingly was the *raison d'être* of the alliance between the two species. There is no reason to suppose that interest in the horse will diminish as long as economic conditions do not become too harsh. As for technology, developments in this area seem to happen at ever increasing speed. It can be anticipated that the increasing availability of high-performance micronized equipment that uses telemetry for data transfer, or is equipped with sophisticated lightweight data logging tools, will be increasingly used in real-life training and competition conditions. The day may even be not too far off that equipment of this kind becomes a compulsory feature of competition in some kinds of equestrian activities (think of rein strain gauges for dressage or heart rate equipment for endurance horses). Another branch of equine biomechanical research that is likely to flourish in the next decade is advanced modeling of various parts of the equine locomotor system with the aim to assess the effect of certain equestrian activities or environmental conditions (such as surface type) on lesion-prone structures of the horse. Research of this type will be driven, as always, by scientific curiosity, but also may become badly needed because of considerations of animal welfare that become of increasing concern to the general public.

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CHAPTER 2

Measurement techniques for gait analysis

Hilary M. Clayton, Henk C. Schamhardt (deceased)

Introduction

In a qualitative evaluation of a horse's gaits or movements, the human eye captures the image and the brain processes the information to form an opinion based on evaluating the observed motion in the context of previous experience. Even though some judges of horses and equestrian sports are very astute observers, subjectivity is inherent in this type of judgment. In assigning a lameness grade, clinicians draw on their powers of observation and previous experience to assign a lameness score in a semi-quantitative analysis. Experienced clinicians may be consistent in their scores (Back et al., 1993), but there is considerable variation between clinicians (Keegan et al., 1998).

Scientific analysis requires accurate quantitative data describing the movements and the associated forces. Kinematic analysis measures the geometry of movement without considering the forces that cause the movement. At the present time, the majority of kinematic evaluations are performed using optoelectronic systems consisting of integrated hardware and software components. Kinetics is the study of the internal and external forces that are associated with the movements. A variety of transducers, including strain gauges, piezoelectric and piezoresistive transducers, accelerometers, gyroscopes and magnetometers are used in kinetic studies. Several transducers can be combined into force plates and force shoes for measuring ground reaction forces (GRFs) or into mats for mapping pressure distribution. Electromyography (EMG) detects the electrical activity associated with muscular contraction as a means of determining muscular activation patterns during different activities. Variables that are not or cannot be measured directly may be calculated from the data by computer modeling.

Interpreting the effects of biological variability

Variability is inherent to data obtained from repeated measurements on biological material. For example, when the horse is guided over the force plate, the chance for a correct hit by one fore hoof is about 50%, with the number of hits being approximately evenly distributed between the right and left limbs. After several runs, it is likely that a different number of correct hits will have been recorded from the right and left limbs. When calculating the mean and the standard error of the mean (SEM) for a force variable (e.g. peak vertical force) by averaging the data of these runs, the mean of the data obtained from the limb with the higher number of correct hits usually has a lower SEM. Are data from that limb more 'correct' than those from the other limb? Obviously not, but it is not easy to define a universal, statistically correct recipe to deal with this problem. In practice, most laboratories collect data until a certain minimum number of correct hits have been recorded from each limb. In sound horses, both the kinematic and force variables are quite stable, and analysis of three to five strides is sufficient to give a representative value for kinematic (Drevemo et al., 1980a) or GRF (Schamhardt, 1996) analysis. The mean value is then used in further stages of the analysis as being representative of that variable for a particular limb in one horse. Most of the stride variables show good repeatability over the short and long term (Drevemo et al., 1980b; van Weeren et al., 1993; Ishihara et al., 2005; Lynch et al., 2005), and the stride kinematics of a young horse have already assumed the characteristics that they will have at maturity by the time the foal is 4 months of age (Back et al., 1994).

When planning an experiment, knowledge of the reliability of a variable should be combined with estimates of the sample size required to detect significant differences. Thus, knowledge of variability within and between recording sessions is helpful in selecting variables for analysis and in calculating the number of trials and subjects needed to obtain meaningful results in research studies.

Some horses may, inherently, show more variability than others (Lynch et al., 2005) and variability may be affected by many of the conditions that are being studied, such as lameness, the presence of a rider and the fit of the saddle. Horses with more severe lameness tend to have larger coefficients of variation for kinetic variables, both within and between horses (Ishihara et al., 2005). On the other hand, variability in stride length increased significantly when lameness was reduced by intra-articular or perineural anesthesia (Peham et al., 2001). It was suggested that variations from the optimal motion pattern are associated with pain, so lame horses maintain a highly consistent kinematic pattern, whereas sound horses are not constrained by the association between kinematic variation and pain, so other influences on motion, such as external stimuli become more influential. In horses moving on a treadmill, variability in forward velocity and acceleration decreased when the horses were ridden but the same variables had higher variability when the rider used a poorly fitting saddle compared with a well fitting saddle (Peham et al., 2004).

Variability between individual horses affects the response to certain interferences, such as drug treatment and shoeing, which differ qualitatively and quantitatively in different animals. Impressive libraries of statistical routines have been developed to extract trends in the data, to detect differences between groups, or to identify a 'statistically significant' response to a certain treatment. Unfortunately, the prerequisites for these statistical tests, such as normal distribution of the data or lack of correlation between variables, may invalidate their use in a particular study. Before conducting an experiment, an hypothesis is formulated, and an appropriate experimental design and statistical model are determined to test that hypothesis. After collection of data, it is not unusual to find dependency between variables within series of data, which disqualifies a particular statistical test. A detailed discussion of the pitfalls and problems associated with statistical testing is beyond the scope this text. Readers are advised to consult a suitable statistical text or a statistician to avoid perpetuating the use of incorrect analyses, which have appeared frequently in the literature.

A statistical test determines the likelihood that a certain hypothesis can be accepted, or has to be rejected. However, the answer is not absolute: for example, having selected an uncertainty level of $p < 0.05$, the correct decision to accept or reject the hypothesis will be made in 95% of cases but has a 5% chance of being wrong, and one observation out of 20 will differ significantly due to chance. Therefore, statistical tests are not proof that a certain hypothesis is true or false. The majority of equine locomotion studies are based on a rather small number of subjects, which may be insufficient to give the required power for a statistical analysis. In these cases, trends in the data may suggest a biologically significant effect that cannot be proven statistically but is, nevertheless, important.

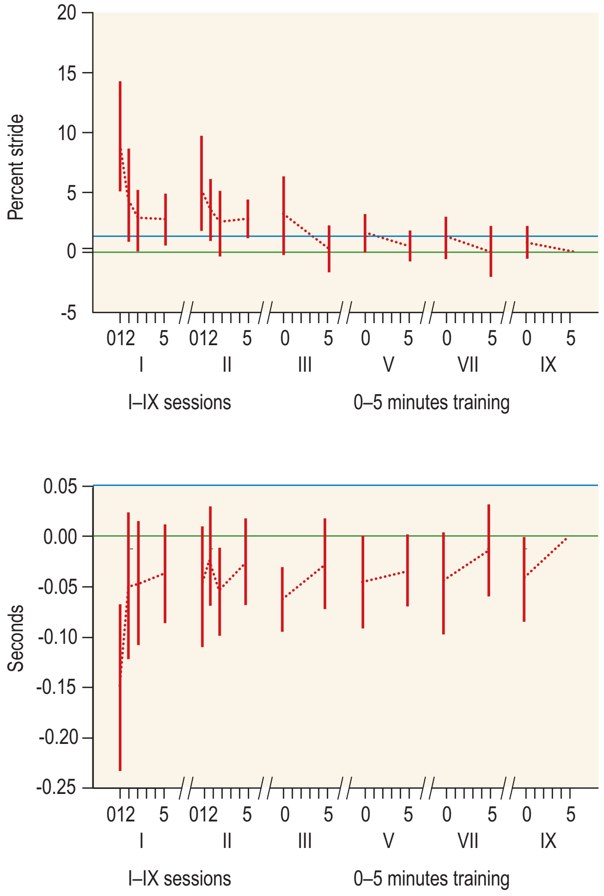

Fig 2.1 Habituation to treadmill locomotion in 10 horses determined by changes in hind limb stance duration, expressed as a percentage of stride duration (above) and in seconds (below). The horizontal axis shows the number of training sessions, each of 5 min duration. The vertical axis shows the relative stance duration. Reductions in relative stance duration are regarded as a sign of habituation. The horizontal line indicates the 'habituation limit' based on data of the final recording session. Vertical bars indicate standard deviations within 10 horses.

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Treadmill evaluation

The treadmill is extremely useful for equine gait analysis due to the ability to control the speed of movement and the environment around the horse. It must be recognized, however, that stride kinematics on the treadmill differ in some respects from over ground locomotion (Fredricson et al., 1983; Barrey et al., 1993; Buchner et al., 1994b). Horses trotting at the same speed under both conditions use a higher stride frequency and a longer stride length on the treadmill (Barrey et al., 1993). The treadmill is also associated with longer stance durations, earlier placement of the forelimbs, greater retraction of both fore and hind limbs and reduced vertical excursions of the hooves and the withers (Buchner et al., 1994b).

A period of habituation is required before horses move consistently on the treadmill, with habituation occurring more rapidly at faster gaits. Rapid adaptation is seen during the first few training sessions, and by the end of the third 5-min session, the kinematics of the trot have stabilized (Fig. 2.1), whereas walk kinematics are not fully adapted even at the tenth session (Buchner et al., 1994a). During the first session and, to a lesser extent at the start of subsequent sessions, the horse takes short, quick steps, with the withers and hindquarters lowered, and the feet splayed to the side to widen the base of support. Even experienced horses take at least one minute for their gait pattern to stabilize each time the treadmill belt starts moving (Buchner et al., 1994a). When measurements are made during treadmill locomotion, it is recommended that horses habituate for one minute after a change of gait or speed before making steady state measurements (Buchner et al., 1994a).

Horses moving on a treadmill use less energy than horses moving over ground at the same speed (Sloet & Barneveld, 1995), which may be partly due to a power transfer from the treadmill to the horse. Although the speed of the treadmill belt is assumed to be constant, in fact it is decreased by about 9% in early stance due to the frictional effect of the vertical force component and the decelerating effect of the longitudinal force component exerted by the horse's hoof. Towards the end of the stance phase the frictional effect of the vertical force declines while the propulsive longitudinal force tends to accelerate the belt (Schamhardt et al., 1994).

Although the kinematics and energetics of treadmill locomotion are not exactly equivalent to over ground locomotion, this does not diminish its value for clinical and research studies involving comparisons between locomotion on the treadmill under different conditions, for example in evaluating hoof balance and the flight arc of the hoof.

Kinematic analysis of horses moving on a treadmill has been used to study many aspects of equine locomotion, including movements of the limbs (Back et al., 1995a, 1995b), ontogeny of the trot (Back et al., 1994), response to training (van Weeren et al., 1993; Corley & Goodship, 1994), development of gait asymmetries (Drevemo et al., 1987) and kinematic adaptations used by the horse to manage lameness (Peloso et al., 1993; Buchner et al., 1995, 1996a, 1996b). The ability to incline the treadmill belt allows studies of stride kinematics when horses move on an incline or decline (Sloet et al., 1997; Hoyt et al., 2000; Dutto et al., 2004b; Hodson-Tole 2006).

Mounted studies have also been performed on the treadmill, which provides a consistent speed and environment for assessing the influence of a rider (Barrey et al., 1993; Peham et al., 2004), the effects of different training techniques or riding styles (Gomez Alvarez et al., 2006; Weishaupt et al., 2006b) and the role of saddle fit (Peham et al. 2004; Meschan et al., 2007).

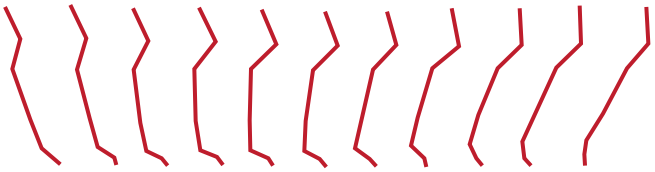

Fig 2.2 Stick figure of the forelimb of a horse trotting over ground. The figures are shown at intervals of 10% of stance duration.

Kinematic analysis

Kinematic analysis quantifies the features of gait that are assessed qualitatively by visual evaluation in terms of temporal (timing), linear (distance) and angular measurements. Visualization of kinematic data is facilitated by constructing animated stick figures (Fig. 2.2) and by plotting the results graphically. Statistical analysis can be used to compare the entire curves (e.g. Deluzio & Astephen, 2007) or to compare discrete values that represent important events.

At the present time, the most common method of motion analysis involves optical motion capture, which may be accomplished using passive markers, active markers or marker-less methods. Passive markers are coated with a reflective material that reflects back along the same path as the incident light. Active markers are usually LEDs that are distinguished by flashing in a temporal pattern. Marker-less systems are based on pattern recognition software that locates and tracks the area of interest.

Optical motion capture is generally adequate for animation and gait analysis. Markers are tracked automatically based on the emission and detection of infrared or visible light, though other methods, such as ultrasonic tracking and videographic analysis are also used. Optical technology is limited by its use of cameras to record activity; multiple cameras surrounding the action are needed to generate three-dimensional models, which generally restricts optical motion capture to a laboratory setting. In addition to the accurate (and expensive) systems used for precision analysis, less sophisticated video-based analysis systems are available that provide less accurate measurements but at a more affordable price.

The sequence of events for motion analysis involves attaching markers to the subject, setting up and calibrating the recording space, recording the subject in motion, tracking the markers to obtain digital coordinates, and data analysis that might include smoothing, normalization, transformation and interpretation of the results. Not all of these steps are required for every motion analysis project.

Markers

Most motion analysis systems are based on tracking markers fixed to the skin or the bones. For two-dimensional analysis, circular markers, 1–3 cm in diameter are used, with bigger markers giving better accuracy when the resolution of the system is poor (Schamhardt et al., 1993a). Retroreflective material, which reflects light back along the same path as the incident light, can be purchased in sheets (Scotchlite, 3M Corp., St Paul, MN) and used to make markers of a suitable size or precut circles can be purchased at a higher price. Retroreflective paint (Scotchlite 7210 Silver, 3M Corp., St Paul, MN) is also available, but clumping of the reflective beads makes it difficult to use.

For three-dimensional studies, the views from multiple cameras are integrated so that movements of the markers can be extrapolated into three dimensions. Spherical or hemispherical markers are used because they retain their circular shape when viewed from different angles. Spherical markers can be purchased or they can be fabricated from polystyrene or balsa wood balls. These markers are typically 1–3 cm in diameter, and are available from hobby stores. If necessary, the balls can be cut in half before covering them with strips of retro-reflective tape or reflective paint. The optimal diameter of the spheres depends on the resolution of the cameras. Smaller markers are lighter in weight, which facilitates marker retention, and allows a larger number of markers to be differentiated within a small volume.

Adhesion of skin markers presents some problems, especially when the horse travels at high speed or sweats profusely. Double-sided tape or high performance glue may be effective for securing the markers, but some types of glue, such as cyanoacrylate, are difficult to remove completely at the end of the study, which may pose a problem in client-owned horses. A little experimentation may be needed to find a range of appropriate products that are suitable for attaching markers under a variety of circumstances.

When markers are fixed to the skin, they are usually attached over specific bony landmarks. Accurate palpation skills are a prerequisite. Inaccuracy in identification of anatomical landmarks is a major source of error in kinematic analysis (Weller et al., 2006). In order to minimize the inaccuracies, care should be taken that the horse is standing squarely with weight on all four limbs. Any change in position or loading of a limb alters the cutaneous relationship to the underlying bone. It is useful to mark the attachment sites on the skin or hoof wall to facilitate reattachment in the same place if a marker is lost during data collection or if markers are removed and replaced during sequential recording sessions.

When markers fixed to the skin are used to represent motion of the bones, sliding of the skin over the bones introduces a significant source of error. In the proximal limb, the skin moves by as much as 12 cm relative to the bone in the sagittal plane (van Weeren et al., 1990b), which is sufficient to change the entire shape of the angle–time diagrams at the proximal joints (Back et al., 1995a). In the proximal limbs, uncorrected data cannot be used for absolute angular computations or for measuring muscle or tendon lengths based on limb kinematics. Correction for skin displacement may not be of primary importance in clinical applications, especially when comparing data in a repeated measures design, but it is essential in biomechanical applications when absolute values are important (van Weeren et al., 1992).

Bone-fixed markers are usually attached via a Steinmann pin inserted percutaneously into the bone. A cluster of at least three tracking markers is rigidly attached to the pin immediately before data collection (Chateau et al., 2004, 2006; Clayton et al., 2004, 2007a, 2007b; Khumsap et al., 2004).

Marker locations are chosen in accordance with the purposes of the analysis. Calculation of the angle between two limb segments in two dimensions requires a minimum of three markers: one over the center of joint rotation and one on each segment, preferably as far as possible from the marker representing the joint center. Figure 2.3 shows the approximate centers of joint rotation in the sagittal plane in the fore and hind limbs (Leach & Dyson, 1988). These locations are used with software that requires markers to be placed over the joint centers. An alternative technique uses two markers aligned along the long axis to represent the orientation of the segment with the difference between segmental angles being the joint angle. Ideally, marker locations should be easily identified by palpation and should be in sites where skin displacement relative to the underlying bones is minimal or correction algorithms are available for extracting the effects of skin displacement.

Markers are placed on the dorsal midline of the back to evaluate trunk motion (Licka & Peham, 1998; Faber et al., 2002; Johnston et al., 2004). These trunk markers can also be used to check that the horse is moving straight and is aligned with the axes of the Global Coordinate System (GCS) during data collection (Fig. 2.4). Markers on the poll, withers and croup are useful for evaluating vertical excursions of these reference points and for detecting

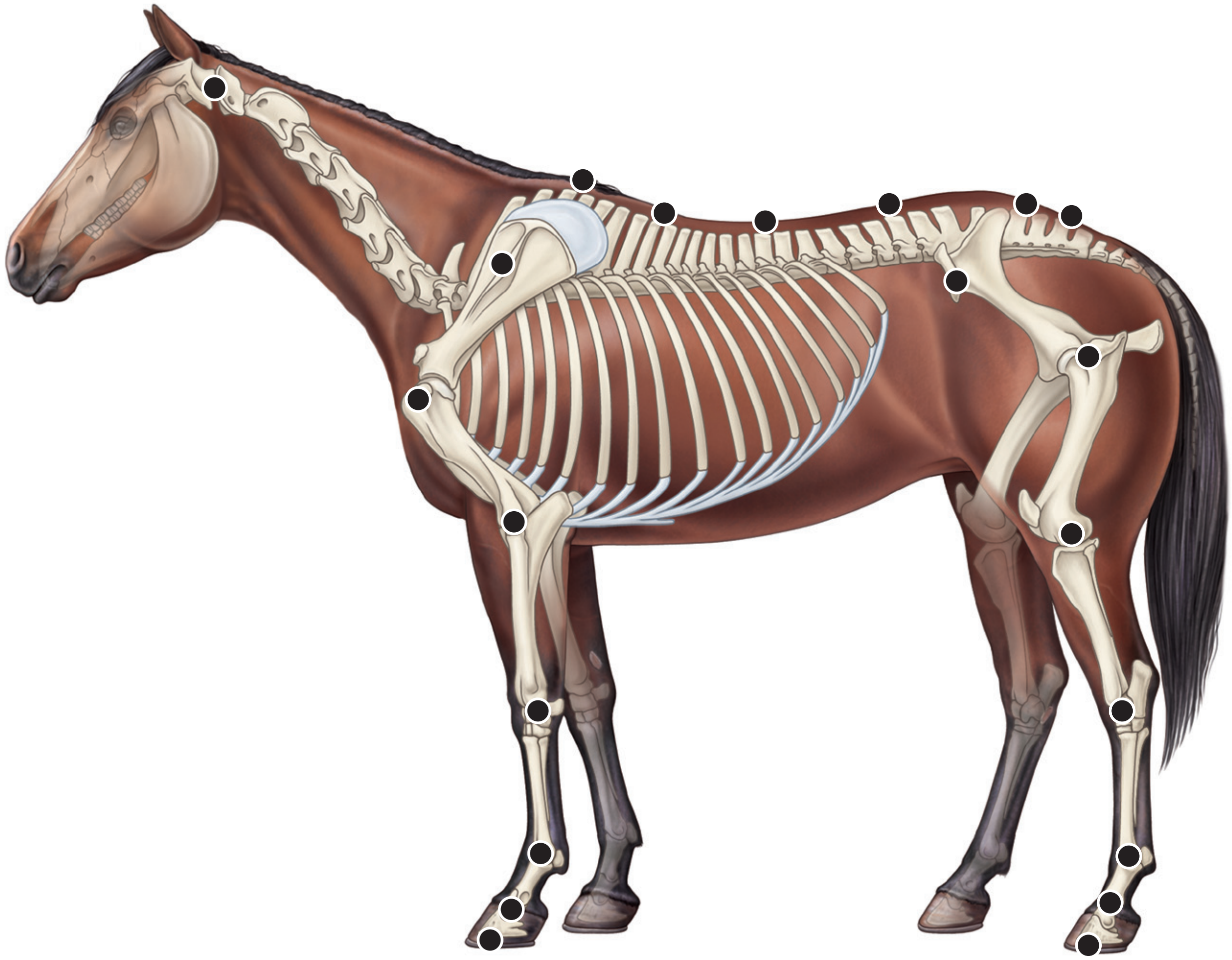

Fig 2.3 The black dots represent locations that are commonly used for skin marker placement for two-dimensional kinematic analysis. Limb markers are placed over the centers of joint rotation.

asymmetries associated with lameness (Buchner et al. 1996a; Keegan et al., 2004).

Three-dimensional analysis requires a minimum of three non-colinear markers per segment. Ideally, the markers should be widely distributed over the segment and, as for two-dimensional analysis, placed in locations that show minimal skin displacement or for which correction algorithms for skin displacement are available. Each marker must be visible to at least two cameras throughout the movement and accuracy improves with an increase in the number of cameras tracking a marker. When markers are required in locations where they are difficult to track, it is possible to use a virtual targeting system (Nicodemus et al., 1999). This method relies on the fact that, for rigid body motion, the location of any point on a body does not change with respect to that body. Therefore, if the location of a point on a segment is known with respect to the position of the markers on that segment and the orientation of the segment is known in a GCS, then the location of that point on that segment can be calculated in the GCS. The virtual targeting method employs two sets of markers: tracking markers and virtual markers. Three (virtual or tracking) markers attached to each segment are used to define the segmental coordinate system: two are oriented along the long axis of the segment and the third is perpendicular to that axis. Three non-collinear tracking markers are placed on the segment in appropriate positions to track the motion of the segment in the GCS, i.e. at locations that are readily visible to the cameras during locomotion and at locations for which the skin displacement is known. A stationary file is recorded with both the virtual and tracking markers in place, after which the virtual markers are removed. Trials are recorded with only the tracking markers in place.

In the sagittal plane, skin displacement relative to the underlying bones has been quantified and correction algorithms have been developed to calculate skin motion relative to specific bony landmarks from the scapula to the metacarpus and from the pelvis to the metatarsus of walking and trotting Dutch Warmblood horses (van Weeren et al., 1990a, 1990b, 1992). However, these algorithms are only valid for horses of similar conformation, moving at the same gaits and at similar speeds. For three-dimensional analysis, correction algorithms are available for sites on the crural and metatarsal segments (Lanovaz et al., 2004) and on the forearm segment (Sha et al., 2004) of trotting horses.

Calibration

The recording area or volume must be calibrated in order to scale the linear measurements. The accuracy of the calibration directly determines the accuracy of the final three-dimensional data (DeLuzio et al., 1993), which emphasizes the importance of investing the necessary effort into calibration of the volume space in which the measurements are made.

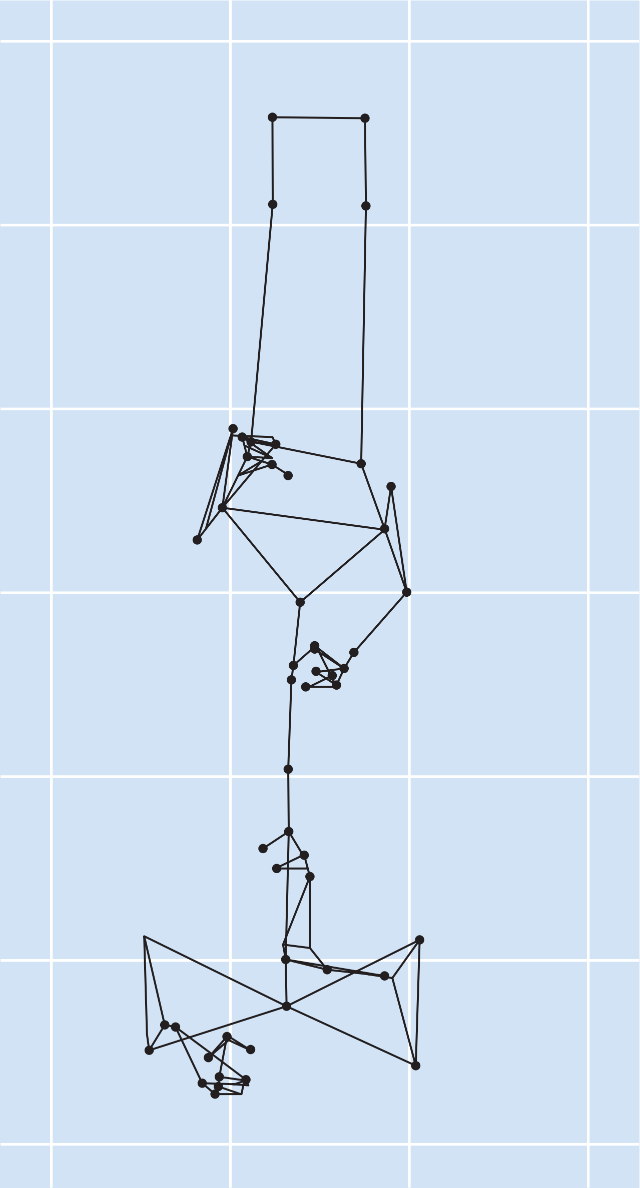

Fig 2.4 Dorsal view of horse trotting through data collection volume recorded using Motion Analysis System. The grid pattern shows the alignment of the horizontal axes of the global coordinate system (GCS). The position of the markers distributed along the horse's dorsal midline and on the left and right sides of the head and neck indicates that the craniocaudal axis of the horse's body is aligned with the longitudinal axis of the GCS. The shoulders are slightly turned to the right due to the retraction of the right forelimb.

For two-dimensional analysis, a rectangular frame or a linear ruler is recorded in the plane of movement in different areas of the movement space. If the horse deviates from the plane of calibration during data collection, errors are introduced in the linear data, though the timing data are not affected. Correction algorithms can be used to adjust the linear data if the horse moves along a line parallel to the intended plane of motion, but if the horse travels at an oblique angle to the camera, it introduces image distortion. Linear measurements in the longitudinal direction (e.g. stride length) are proportional to the cosine of the angle at which the horse moves relative to the desired direction. As long as the oblique movement angle is less than about 15°, this error is smaller than 5%. If the analysis involves measuring a transverse distance, such as step width between the left and right limbs, the error is larger and increases in proportion to the sine of the oblique movement angle. If the horse moves at an angle of 15°, the error in the transverse direction can be as large as 26%.

For three-dimensional studies a calibration frame with non-coplanar control points can be used. A larger frame with more numerous control points gives a more accurate reconstruction. The accuracy of the data is markedly reduced outside the calibrated volume, so a large, custom-designed frame is required for equine studies.

Modern motion analysis systems are calibrated using a dynamic linearization technique. First, the x, y and z axes of the GCS are defined, then a wand of appropriate length for the size of the capture volume and with markers at known locations is waved in three planes throughout the capture volume to establish camera linearization parameters. Software locates the cameras, calibrates the volume, corrects for camera lens distortions and calculates the error in linear measurements.

Sampling frequency

In order to reconstruct (interpolate) a signal from a sequence of samples, sufficient samples must be recorded to capture the peaks and troughs of the original waveform. If a waveform is sampled at less than twice its frequency the reconstructed waveform will effectively contribute only noise. This phenomenon is called 'aliasing'. For most equine kinematic studies, a sampling frequency of 120 Hz is adequate, unless the objective is to study short duration events such as impact, which require a much higher sampling frequency.

Digitization

Digitization determines the coordinates of the markers in two-dimensional or three-dimensional space within the GCS. Markers may be tracked manually, for example when there is too much ambient light for automated tracking or when markers cannot be used as in a competition. In addition to the time required, this tedious process creates more digitizing noise than automated marker tracking. With automated tracking, the system locates each marker and then calculates its centroid. Many automated systems can track complex marker sets in real time. However, the operator should check each digitized field during post-processing to make adjustments for digitizing errors, such as marker misidentification, before accepting the data for further analysis.

Smoothing

During digitization small errors are introduced that constitute 'noise' in the signal. The effect of noise is not too great in the displacement data, but it becomes increasingly apparent in the time derivatives, i.e. the velocity and acceleration data (Fioretti & Jetto, 1989) as shown in Figure 2.5. Smoothing removes high-frequency noise introduced during the digitization process using one of two general approaches: a digital filter followed by finite difference technique or a curve-fitting technique (e.g. polynomial or spline curve fitting). Selection of an appropriate smoothing algorithm and smoothing parameter for a specific purpose requires some expertise and is discussed further in Chapter 3. As a guideline, a low-pass digital filter with a cut-off frequency of 10–15 Hz is adequate for most kinematic studies of equine gait. However, if the movement of a marker has an oscillatory component, as occurs when loose connective tissue is interposed between the skin and the underlying bones, these oscillations are essentially tied to the movements themselves and cannot be removed by smoothing (Schamhardt, 1996).

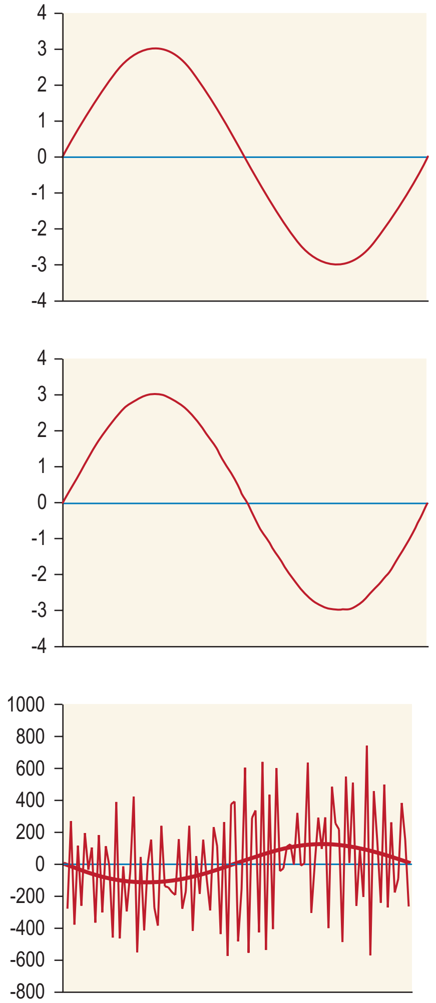

Fig 2.5 Effect of noise on derived functions. The graphs show a smooth curve (top) to which a small amount of noise has been added (center) and the second derivative from the smooth (thick red line) and noisy (thin red line) data (bottom).

Transformation

The transformation process integrates the calibration information with the digitized coordinates to scale the data. For calculating the x, y and z coordinates of the markers within the GCS, direct linear transformation (DLT) is the standard procedure for combining two or more two-dimensional views into a single three-dimensional view. This method has the advantage of not needing any information about camera locations; the transformation is based on knowledge of the coordinates of the control points on the calibration frame, which are determined for each camera view.

For studies in which three-dimensional angles are calculated, data are transformed from the GCS onto a segmental coordinate system for each segment. This process involves recording a stationary file with markers in locations that can be used to establish the axes for each segmental coordinate system. These markers may be the same as the tracking markers or they may be virtual markers that are removed after recording the temporary file.

Normalization

Normalization of data facilitates comparisons between different horses by standardizing certain parameters. Time normalization to stride duration expresses the values of the variables as a percentage of stride duration. This facilitates comparisons between strides that have slightly different durations, and allows the construction of mean curves from a number of strides. Depending on the objectives of the study, normalization to stance duration or swing duration may be more appropriate than using total stride duration. The most common method of performing time normalization is to use cubic spline interpolation to resample the curve at a set number of intervals (usually 101), which gives values at intervals from 0–100%.

Many kinematic variables are velocity-dependent. In designing research studies, consideration should be given to standardization of velocity. There are several ways in which this might be achieved. One method is to set a target velocity that all horses must adhere to within a predetermined, narrow range. This may be adequate when all the subjects are of similar size but is less satisfactory for horses that differ in size. On the treadmill, an energetically optimal speed can be determined at which the variation between motion cycles is minimized (Peham et al., 1998). This is a good method when performing repeated analyses of the same horse. However, if the protocol involves lameness, it is likely that the horse will have a slower preferred velocity when lame. An alternative approach to controlling the effects of velocity involves measuring velocity dependent changes in the variables, then developing a regression equation to predict the values of these variables at different velocities (Khumsap et al., 2001).

Joint angles in the sagittal plane may be reported in terms of the absolute joint angle, which is usually measured on the anatomical flexor aspect of the joint. Alternatively, flexion (positive) and extension (negative) angles can be expressed relative to the position at which the proximal and distal segments are aligned. In some studies, joint angular measurements have been standardized to those obtained in the square standing horse (Back et al., 1994), so that the angles are reported as deviations from this square standing position (flexion positive, extension negative). Although the patterns are the same regardless of the method of measurement, the values differ considerably, which impairs comparisons between data from different studies.

A drawback to reporting absolute values for kinematic variables is that conformational differences increase the variability between horses, which decreases statistical power and may make it difficult to detect real differences between experimental conditions. In a comparison of different methods of standardization for removing the effects of conformational variation, it was shown that subtraction of either the standing angle or the impact angle reduced variability without changing the data. Subtraction of the average joint angle during the trial or multiplicative scatter correction reduced variability even further but some of the variables changed significantly (Mullineaux et al., 2004)

Horses vary greatly in size and to compensate for the effect of size, data can be scaled such that the kinetic and gravitational forces are proportional to the horse's height and mass (Alexander, 1977).

Temporal variables are adjusted for height at the withers using the equations for acceleration and velocity (Alexander, 1977).

$$\text{acceleration} = \frac{\text{distance}}{\text{time}^2} \quad \text{then} \quad \text{time} = \sqrt{\frac{\text{distance}}{\text{acceleration}}} = \sqrt{\frac{\text{height}}{\text{g}}}$$

$$\text{velocity} = \frac{\text{distance}}{\text{time}} = \frac{\text{distance}}{\sqrt{\dfrac{\text{distance}}{\text{acceleration}}}} = \sqrt{\text{distance} * \text{acceleration}}$$

$$= \sqrt{\text{height} * \text{g}}$$

where height is subject height at the withers (m) and g is gravitational acceleration (9.8 m/s^2).

Stride, stance and swing duration may be standardized by dividing measured stride, stance and swing duration by the adjusted time and then expressed as stride duration in dimensionless units (strideDU), stance time in dimensionless units (stanceDU) and swing duration in dimensionless units (swingDU).[12]

$$\text{strideDU (s/s)} = \frac{\text{stride duration}}{\sqrt{\text{height/g}}}$$

$$\text{stanceDU (s/s)} = \frac{\text{stance duration}}{\sqrt{\text{height/g}}}$$

$$\text{swingDU (s/s)} = \frac{\text{swing duration}}{\sqrt{\text{height/g}}}$$

Similarly, subject velocities are standardized by dividing measured velocity by adjusted velocity and expressed as velocity in dimensionless units (VDU).

$$\text{VDU (ms/ms)} = \frac{\text{velocity}}{\sqrt{\text{height} * \text{g}}}$$

An objective method of predetermining an equivalent velocity for horses of different sizes is to adjust the velocity on an individual basis by taking into account height at the withers and the effects of gravitational acceleration as described above (Alexander, 1977). After setting the VDU, the target velocity for each horse is calculated.

$$\text{target velocity} = \text{VDU (ms/ms)} * \left(\sqrt{\text{height} * \text{g}}\right)$$

GRFs are standardized to the subject's body mass and expressed as force per kg body mass (N/kg). Impulses are affected by both mass and height at the withers. The measured impulse (force*stance duration) is divided by the force due to body mass (weight*g) multiplied by the adjusted time, and expressed as the impulse in dimensionless units (IDU). The equation to obtain IDU is:

$$\text{IDU (Ns/Ns)} = \frac{\text{force} * \text{stance time}}{\text{weight} * \text{g} * \sqrt{\text{height/g}}}$$

Kinematic data

Kinematic data include temporal, linear and angular variables. Temporal data, which describe the stride duration and the limb coordination patterns, are calculated from the frame numbers and the sampling frequency. Linear variables, which describe stride length, the distances between limb placements, and the flight paths of the body parts, are calculated from the coordinates of the markers combined with the calibration information. Angular variables describing the rotational motion of the body segments and joints are calculated from the coordinate data.

Analyses may be performed in two or three dimensions. Since the horse's limbs have evolved to move primarily in a sagittal plane, most of the useful information is captured by the two-dimensional lateral view, and in many situations the extra effort involved in extracting three-dimensional data is not warranted. However, there are times when knowledge of abduction/adduction or internal/external rotations would be useful, especially during sporting activities and in relation to lameness.

Sagittal plane analysis

Data are collected in a global (or laboratory) coordinate system (GCS). A common convention is for the z-axis to be vertical and to align the two horizontal axes (y: longitudinal; x: transverse) with the force plate axes or with the longitudinal and transverse axes of the runway. If the horse moves straight along the length of the runway, the y-z plane of the GCS corresponds with the horse's sagittal plane.

Multi-planar analysis

An approach that has been used in some equine studies is to project the three-dimensional coordinate data onto three orthogonal planes that are tied to the GCS (Fredricson & Drevemo, 1972). Provided the horse moves in a direction parallel to a global coordinate axis, the analytic planes become the sagittal (side view), frontal (front or rear view) and dorsal (dorsal or ventral view) planes. In effect, this method degrades the three-dimensional analysis into a series of quasi-two-dimensional analyses. Joint motion that is not parallel to one of the projection planes cannot be accurately measured and, since the segments are defined as simple lines between landmarks, rotations along the long axis of a segment are impossible to measure.

Three-dimensional analysis

A true three-dimensional analysis requires multiple cameras that are synchronized precisely and with each marker visible to at least two cameras at all times. Each length measurement has three components in space and a segment requires three angle measurements to define its orientation. A three-dimensional joint coordinate system (JCS) is established for the joint based on embedding an anatomically meaningful coordinate system within each limb segment comprising the joint. Flexion/extension, adduction/abduction, and internal/external rotation are usually expressed as motions of the distal segment relative to the fixed proximal segment (Fig. 2.6). The angles can be described independently of each other, which allows for examination of complex coupled motion in a joint. Angles measured with the JCS are independent of the joint centers of rotation.

One method of expressing three-dimensional joint motions is based on a strictly ordered sequence of three rotations, known as Euler angles. In aeronautical terminology these are referred to as pitch, yaw and roll. The drawback to the use of Euler angles is the need to specify the order of rotations. In an effort to express joint motion in a context that is more meaningful to clinicians, Grood and Suntay (1983) proposed the use of a JCS for the human knee joint in which the rotations are consistent with the clinical definitions of flexion/extension, abduction/adduction and internal/external rotation. The first axis of rotation (flexion/extension) was attached to the segment proximal to the joint, the third (internal/external rotation) axis was attached to the distal segment and the second (adduction/abduction) axis was a floating axis that was mutually perpendicular to the other two axes and was not aligned with the planes of either segment (Fig. 2.6). For each axis, there is a rotation around the axis and a translation along the axis. All three rotations take place at the same time, as in a mechanical linkage, thus eliminating the need to specify the order of rotations. The method of Grood and Suntay (1983) brought a wider acceptance of the value of the JCS in a clinical setting, though it is now understood that their method is actually identical to the Euler angle method.

When using the JCS method, kinematic analysis is typically performed in three steps. The first step is to define a coordinate system on each bone. Second, the rotation matrix and translation vector relating the GCS with the JCS is obtained from three-dimensional marker coordinates during motion using a singular value decomposition method (Soderkvist & Wedin, 1993). This algorithm produces a rotation matrix and a translation vector that describe the rotation and translation of the segmental coordinate system from its neutral position in the stationary file to the orientation in each frame of tracked data. In the final step, matrix equations are used to extract the three rotation angles and three translations (Grood & Suntay, 1983). Relative angular motions (helical angle changes) between the segments may be calculated using a spatial attitude method (Spoor & Veldpaus, 1980; Woltring, 1994) or Euler angles may be calculated (Ramakrishnan & Kadaba, 1991). Software is

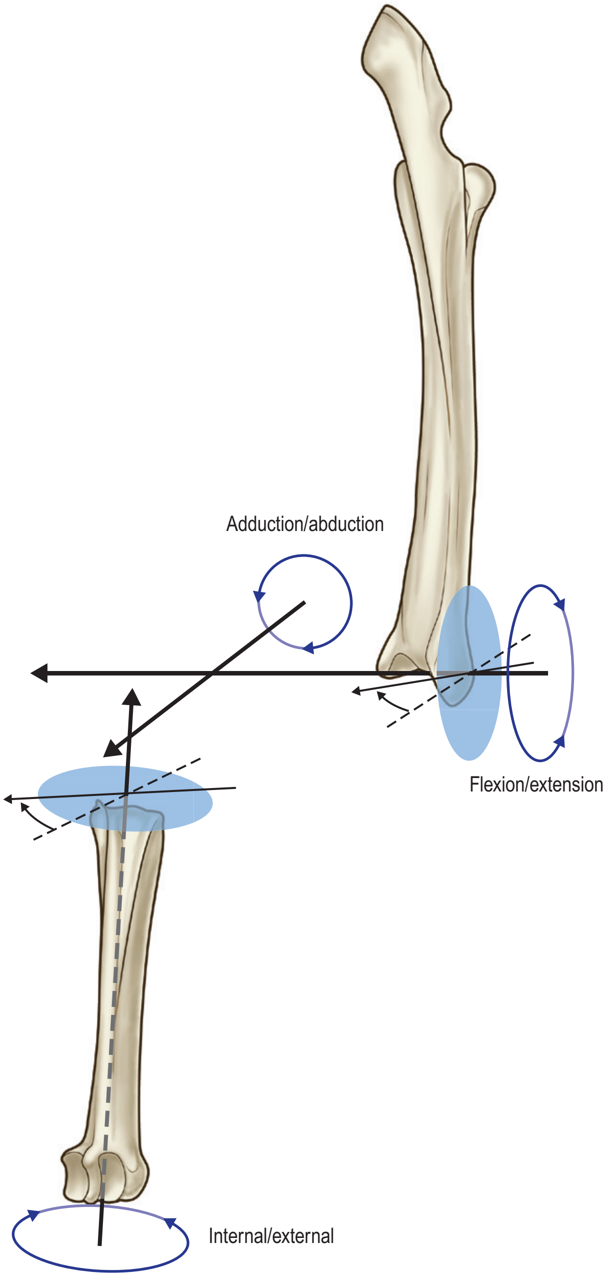

Fig 2.6 Three-dimensional joint coordinate system for kinematic analysis. Flexion/extension and external/internal rotation are expressed in terms of the distal segment rotating relative to the proximal segment around axes embedded in the proximal and distal segments, respectively. Abduction and adduction are relative to the floating axis, which is mutually perpendicular to the other two axes.

available to perform these steps or computer code can be accessed in the public domain. Markers on the model are defined and, from the marker trajectories, joint rotations and translations are solved iteratively by global optimization.

When using a segment-based or bone-based local coordinate system, decisions regarding the establishment and orientation of the axes have important effects on the results of the analysis and must, therefore, be stated clearly (Capozzo et al., 2005). Both joint kinematics (Beardsley et al., 2007) and net joint moments (Schache & Baker, 2007) vary significantly according to the coordinate system used and, even though the alternative frames of reference are mathematically valid, differences in output affect interpretation of the results. Clinical conclusions can be upheld or refuted, based on the same data set, subject to coordinate system definitions (Beardsley et al., 2007). Choice of the coordinate system is, therefore, critical to the outcome of a study.

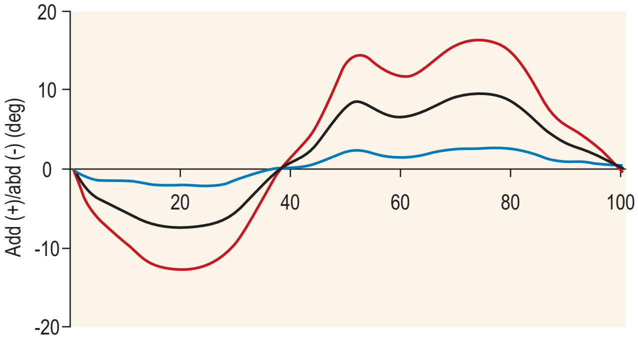

Fig 2.7 Adduction and abduction of the metacarpophalangeal joint during trotting for the segmental coordinate system that was defined by a standing pose (black line), after +10° (inward) rotation (red line) and after −10° (outward) rotation (blue line) of the segmental coordinate system of the proximal phalanx around the longitudinal axis of the bone.

In equine studies, limb segment axes have been based on anatomical landmarks identified by palpation and/or fluoroscopy (Khumsap et al., 2004; Clayton et al., 2004, 2007a, 2007b) or using a template attached to the bones (Chateau et al., 2004, 2006). A right-handed coordinate system is used to establish the three axes around which flexion/extension, abduction/adduction and internal/external rotation occur. Errors are reduced if the axis aligned with the longest dimension of the bone is established first.

Kinematic crosstalk is a common problem in using the JCS method. Flexion/extension angles are robust due to their large signal to noise ratio and misalignments between the horse or the plane of motion and the GCS tend to have little effect on flexion/extension measurements where this is the predominant type of motion (Ramakrishnan & Kadaba, 1991). However, these misalignments will cause some of the flexion movement to be misinterpreted as abduction. Figure 2.7 shows the effect of a small (±10°) change in alignment of the flexion/extension axis on the amount of motion ascribed to abduction/adduction at the fetlock joint (Clayton et al., 2007a). Another problem with the JCS methodology is gimbal lock, which causes the rotation angles to become increasingly sensitive to measuring errors when the second rotation approaches ±90° (Woltring, 1994).

Methods of kinematic analysis

This section will give a brief review of older techniques used in kinematic data collection, and will then describe the principles of modern motion analysis systems in greater detail.

Electrogoniometry

An electrogoniometer or elgon is a device for measuring joint angle changes. It consists of a potentiometer attached to two rigid, rotating arms that are fixed to the limb with tape or straps, so that the center of the elgon lies over the center of rotation of the joint (Fig. 2.8). A change in joint angle alters the electrical resistance of the potentiometer, which is calibrated with a protractor. Permanent records, or goniograms, can be recorded on an oscilloscope and the data stored for later analysis.

In horses, electrogoniometry has been used to record joint movements at different gaits in normal and lame horses (Adrian et al.,

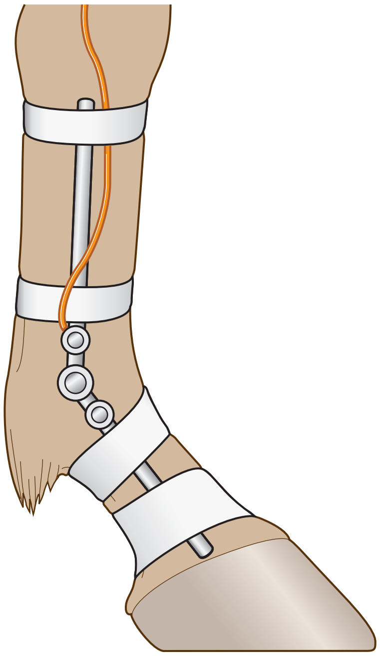

Fig 2.8 Electrogoniometer (elgon) placed over the equine fetlock joint.

1977), to diagnose obscure lameness, and to evaluate changes in joint motion after medical or surgical treatment (Taylor et al., 1966; Ratzlaff et al., 1979). The availability of image-based motion analysis systems has superseded the use of electrogoniometry.

Photographic systems

In the past high-speed cinematography was the most commonly used optical technique for kinematic analysis, but it was an expensive and tedious method that has declined in popularity since the advent of high-resolution video cameras and optoelectronic motion analysis systems. TrackEye (Image Systems AB, Linköping, Sweden) is an image digitizing system that processes high-speed film to provide accurate two-dimensional or three-dimensional data. This system has been used for equine kinematic analysis at Uppsala University.

Videography is now the standard photographic recording and analysis technique. The availability of video replay is especially useful for sports applications or in a clinical setting. The level of sophistication ranges from simple visual appraisal through the use of interactive software to turnkey systems that autodigitize reflective markers. Some video systems also offer a manual digitizing option that can be used when there are no markers on the subject, for example during competition. Manual digitizing is also a useful option when the autodigitizing system has difficulty differentiating between markers placed close together, markers that cross each other as the horse moves or markers that are temporarily obscured. It is important to verify marker identifications before accepting the data for further analysis to avoid errors in the raw data being propagated throughout the subsequent analysis.

For single camera, two-dimensional studies, the video camera is precisely oriented with its axis perpendicular to the plane of interest. To overcome the limitations of a small field of view, a panning camera can be used. For three-dimensional studies, precise camera positioning is less important, so long as each marker is visible to at least two cameras at all times. If the angle between cameras is small, however, it may reduce the accuracy along the axis running toward the cameras.

A standard camcorder records 30 frames/s in the NTSC format and 25 frames/s in the PAL format. Each frame consists of two interlaced video fields recorded 1/60 s (NTSC) or 1/50 s (PAL) apart. Software displays successive fields sequentially giving an effective sampling rate of 60 fields/s (NTSC) or 50 fields/s (PAL). High-speed video cameras are useful for studies of short-duration events or rapid movements but the lighting conditions become critical at faster recording speeds. Comparisons of joint displacement data from horses cantering on a treadmill showed minimal loss of information in terms of angular data when the sampling rate was reduced from 200 Hz to 50 Hz (Lanovaz, unpublished). Linford (1994) compared the temporal stride variables in horses trotting on a treadmill by analyzing the same ten strides with cameras sampling at 60 Hz and 1000 Hz, respectively. Mean values for stride duration, stance duration, swing duration, and breakover did not differ by more than 3.3 ms. Thus, 60 Hz is an adequate sampling rate for kinematic analysis of many aspects of equine locomotion, but a large number of strides must be analyzed to produce a representative mean value for temporal events of short duration. At gaits faster than a walk, a higher sampling rate is preferable, especially if the displacement data will be processed further.

High-speed video cameras capable of recording at very high frame rates (up to several thousand frames per second) usually offer only a few seconds of recording time unless the video is recorded to a hard drive in a separate recording unit or computer. These cameras require very good lighting; the shorter the exposure time, the more illumination is needed to maintain acceptable image quality. High speed, high-resolution camcorders are available that are easy and convenient to use and record for a reasonable duration to a digital tape or DVD.

A number of software packages with varying levels of sophistication are marketed for video-based kinematic analysis. These packages may offer marker-less tracking, simultaneous multiple two-dimensional video capture and stroboscopic imaging. Marker-less tracking digitizes unique user specified patterns on a frame-by-frame basis without markers or manual intervention. If the image contains a distinguishable pattern that is visible across several frames, the system can recognize a point within the pattern and track it automatically for the entire sequence (Fig. 2.9). By simultaneously collecting multiple two-dimensional camera views, it is possible to perform a multi-planar analysis. Images that represent distinct events, such as ground contact, midstance and lift-off, can be viewed to create stroboscopic files.

Some packages, such as Dartfish (Dartfish, Fribourg, Switzerland), that are designed for use by athletic coaches and trainers are relatively inexpensive and easy to use. Software targeted to the equine market includes Equinalysis (Equinalysis, Gwehelog Usk, UK), Equine Gait Trax Digital Motion Analysis System (Motion Imaging Corp., Simi Valley, CA) and Ontrack (Lameness Solutions, LLC., Altrincham, UK). Software offering a more complete biomechanical profile that can be used with video data includes the Ariel Performance Analysis System (Ariel Dynamics Inc., Trabuco Canyon, CA), SIMI Motion (Simi Reality Motion Systems GmbH, Unterschleissheim, Germany), KinTrak/Orthotrak (Motion Analysis Corp., Santa Rosa, CA) and Vicon MOTUS (Vicon, Los Angeles, CA). Appropriate software should be chosen depending on the level of sophistication required and the available budget.

Optoelectronic systems

The majority of equine gait labs use digital optical motion capture systems that offer automatic marker identification with real-time processing of the three-dimensional coordinates to display graphs and stick figures of the motion and other types of calculated data during or immediately after the movement occurs. Other sources of analog or digital data from force platforms, EMG systems,

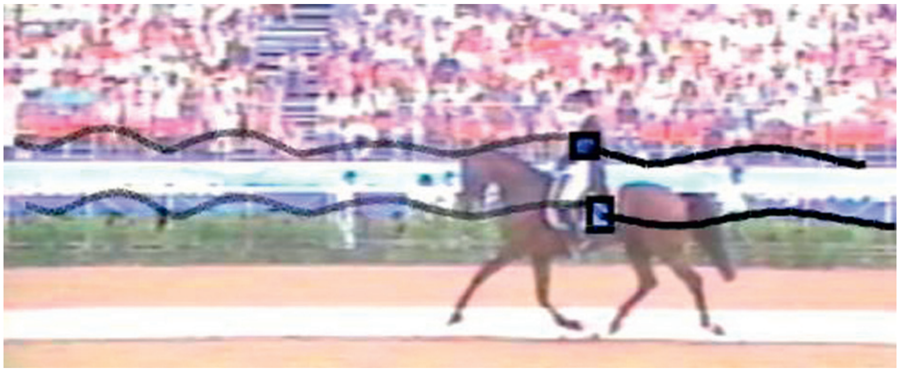

Fig 2.9 Black lines track the trajectories of a marker on the horse and a marker on the rider during a video clip showing a transition from extended trot to collected trot. Produced using Dartfish TeamPro software (Dartfish, Fribourg, Switzerland).

Fig 2.10 Data collection using a Motion Analysis System in the McPhail Equine Performance Center at Michigan State University, USA.

dynamometers, foot switches, event recorders, etc., can be synchronized with the system. Kinematic data may be recorded using active markers (markers that emit a signal) or passive markers (markers that detect or reflect a signal). Most of the equine gait laboratories currently use optoelectronic systems based on passive markers, such as the Motion Analysis System (Motion Analysis Corp., Santa Rosa, CA), Vicon MX (Vicon, Oxford, UK) or ProReflex MCU (Qualysis Inc., Glastonbury, CT). Figure 2.10 shows data collection in progress using a Motion Analysis System in the Mary Anne McPhail Equine Performance Center at Michigan State University.

In choosing cameras for an optoelectronic system, there is a balance between range, speed, size, performance and cost. The current industry standard is to use digital camera systems that have a ring of strobed lights (visible red, infra-red) surrounding the lens; the strobe frequency corresponds with the sampling rate. Desirable features include a combination of high resolution (high pixel count) and a high frame rate, though at higher sampling rates the resolution may be reduced or the image may be displayed in split-screen mode. Cameras with more pixels allow the use of larger capture volumes, smaller markers and more complex marker sets, all of which are advantageous when working with horses. The advantages of digital technology over its analog predecessors are that there is no degradation of the signal over distance, less noise, and no re-sampling of data on another piece of electronics. The signal processing is embedded in the camera and the signal goes directly to the tracking computer via an ethernet connection. By streamlining the system of motion capture from camera to computer, the amount of hardware is reduced and there is less potential for equipment problems. Regardless of the type of camera used, a high-quality lens will improve the accuracy of the entire system and an electronic shutter synchronized with the strobed lights will remove motion blur.

Software packages for kinematic analysis offer a simple and powerful interface that facilitates set up, calibration, motion capture (real-time and for post processing), editing and saving data in a chosen format. The software delivers six-degrees-of-freedom data for the full range of targets using reflective markers and high speed, high-resolution cameras. In this way, the system can provide the highest order positional and angular accuracy. The interface synchronizes with other analog and digital devices, such as video cameras, force plate, pressure mat and EMG. The on-screen display may allow simultaneous display of several panels showing video, a three-dimensional stick figure viewed from any perspective, together with graphical outputs of the data. A considerable volume of literature in the field of equine locomotion has been based on the use of optoelectronic systems with passive markers.

Motion analysis systems based on active strobed markers offer automated marker identification by sequencing the temporal output of different markers, which avoids marker confusion or swapped trajectories. These systems include Optotrak Certus (NDI, Waterloo, ON) and Codamotion (Charnwood Dynamics Ltd., Rothley, UK). An advantage to Codamotion is that its precalibrated sensor units are portable and can be set up in any location to measure three-dimensional coordinates without the need for a calibration process.

Electromagnetic systems

Electromagnetic systems, such as Flock of Birds (Ascension Technologies, Burlington, VT) are used as three-dimensional tracking

Fig 2.11 Zebris system in use at the National Veterinary School of Alfort, France. Triads of ultrasound microphones fixed rigidly to the limb segments (left) are located relative to a fixed system of three ultrasound transmitters as data are collected from a horse moving over ground (right).
Photograph courtesy of Dr. H. Chateau.

devices for applications that include real-time visualization, and target acquisition. The magnetic tracking has accuracy comparable with an optical motion system (Hassan et al., 2007). Drawbacks to the use of an electromagnetic system include the problem of metal interference, the relative heaviness of the receivers, the presence of wires and the small data capture volume.

Ultrasonographic system

An ultrasonographic system for real-time, three-dimensional gait analysis (Zebris CMS-HS, Medizintechnik Gmbh, Isny, Germany) is based on temporal delay of ultrasound signals. The system uses marker triads consisting of three small ultrasound microphones (Fig. 2.11) that operate sequentially and are mounted at a predetermined distance from each other (Fig. 2.11). The position of the markers is determined relative to a fixed system of three ultrasound transmitters and the x, y, z coordinates of the markers are determined by triangulation, based on the delay in the ultrasound pulses.

In standard laboratory conditions, the precision of the Zebris system was measured as ±0.14 mm for linear measurements and ±0.16° for angular measurements, but the precision decreased if the distance between the transmitters and the microphones exceeded 1.5 m. This restricts the size of the data collection volume and does not permit recording of data for a complete stride during over ground locomotion (Chateau et al., 2003). Although the maximum sampling frequency is 100 Hz, the relationship between sampling rate, measuring distance and time between ultrasonic pulses is such that a sampling frequency of 50–60 Hz is practical for equine studies (Chateau et al., 2003). Ultrasound reflections can induce systematic errors (about 0.2°) and impair the repeatability of the measurements. Wind decreases the precision of the measurements in proportion with its speed and temperature also has an effect, so it is necessary to configure temperature in the software. This system has been used in precision analysis of the stance phase of horses walking and trotting over ground and in analysis of the stance and swing phases of horses walking and trotting on a treadmill (Chateau et al., 2004, 2006).

Kinetic analysis

Kinetic analysis measures locomotor forces, both external and internal to the body. Forces developed by muscles are transformed into rotations of the limb segments that ultimately produce movement. The forces between the hoof and the ground during locomotion can be recorded using a force plate (e.g. Pratt & O'Connor, 1976; Seeherman et al., 1987; Merkens et al., 1988, 1993a, 1993b; Dutto et al., 2004b) or a force shoe (Björck 1958; Frederick & Henderson 1970; Hjertén & Drevemo, 1987; Barrey, 1990; Ratzlaff et al., 1990, 1994; Keg et al., 1992; Roepstorff & Drevemo, 1993; Kai et al. 2000; Rollot et al., 2004; Roland et al., 2005). Transmission of forces and accelerations through the body are recorded by strain transducers, ultrasonic transducers, accelerometers, gyroscopes and magnetometers attached directly to the segment.

Ground reaction force

During the stance phase of the stride, the hoof exerts a force against the ground and, according to Newton's third law of motion, the ground exerts a reaction force against the hoof that is equal in magnitude and acts in the opposite direction. This ground reaction force (GRF) is fully described by its magnitude, direction and point of application. To aid in understanding the effects of the GRF, the three-dimensional force vector may be resolved into components acting in the vertical, longitudinal (craniocaudal), and transverse (mediolateral) directions. When the frame of reference changes, for example if the horse moves on an incline or decline, the components may be aligned with the ground rather than the global reference frame (Dutto et al., 2004b). Measurement devices may provide

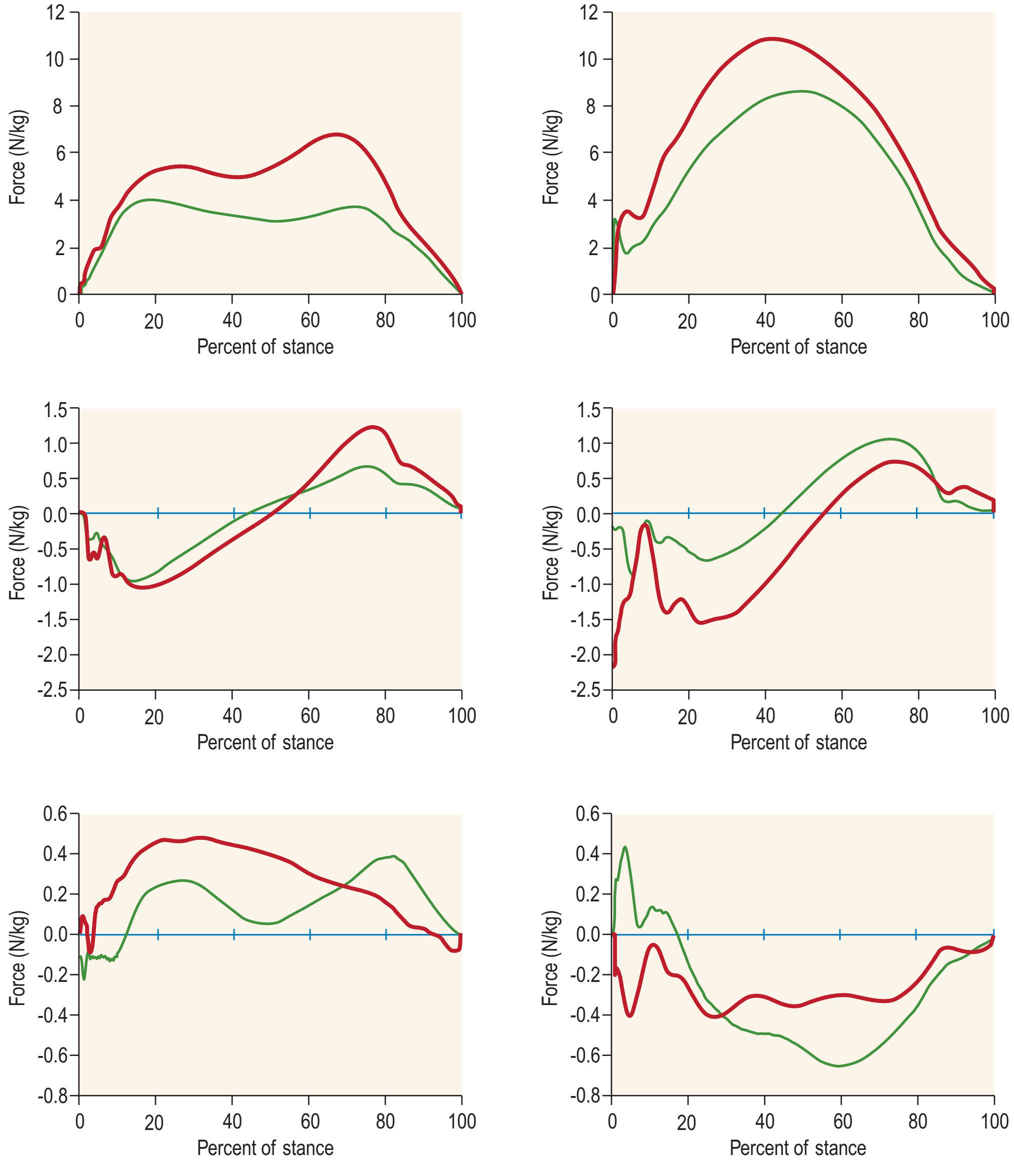

Fig 2.12 Vertical (above), longitudinal (center) and transverse (below) components of the ground reaction force for a horse at the walk (left panel) and at the trot (right panel). For the longitudinal force the cranial direction is positive and for the transverse force the medial direction is positive. Forelimb (red line); hind limb (green line).

complete three-dimensional data or a more limited range of GRF components, so the method of measurement should be chosen in accordance with the goals of the study.

Standard GRF patterns have been developed for Dutch Warmbloods at a walk (Merkens et al., 1988), trot (Merkens et al., 1993a) and canter (Merkens et al., 1993b). Since there are significant differences between breeds (Back et al., 2007), the Dutch Warmblood data must be adapted to other breeds by incorporating appropriate parameters and weighting factors into the formulae used to develop the standard patterns. For example, when forces are normalized to body weight, Quarter Horses have lower vertical GRFs than Dutch Warmbloods trotting at a similar velocity (Back et al., 2007).

Figure 2.12 shows the three force components (vertical, longitudinal, transverse) during the stance phase of a forelimb at a walk and trot. The vertical force, which represents the anti-gravity support function of the limb, is always positive. The longitudinal force, which provides acceleration and deceleration, has negative and positive phases. In the early part of the stance phase, the longitudinal force brakes (decelerates) the horse's forward movement as a result of friction that prevents the hoof slipping forward. Later in the stance phase, it changes to a propulsive (accelerating) force. The direction of the horse's motion across the force plate determines whether acceleration or deceleration is recorded as positive. Software correction is applied to standardize the sign convention. The transverse force, which increases during sideways or turning movements, is small in magnitude when moving in a straight line and is directed medially. The left to right values recorded by the force plate can be converted during post-processing to represent medial and lateral values for each limb. During turning the transverse force acts toward the center of the turn or toward the direction of lateral motion.

For a walking horse, the peak vertical GRF has a magnitude of the order of 60% body weight at walk and 90% body weight at a moderate speed trot (Fig. 2.12). At slower walking velocities the vertical force trace tends to be biphasic with the second peak being higher in the forelimbs and the first peak being higher in the hind limbs. During walking, peak values of the vertical and longitudinal forces in the forelimb increase with velocity, but the corresponding impulses decrease as a consequence of a reduced stance duration (Khumsap et al., 2002). In the hind limb, however, an increase in walking velocity affects only the first peak in vertical force (Khumsap et al., 2001). In the trot, sharp spikes usually occur immediately after initial ground contact during the period of impulsive loading (impact phase). The trace then rises smoothly to peak around the time the limb is at its midstance position, which is marked by the cannon segment being vertical, after which it decreases to lift-off (Fig. 2.12). The peak value of the longitudinal force is 10–15% of the horse's body weight at the walk and trot, with marked spiking occurring during the impact phase at trot. The transverse force is much smaller in magnitude, around 2% body weight at the trot (Fig. 2.12). The center of pressure is located under the middle of the hoof during most of the stance phase, moving rapidly toward the toe at the start of breakover.

Values representing the peak forces and their times of occurrence are extracted from the force history. Impulses are determined by time integration of the force curves. A procedure that combined over 90 numbers describing the peak amplitudes, their times of occurrence, and the impulses has been described as the H(orse) INDEX (Schamhardt & Merkens, 1987). This method is valid but has some drawbacks in that the variables used to calculate the index are selected by the user and are essentially dependent on the shape of the signal. Moreover, it does not take account of the real pattern of the curve, which can be accomplished by different techniques that are more suitable for comparison of curve patterns.

The stance durations, GRF amplitudes and impulses are symmetrical in sound horses at the walk (Merkens et al., 1986, 1988) and trot (Seeherman et al., 1987; Merkens et al., 1993a; Linford 1994; Weishaupt et al., 2004a). Analysis of ground reaction forces is a reliable way to quantify lameness, with peak vertical force and vertical impulse being the variables with highest limb specificity and sensitivity in grading lameness (Weishaupt, 2004b, 2006a). An example of the changes in ground reaction forces in superficial digital flexor tendonitis is shown in Figure 2.13. Lameness models include pressure on the hoof sole (Merkens & Schamhardt, 1988); collagenase-induced tendinitis in the flexor tendons (Clayton et al., 2000a) or desmitis of the suspensory ligament (Keg et al., 1992); and surgical creation of a cartilage defect (Morris & Seeherman, 1987; McIlwraith et al., 2011). In addition to its value for detecting lameness, the force plate is a sensitive tool for measuring the response of lame horses to diagnostic anesthesia (Keg et al., 1992) or to therapeutic intervention (Gingerich et al., 1979).

Ground reaction force has also been used for postural sway analysis, which projects movements of the center of pressure onto a horizontal plane. A stabilogram (Fig. 2.14) is a graphic representation of the motion of the center of mass in craniocaudal and mediolateral directions over a period of time. Techniques for postural sway analysis has been described in horses (Clayton et al., 2003a; 2012) and disturbances in balance after administration of a sedative have been quantified (Bialski et al., 2004). Postural sway analysis also shows promise as a technique for detection of neurological diseases (Clayton et al., 1999).

Normalization

GRFs vary with body mass (Barr et al., 1995). Comparisons between horses are facilitated by normalizing the force traces to the horse's weight, so they are expressed in Newtons/kilogram body weight (N/kg). GRFs may also be standardized to the duration of the stance phase, which allows comparison of the forces occurring at a percentage of stance duration in strides with different durations.

Force plate

A force plate is a steel plate that can be mounted in a runway or recessed into the ground. For equine use, it is usually covered with a non-slip material (Fig. 2.15). When a horse steps on the plate, the force is detected by transducers at its corners, and is converted to an electrical signal that is amplified and recorded. Two types of force transducers are used: strain gauge and piezoelectric. Strain gauges have a linear response, are relatively insensitive to temperature, and can be miniaturized. The disadvantage is their low sensitivity. By comparison, piezoelectric transducers have high responsiveness and can be miniaturized but they are sensitive to temperature and humidity and are not amenable to static calibration. Variables measured by the force plate include stance duration, magnitude of the vertical, longitudinal (horizontal craniocaudal) and transverse (horizontal mediolateral) forces, time when the peak forces occur, the impulses (areas under the force–time curves), and point of application of the force (center of pressure or point of zero moment).

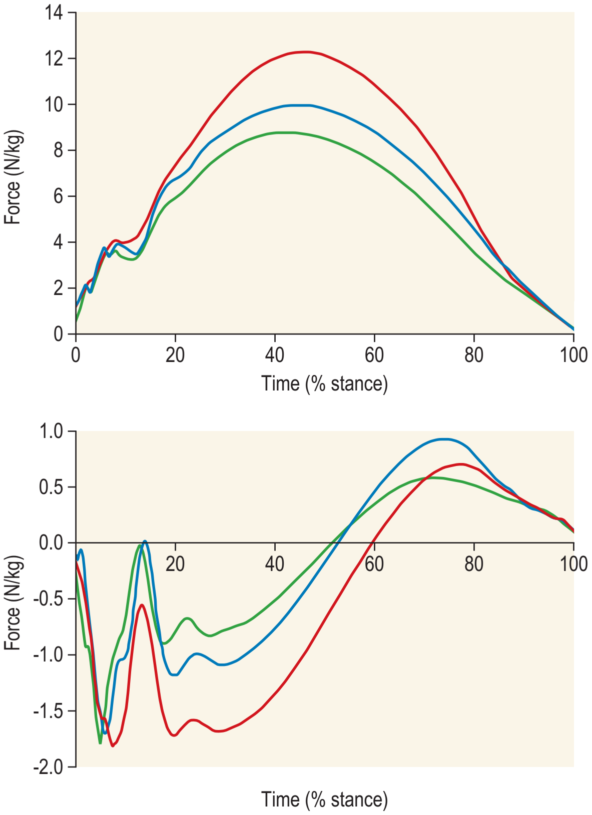

Fig 2.13 Vertical (above) and longitudinal (below) ground reaction forces of forelimbs in sound condition (mean value of left and right forelimbs in blue) and after induction of superficial digital flexor tendonitis in one forelimb (lame, forelimb in green and compensating forelimbs in red shown separately).

From Clayton et al. (2000) Am. J. Vet. Res. 61, 191–196 with permission of American Veterinary Medical Association, http://avmajournals.avma.org/loi/ajvr.

In selecting a force plate for equine use, it is important to choose one that has a linear response over an appropriate range of forces, taking into account the weight of the horses and the gaits and speeds to be studied. The dimensions of the plate should maximize the chance of getting a good strike from one fore hoof followed by the hind hoof on the same side at the selected gait. If two hooves strike the plate simultaneously, it is not possible to separate their effects. Shorter force plates (60–90 cm) are ideal for collecting data at the walk, but a length of 90–120 cm is preferable for use at the faster gaits. Width of the plate is not generally a limiting factor: 50–60 cm is adequate. Depending on the dimensions of the force plate, it is typical for a good strike to be recorded for every two to six passes at the walk, trot and canter (Niki et al., 1982; Merkens et al., 1986, 1993a, 1993b). During jumping, the obstacle is moved

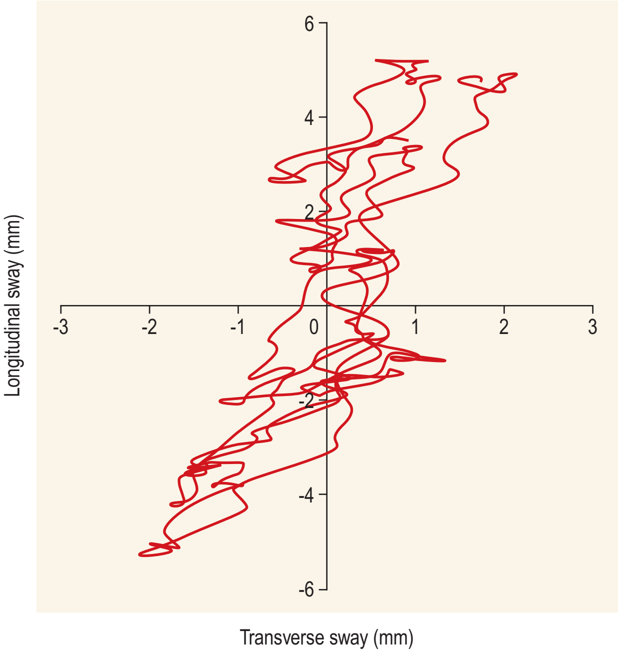

Fig 2.14 The stabilogram is a graphic representation of the motion of the horse's center of mass projected onto a horizontal plane. In the graph shown here, the line traces the motion of the center of mass during a 20 s recording period at 1000 Hz. The 0,0 location, which is the centroid of all the points, is located at the intersection of the transverse and longitudinal axes. The head is toward the top of the figure and the horse's left is on the left. Note the different scales on the vertical and horizontal axes.

Fig 2.15 Horse stepping on force plate during data collection.

relative to the stationary force plate, to increase the likelihood of getting a good strike with a particular limb at lift-off or landing (Schamhardt et al., 1993b). The horse should move parallel with the long axis of the force plate to avoid cross talk between the horizontal transducers. Companies that manufacture force plates suitable for equine use include AMTI (Watertown, MA), Bertec Corporation (Columbus, OH) and Kistler Instruments Corp. (Amherst, NY).

Installation and calibration of the force plate are critically important to the quality of the data collected. The plate should be embedded in a concrete pit to isolate it from surrounding vibrations and the supporting surface must be absolutely level to avoid cross talk between the vertical and horizontal channels. Before recording data, the calibration should be checked by placing a known weight, similar in magnitude to the loads that will be applied during normal use, at different locations on the force plate. The same vertical force should be recorded independent of location, and the position of the center of pressure should match the actual location of the load.

Simple procedures for checking force plate calibration on a daily basis have been described (e.g. Lewis et al., 2007). Since GRFs vary with velocity (McLaughlin et al., 1996; McGuigan & Wilson, 2003), measurement and control of velocity are important in studies of GRFs. Provided the horse's velocity over the force plate is maintained within a narrow range, the GRFs are consistent and repeatable between strides, with analysis of five strides being sufficient to provide representative data (Merkens et al., 1986). Methods of measuring the horse's average velocity over the plate include the use of timing lights that record the time taken to cover a known distance or dedicated kinematic software. Sensors for a simple infrared timing device that measures the time elapsing as the horse passes through the data collection volume can be purchased inexpensively. Alternatively, software can be written to track a position marker (as described above) on the horse's torso and calculate average speed and speed variation during the trial. Depending on the objectives of the study, data from runs that fall outside a predetermined range of velocities may be discarded.

Bad trials occur when the horse fails to strike the force plate, when the hoof contacts the edge of the plate, when more than one hoof is on the plate simultaneously, and when the horse's body axis or direction of movement are not aligned with the axes of the force plate. These problems may be recognized by the force traces having an unusual shape or magnitude or failing to return to the baseline between individual limb contacts. It is helpful to use kinematic data to verify which hoof is on the force plate and its precise location, and also to check the alignment of the horse and the direction of movement.

Variables with low variability require fewer animals, trials and days to obtain accurate data while maintaining adequate statistical power. Inter-day reliability of force plate data over three consecutive days is high for stance duration, peak vertical force and vertical impulse (<10% variability of the mean), while longitudinal force peaks and impulses have larger variation (>20% variability of the mean) (Lynch et al., 2005). In lame horses, peak vertical force and vertical impulse have the lowest between- and within-horse coefficients of variation and the highest correlations with subjective lameness grade. Peak vertical force also has high sensitivity and specificity for lameness classification (Ishihara et al., 2005).

Although force plates for equine use are usually covered with rubber matting, it is possible to place different surface materials on top of the force plate. For example, a steel-reinforced concrete top-plate has been used to simulate the surface of a road in a study of energy dissipation during hoof slippage at the start of stance (Wilson & Pardoe, 2001).

At the University of Zurich, a force plate suitable for equine use has been embedded in a treadmill (Fig. 2.16) to measure the vertical forces of all four limbs over an unlimited number of steps at any gait (Weishaupt et al., 2002). The force measuring system consists

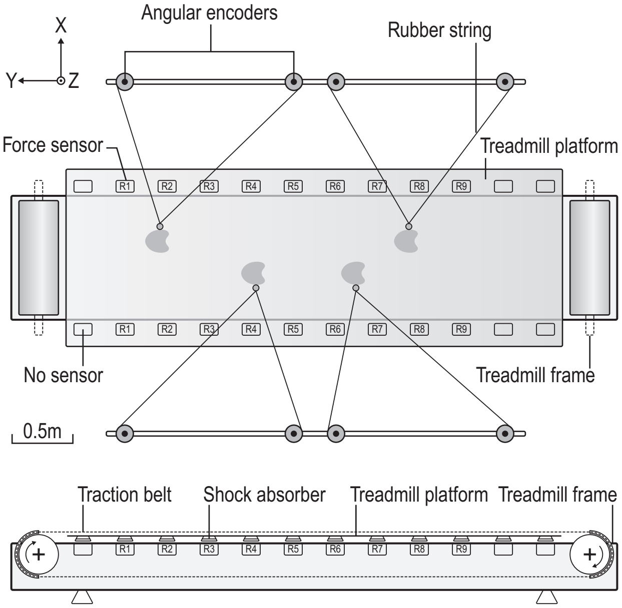

Fig 2.16 Schematic illustrations representing the overhead (above) and cross-sectional lateral (below) views of the instrumented treadmill for use in determination of vertical ground reaction forces in horses at the University of Zurich. There are 18 force sensors and four triangulation units for determining coordinates of each hoof.

Diagram courtesy of Dr. Michael Weishaupt.

of 16 piezoelectric force transducers mounted between the treadmill frame and the supporting steel plate over which the belt moves. Each transducer measures the vertical force at the corresponding bearing of the supporting plate. Transfer coefficients have been determined and tabulated for each of the 16 transducers for each square centimeter of the treadmill surface by the application of a test force. The coordinates of a hoof on the treadmill surface are calculated by triangulation based on angle values derived from two electrogoniometers. For each sampling instant, a set of 16 linear equations are formulated containing the four unknown hoof forces, the four x–y coordinates of the hoof force application, their corresponding transfer coefficients and the 16 forces from the sensors, from which the individual hoof forces are extracted. This treadmill has been used to determine GRFs and interlimb temporal coordination data of clinically sound Warmblood horses at the trot (Weishaupt et al., 2004a), the characteristics of lameness in the hind limbs (Weishaupt et al., 2004b) and in the forelimbs (Weishaupt et al., 2006a) and the effect of head and neck position on vertical ground reaction forces in dressage horses ridden at walk and trot (e.g. Weishaupt et al., 2006b) (Fig. 2.17).

Force shoes

A force shoe is a portable device that measures one or more components of the ground reaction force during a large number of successive stance phases, thus overcoming a limitation of the force plate. Force shoes also have the advantages of being amenable to use on different surface types, and being able to collect data from more than one limb at a time. The force-measuring device may be attached directly to the hoof, sandwiched between a base plate and a shoe, or placed inside a boot attached to the hoof. Force shoes are technically difficult to construct and the weight of the shoe may affect limb kinematics and forces. Several researchers have used force shoes experimentally, but none is currently marketed commercially.

Fig 2.17 Horse being ridden on a treadmill instrumented for measurement of vertical ground reaction forces at University of Zurich, Switzerland. The hooves are attached by rubber bands to goniometers that triangulate the hoof positions.

Photograph courtesy of Dr. Michael Weishaupt.

Both strain gauge and piezoelectric transducers have been used in the construction of equine force shoes, with the same advantages and disadvantages as when they are used in force plates. An additional practical consideration in the force shoe application is that the output of piezoelectric transducers can change in response to movement of the lead wires.

An early force shoe (Björck, 1958) used strain gauges to measure vertical and horizontal forces in draft horses. The force patterns resembled those obtained by other methods but the size of the shoe (height: 24 mm; weight: 1800 g) limited its use. Several years later, a similar shoe weighing 2300 g was used to measure vertical and horizontal components of the GRF at trot (Hjertén & Drevemo, 1987). A different device had three force sensors sandwiched between a base plate nailed to the hoof wall and a ground plate that was attached to the base plate, thus preloading the force sensors (Frederick & Henderson, 1970). It was used to measure vertical forces at walk, trot and gallop.

A much lighter (200–300 g) force shoe based on three strain gauge measuring units, one at the toe and one at each quarter, was developed and used to measure vertical, longitudinal and transverse forces (Roepstorff & Drevemo, 1993). The output correlated well with that of a force plate when all three measuring units were in contact with the ground, but when one or more units lost contact with the ground, for example during breakover, the correlation between force shoe and force plate signals deteriorated. This shoe was used to compare GRFs on treadmill belts with different compositions (Roepstorff et al., 1994).

Kai et al. (2000) developed a force shoe based on four strain gauges mounted on an aluminum plate and supported by a stainless steel plate in such a way that vertical forces were transmitted by the load cells, whereas shear forces were borne, not by the load cells, but by bolts that prevented horizontal movement of the steel plate relative to the underlying aluminum plate. Three accelerometers were integrated into the shoe to measure three-dimensional impact accelerations. The total weight of the assembly was 480 g. The shape of the vertical GRF curves during walking, trotting and cantering on a treadmill resembled force plate recordings.

A force shoe developed specifically for characterizing the GRF and moment vectors during galloping (Fig. 2.18) (Roland et al., 2005) had two parallel plates with three rectangular strain-gauged sensing posts sandwiched between them: two at the widest part of the shoe and one at the toe. The size and contour of the solar surface of the

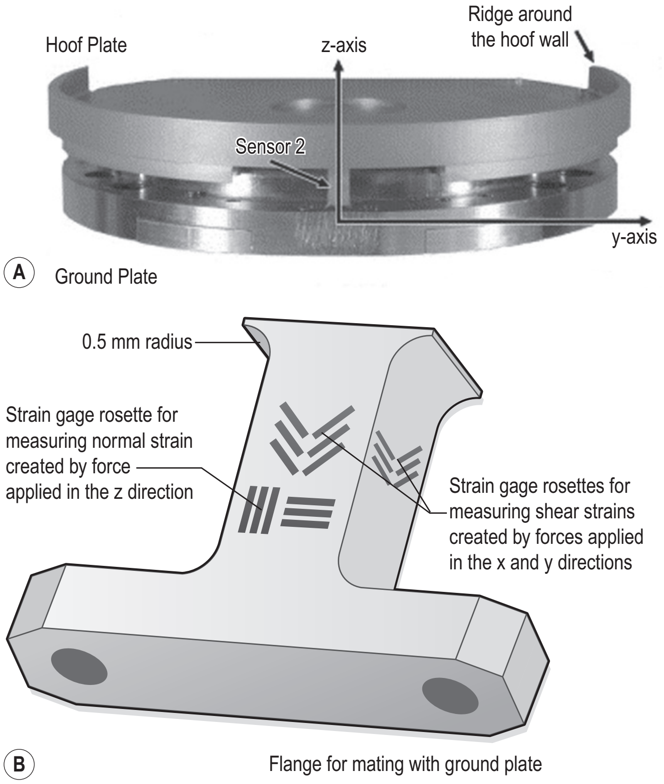

Fig 2.18 Above: dynamometric horseshoe viewed from the toe with coordinate axes superimposed. The x-axis is perpendicular to the plane of the photograph. The elevation of the x–y plane coincides with the bottom plane of the ground plate. The location of the y–z plane is palmar from the center of sensor 2, two-thirds of the distance from sensor 2 to a line between the other two sensors (not visible). Below: diagram indicating strain gage placement on the sensors as viewed from below. Opposite sensor faces have the same gage pattern.

Reprinted from Roland, E.S., Hull, M.L., Stover, S.M., 2005. Design and demonstration of a dynamometric horseshoe for measuring ground reaction loads of horses during racing conditions. J. Biomech. 38 (10), 2102–2112, with permission from Elsevier.

base plate matched the size and shape of the solar surface of a Thoroughbred hoof. The data were measured in a local coordinate system aligned with the hoof, whereas force plate measurements are in a global coordinate system fixed to the ground. When the hoof was flat on the ground, the three-dimensional GRF patterns and amplitudes agreed well with previously reported force plate data but there were differences at the start and end of stance when the hoof was not flat on the ground. The entire shoe weighed 860 g, which is likely to affect swing phase kinematics due to the added inertia.

The first equine force shoe based on piezoelectric sensors was developed by researchers at Washington State University. The first prototype had a single piezoelectric transducer in a housing over the frog. A later version that had three piezoelectric transducers located at the medial heel, the lateral heel and the toe gave a better correlation with simultaneous force plate recordings. It was used primarily in studies of galloping Thoroughbreds (e.g. Ratzlaff et al., 1990), and provided unique data when a horse wearing the shoe sustained a rupture of the distal sesamoidean ligaments while galloping on a training track (Ratzlaff et al., 1994).

Another design used four three-axis piezoelectric load cells located medially and laterally at the quarters and heels (Fig. 2.19) (Rollot et al., 2004). In this case, the load cells were sandwiched between a base plate that was nailed to the hoof and a shoe that was attached to the base plate using four screws. These screws were tightened to preload the load cells with a compressive force of about 15 kN. The total weight of the assembly was around 700 g. When compared with data from a force plate, the force shoe represented the shape of the GRF curve but the amplitude was reduced, which was explained by the fact that the screws used to sandwich the sensors were supporting some of the load. Another issue was that rotation of the hoof and shoe relative to the ground, especially during contact and breakover, resulted in crosstalk between the longitudinal and vertical forces. On sand, weight bearing over the frog and sole reduced the force recorded by the instrumented shoe relative to the actual GRF.

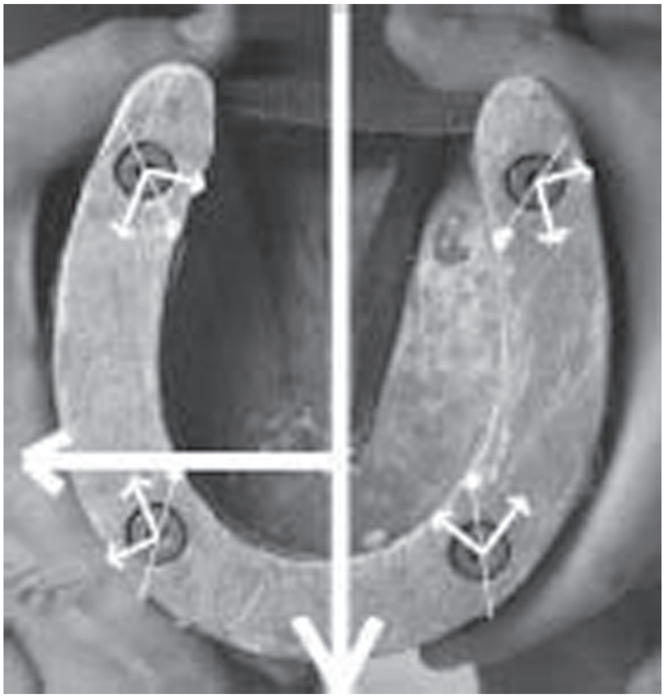

Fig 2.19 Force shoe attached to hoof and viewed from the solar aspect. HL, lateral heel; QL, lateral quarter; QM, medial quarter; HM, medial heel; and global anatomical frame (Xhoof, Yhoof).

Reprinted from Rollot, Y., Lecuyer, E., Chateau, H., Crevier-Denoix, N., 2004. Development of a 3D model of the equine distal forelimb and of a GRF shoe for noninvasive determination of in vivo tendon and ligament loads and strains. Equine Vet. J. 36, 677–682, with permission from the Equine Veterinary Journal.

A force shoe with four transducers located on the medial and lateral sides of the toe and quarters, was integrated into the bottom of an easy boot and used to measure the vertical GRF component at walk and trot (Barrey, 1990). This shoe was used to compare different track surfaces (Barrey et al., 1991).

Although a force shoe would be an ideal method of measuring GRFs, there are significant technical difficulties in constructing one that is accurate and reliable throughout the equine stance phase. Working within these limitations, some useful data have been generated.

Indirect methods of GRF measurement

An alternative method of determining GRFs is by calculation rather than direct measurement. There are different methods of GRF estimation, each of which has advantages and disadvantages. One method of estimating vertical GRF is based on the spring-like properties of the distal forelimb, which implies that vertical loading of the limb is directly related to the distance from elbow to hoof and also to fetlock angle, which would allow the vertical GRF to be calculated from limb kinematics (McGuigan & Wilson, 2003). This method likens the limb to a strain gauge; the relationship between limb force and elbow-hoof distance or fetlock angle is calibrated using kinematic and force data that are collected synchronously. Peak vertical force can then be estimated from kinematics. A further step involves calibrating the forces indirectly (and without the need for force plate analysis) by estimating limb forces from duty factor, which is the percentage of stride that a limb spends in the stance phase. A prerequisite of this method is a knowledge of the distribution of the total ground reaction force between the individual limbs, which is gained through direct force measurements. The results of a study that used hoof-mounted accelerometers to determine duty factor and then estimate peak vertical forces yielded an overestimation of 13% at walk, an underestimation of 3% at trot, an underestimation of 16% for the trailing limb at canter and an overestimation of 19% for the leading limb at canter (Witte et al., 2004). The substantial errors at canter were attributed to the different functions performed by the trailing and leading limbs in this asymmetrical gait.

Bobbert et al. (2007) used a slightly different approach to calculate force-time histories for the individual limbs based on the assumption that they operated as linear springs. Kinematic data were used to calculate the acceleration of the horse's center of mass and the magnitude and direction of the total GRF vector. Angular momentum of the horse, also calculated from the kinematic data, was combined with the GRF vector to determine the moment arms of the total GRF relative to the two supporting hooves during bipedal support (Bobbert & Santamaria, 2005). The moment arm ratio between fore and hind hooves indicates how the total GRF is distributed between the supporting limbs, so the individual limb forces can be calculated. The forces can be calibrated against distal limb length or fetlock angle, allowing force–time data for the limb can be estimated based on the time history of distal limb length or fetlock angle. Compared with values measured by a force plate, peak vertical GRFs calculated by this method were quite accurate (Bobbert et al., 2007).

Inverse dynamic analysis

Inverse dynamic analysis (IDA) uses kinematic data, GRF data and knowledge of segmental morphology and inertial properties to calculate internal forces within the limb that cannot be measured directly (Winter, 1990). The net joint moment describes the net torque across a joint produced by the soft tissues (muscle, tendon, ligament and joint capsule). Net joint power is a measure of the net mechanical work done across a joint; it is the product of the net joint moment and joint angular velocity. If the net joint moment has the same polarity as the joint angular velocity, then the power is positive (power generation) indicating that the muscles are performing positive (concentric) work, in which the muscle fibers shorten as they generate tension. If the net joint moment has the opposite polarity to the joint angular velocity, the power is negative (power absorption) and the muscles perform negative (eccentric) work, in which the muscle fibers lengthen as they generate tension. Power absorption occurs when muscles act to restrain the rate of joint motion in opposition to gravity or some other force. Net work performed over a period of time is calculated by mathematical integration of the power curve with time.

Input into the inverse dynamic model comes from synchronized kinematic and GRF data, which are combined with morphometric information (segment mass and center of mass) and segment inertial parameters. A link segment model of the limb is constructed, with each limb segment represented as a solid bar with its center of mass located relative to the marker coordinates that define the segment. An inverse dynamic solution described by Winter (1990) and adapted for use in horses (Colborne et al., 1997) is then used to calculate the sagittal plane net joint moments at each joint. Net joint moment and net joint power can be normalized to horse mass and expressed per kg body weight (Nm/kg, W/kg, respectively). For further details see Chapter 19.

Inverse dynamic analysis has been applied in horses to evaluate forelimb net joint moments and powers at walk (Clayton et al., 2000b, 2001) and trot (Clayton et al., 1998; Lanovaz et al., 1999) and during jumping (Dutto et al., 2004a; Bobbert & Santamaría, 2005). The effects of lameness on net joint moments and powers have also been evaluated (e.g. Clayton et al., 2000c; Khumsap et al., 2003).

Tissue strain

Body tissues deform or strain with respect to their preferred shape as a consequence of applied external forces competing with the microscopic internal forces that hold the tissue together. When a tensile force is applied to a solid material, it causes the length to increase, whereas a compressive force causes the length to decrease. A bending force causes both increases and decreases in length in different parts of the tissue. Stress is the force per unit area; strain is the change in length expressed as a percentage of the original length.

In ideally linearly elastic materials, deformation is proportional to the applied force and the material restores its original shape as soon as the deforming force is removed. Deformation of the material, usually expressed in terms of *strain* (ε), is defined as:

$$\varepsilon = \frac{l_1 - l_0}{l_0}$$

where l_0 is the original (or resting) length, l_1 is the length after deformation, and $l_1 – l_0$ represents the change in length. Usually, the resting length is defined as the length at zero loading force. Because strain is a relative measure, it has no units. It is expressed as a fraction or as percentage strain.

Strain transducers

Strain transducers measure the amount of strain based on electrical resistance (liquid metal strain gauge, buckle transducer, implantable force transducer and pressure transducer), variation of magnetic field (Hall effect transducer), or variation of light flow (optic fiber). Ideally, transducers should be reliable, easy to implant, induce minimal distortion or length change in the tissue and not cause a significant inflammatory reaction. Implantation requires surgery using local or general anesthesia. A drawback is that the time required to recover from anesthesia delays the start of data collection, which is a relevant concern when using transducers that have a limited lifespan or that induce the development of fibrous healing reactions (Ravary et al., 2004). Since strain gauges are small devices, they collect data from a limited area that is not necessarily representative of the total strain or load of the entire structure.

The most commonly used type of strain gauge changes its electrical resistance in response to deformation in a certain direction; the change in resistance is converted to a voltage output that is proportional to the strain. Voltage outputs are stored for later processing by a computer. A combination of three strain gauges stacked at 45° angles to each other forms a rosette gauge capable of measuring three-dimensional strains.

Measuring strains in hard tissues

Hard tissues, such as bone, deform slightly in multiple directions as a result of the combined effects of weight bearing, tension in the muscles and tendons, and inertial effects due to acceleration of the limb. Rosette (three-dimensional) gauges, bonded to a bone surface using a thin layer of cyanoacrylate glue, deform with the surface to provide information about the compressive and tensile forces (Lanyon, 1976). The best sites for attaching strain gauges to bones are in areas where the bone lies subcutaneously, so soft tissue

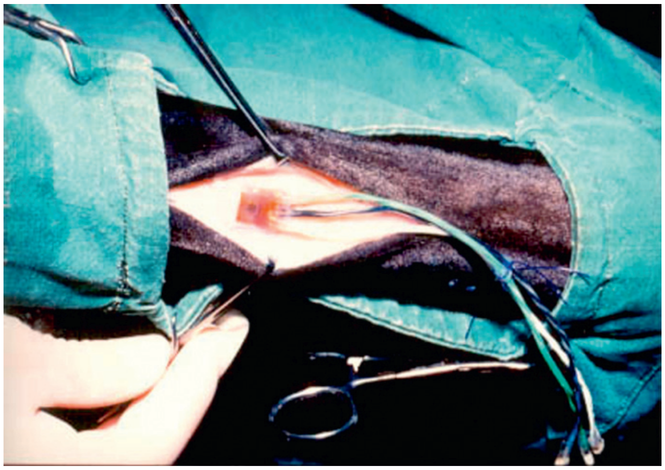

Fig 2.20 Strain gage attached to equine third metacarpal with wires attached.
Photograph courtesy of Dr. H. Davies.

Fig 2.21 Strain gage attached to the hoof wall.
Photograph courtesy of Dr. J. Thomason.

trauma during surgery is minimized. The bone surface is prepared by removing the periosteum and drying the underlying bone before bonding the strain gauge to the bone using cyanoacrylate adhesive (Fig. 2.20). The wires exit the skin through a separate incision. It is important to shield the wires from movement and trauma, since damage to or loosening of the wires is the most frequent reason for failure of the gauges. During data collection, the gauges deform as if they were part of the bone surface. The resulting electrical signal is amplified and transmitted to a data recorder or computer for storage.

A practical problem in quantifying bone strain is that the resting length of bone is difficult to determine. When the horse is standing quietly with the limb lifted from the ground, the loading may be assumed to be small. However, the effects of muscular contraction cannot be excluded completely, and the influence of gravity may also affect the zero-strain determination. Software has been developed to calculate a 'zero-strain compensation' for *in vivo* strain gauge data of horses at the walk, using the assumption that strain is minimal in the middle of the swing phase when the limb is moving forward with an almost constant velocity (Schamhardt & Hartman, 1982).

Surface strain is a consequence of the forces loading the bone. However, the relationship between surface strain and load is complicated, especially in non-homogeneous, non-linear, viscoelastic structures such as bones (Rybicki et al., 1974). Roszek et al. (1993) presented an elegant technique to quantify the loading forces from a post-mortem calibration using multiple strain gauges and known bending and torsional loading forces. Without this kind of calibration, however, bone strain recordings are a valuable, but qualitative, estimate of bone loading.

By using three or four strain rosettes around the perimeter of a long bone shaft, and combining their output with knowledge of the bone's geometry, the distribution of principal strains can be determined. It has been shown that the loading pattern of each bone is fairly consistent in different activities, though peak strain and strain rate vary with gait and speed (Rybicki et al., 1974). This information has been applied in locating the tension surface of various long bones, which is the surface of choice for the application of bone plates. Strain gauges have been bonded to equine long bones to investigate bone loading under various conditions during exercise and training (e.g. Hartman et al., 1984; Schamhardt et al., 1985; Nunamaker et al., 1990; Davies et al., 1993, 2004; Davies 2005).

Strain gauges are easily bonded to the hoof wall (Fig. 2.21) to study the functional anatomy of the hoof capsule under a variety of loading conditions (e.g. Thomason et al., 1992, 2001) and after application of therapeutic shoes (Hansen et al. 2005).

Measuring strains in tendons and ligaments

The use of strain and force transducers in biomechanical studies of tendon and ligament has been reviewed by Ravary et al. (2004). Forces can be estimated (e.g. van den Bogert, 1989) or measured using implanted transducers. Regardless of the type of transducer used, implantation within a tendon or ligament causes tissue damage, which may affect the signal output and limit the number of measurements that can be made.

The long tendons in the lower limb of the horse can be considered as more or less elastic, homogeneous cables. When loaded, their length increases. However, strain in tendons is not as well defined as in bones. An unloaded tendon shrinks in length and the tendon fibers become wrinkled or *crimped*. When elongated, the crimp in the fibers is first straightened out, after which the fibers are stretched elastically up to a point, beyond which permanent elongation occurs.

The load–elongation curve for a tendon has a 'toe' region, which is characterized by having a large elongation for a small load. This region represents straightening of the crimp in the collagen fibers. As loading increases beyond the 'toe' region, there is a linear relationship between load and elongation in the elastic region until the yield point, which occurs around 10–12% strain. Beyond the yield point permanent elongation results as the tendon fibers begin to rupture. A problem in measuring tendon strain lies in defining the initial length of the tendon and the position of zero load, which affects the magnitude of the strains recorded throughout the physiological range. It appears that the resting length, or the length at zero force, can only be approximated. Studies that rely on different criteria for defining zero load give very different strain values during similar activities and at the yield point. An objective method of determining the transition between the toe and the elastic region has been described (Riemersma & van den Bogert, 1993).

In tendons and ligaments, unidirectional strain gauges are adequate to record tensile strains during loading. The force or strain developed within these structures can be measured directly using an implanted transducer that should be sufficiently compliant to measure tissue tension without interfering with its normal use during locomotion (Ravary et al., 2004).

Regardless of the type of transducer used, the electrical signal must be converted to strain (relative elongation of the tissue) or load (internal force within the tissue) by a calibration process in which the sensor itself or the tissue containing the implanted sensor are stretched. Methods of calibration include traction in a materials testing machine, tensile loading with known weights, stretching the tendons *in situ* in the limb by manipulation of the isolated limb or by manually moving the joint, or electrical stimulation of the attached muscle. In animals, direct calibration is often performed post-mortem after anatomical dissection of the tissue. In live animals, calibration must use an indirect method based on mathematical equations of static equilibrium.

Several types of strain gauges have been used to study tendon strains in horses. In a buckle transducer, the tendon is wound over a buckle and preloaded as it passes over the middle support bar. Tendon damage is reduced by adapting the transducer dimensions and the shape of the crossbar to the width of the tendon. Tensile loading straightens the tendon and loads the buckle, and this loading is detected by strain gauges bonded on the transducer surface to measure deformation of the buckle. Calibration of a buckle strain gauge is achieved by *ex vivo* transection of the tendon and application of known force or *in vivo* evaluation of tendon force from joint moment data. Buckle transducers appear to be poorly tolerated and are associated with more postoperative pain than other types of strain gauges. Another problem with the buckle transducer is that, by forcing the tendon to follow a curved course, its initial strain and tension are altered. The possibility of preloading of the tissues is a particular concern when making measurements in short ligaments.

Liquid metal strain gauges consist of compliant tubes filled, under slight pressure, with a metal that is liquid at room temperature (e.g. mercury in silastic). Strain-induced changes in the resistance of the liquid metal are measured, which depend on the length and cross-sectional area of the column of metal. When the gauge is stretched, the liquid column becomes longer and narrower, which is associated with an increase in electrical resistance. Since the gauge is part of a circuit with constant current, a change in electrical resistance induces a change in voltage. These gauges are implanted with some prestrain to ensure detection of any changes in length. Liquid metal strain gauges have the advantage of being calibrated *in vivo*, but they have to be custom made, which is a tricky process. Microdamage in the area of implantation alters the tensile properties of the tendon within a few days, so readings must be taken as soon as possible after surgery (Jansen et al., 1998). Longevity is also adversely affected when oxygen diffuses through the porous silastic tubing and oxidizes the mercury. There is also a possibility of breaking the connecting wires or loss of contact between the wire and the liquid metal column. To reduce the risk of problems, readings should be taken as soon as possible after implantation and it may be necessary to limit the number of *in vivo* measurements that are collected. Liquid metal strain gauges have been used to investigate load distribution between the flexor tendons and suspensory ligament (Jansen et al., 1993), to characterize the behavior of the limb (Riemersma et al., 1988a, 1988b), to assess the effect of support bandages (Keegan et al., 1992) and to detect changes in the loading pattern in response to changes in surface type or shoeing adaptations (Riemersma et al., 1996a, 1996b).

A transducer based on the Hall effect, in which the voltage output of a semiconductor is proportional to the strength of a magnetic field, was used to measure strain in the superficial digital flexor tendon. Although the strains recorded were higher than would be expected, this may have been due to the definition of initial length as the length at heel strike (Stephens et al., 1989).

A force transducer that detects strain from a very small part of the tendon has been applied in horses (Platt et al., 1994). A drawback is that the small area sampled is not necessarily representative of strain in the entire tendon.

A fiberoptic transducer consists of a plastic optical fiber that loses transmitted light under compression. It is implanted into a tendon under local anesthesia by passing a 19-gauge needle transversely across the primary loading axis of the tendon then threading a sterile fiberoptic sensor through the needle. The needle is then removed leaving the sensor embedded in the tendon. One end of the fiber is connected to the light transmitter unit and the other end is connected to the light receiver unit. As the tendon stretches longitudinally, its transverse dimension decreases and squeezes the fiberoptic sensor, causing it to lose light, which is quantified by the receiver. The amount of light lost varies linearly with the applied tension in the tendon (Komi & Ishakawa, 2007). Calibration of the sensor is similar to the buckle transducer. The fiberoptic transducer is relatively unobtrusive (diameter 0.25–0.5 mm), easy to implant and appears to be well tolerated.

An ultrasound probe has been used to measure tendon strain non-invasively (Pourcelot et al., 2005) based on the fact that the speed at which acoustic waves travel through a tendon varies with the mechanical properties of the tissue; when the tendon is loaded, the ultrasound wave travels faster. An ultrasound probe consisting of an emitter and multiple receivers is placed on the skin with the receivers spaced at regular distances along the skin overlying the superficial digital flexor tendon. The ultrasound wave speed is calculated from knowledge of the distance between the receivers. The probe is fixed to the skin of the palmar metacarpal area using an adapted boot (Fig. 2.22). It has been used to evaluate the effects of farriery modifications on loading of the superficial digital flexor tendon at walk and slow trot (Crevier-Denoix et al., 2004).

Sonomicrometry

Sonomicrometry measures distances using transducers, commonly called ‘crystals’, made from piezoelectric ceramic material that transmit and receive sound energy. The crystals are implanted in soft tissue structures where they emit an ultrasonic pulse and detect similar pulses from other crystals. The sonomicrometer measures the time between transmission of the sound wave from one crystal to its reception by the other crystals. The time differences are converted to distance measurements. Specialized digital circuitry makes continuous calculations of the distances between transducer crystals implanted in or attached to soft tissue structures to quantify the active and passive functional properties of moving tissues.

Sonomicrometry is useful in studies of muscle function to determine whether muscles are working concentrically, isometrically or eccentrically and to relate the type of contraction with the amount of force produced. This technique has been used in horses to investigate the relationship between muscle strain and length change of the musculotendinous unit (Hoyt et al., 2005)

Calculation of strains

Numerical modeling of the limb allows simultaneous evaluation of the strain contributions of different ligaments and tendons, even those that are deeply placed. The effect of interventions, such as a change in hoof angle can be studied (e.g. Lawson et al., 2007a). Bone-fixed markers have been used to calculate three-dimensional bone segment trajectories, from which geometric displacement of tendon and ligament insertions were calculated to determine strain of the digital flexor tendons *in vitro* (Rollot et al., 2004). The estimations agreed fairly well with simultaneous measurements of tendon length using needles pinned perpendicularly through the superficial digital flexor tendon in the mid-metacarpal and digital regions. Differences between calculated and measured strains, which were in the range of 12–15%, were due to integration of the length of the proximal scutum (approximately 4 cm), which was not taken into account in the direct measurement of tendon length.

Meershoek et al. (2001a) quantified the parameters for a pulley model to describe the relationships between force and strain of the flexor tendons and between fetlock joint angle and suspensory ligament strain. Evaluation of the sensitivity of the technique indicated

Fig 2.22 Above: ultrasound probe for dynamic measurement of tendon strain. Below: probe shown beside the special boot used to hold it in secure contact with the shaved skin overlying the digital flexor tendons.
Photograph courtesy of Dr. Nathalie Crevier-Denoix.

Fig 2.23 Telemetered system for measuring rein tension showing strain gages inserted between rein and bit with battery operated power source and transmitter-attached to the noseband underneath the horse's chin.

that modeling errors in the mechanical properties of the suspensory ligament and measurement errors in the point of application of the GRF and position of the marker on the distal interphalangeal joint had a substantial effect on accuracy. After correction of these errors, the method was used to calculate mean tendon forces and to evaluate the influence of factors such as surface properties, type of shoe, speed, and fatigue on tendon forces during trotting (Meershoek & Lanovaz, 2001) and jumping (Meershoek et al., 2001b).

When using musculoskeletal models to calculate soft tissue strains in the superficial and deep digital flexor tendons, changes in the dorsopalmar path of the tendons at the level of the proximal sesamoid bones have more influence on calculated tendon strain than changes in their attachments (Lawson et al., 2007b).

Measurement of rein tension

Tension in the reins is one of the mechanisms used by the rider to control the horse's speed and direction. Rein tension can be measured using strain gauge transducers (Preuschoft et al., 1999; Clayton et al., 2003b, 2005). Sensors used for this purpose must be small in size and light in weight (Fig. 2.23) to avoid interfering with the normal movements or functions of the reins and the coupling between bit, transducer and rein must be inextensible. Ideally, the power source and transmitter should be small enough to be worn on the bridle or breastplate (Fig. 2.23) or attached around the horse's neck. Synchronized video images are useful to relate the timing of kinematic events, such as footfalls, with patterns in the rein tension graphs (Fig. 2.24). Useful variables include maximal, minimal and average tension values, rate of increase in tension and width of the tension spikes. Rein tension measurements are applied in evaluations of the effects of tack and rider technique.

Accelerometers, gyroscopes and magnetometers

Accelerometers, gyroscopes and magnetometers provide different pieces of information that can be combined to provide a more complete picture of the movement pattern. They are used in various combinations in gait analysis. Miniaturization of the components allows their attachment to the extremities without affecting kinematics or kinetics.

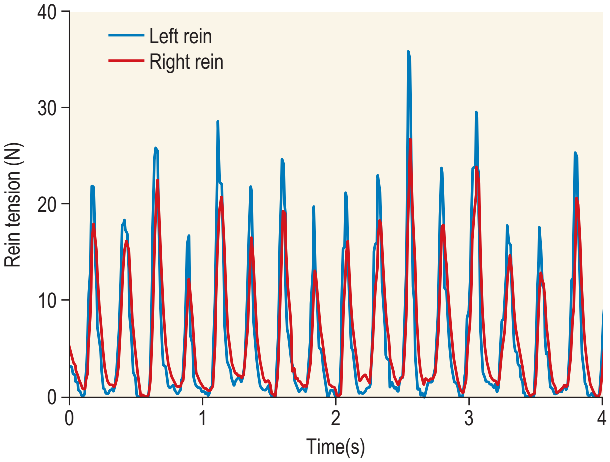

Fig 2.24 Rein tension between the bit and leather side reins for a horse trotting in hand in a straight line.

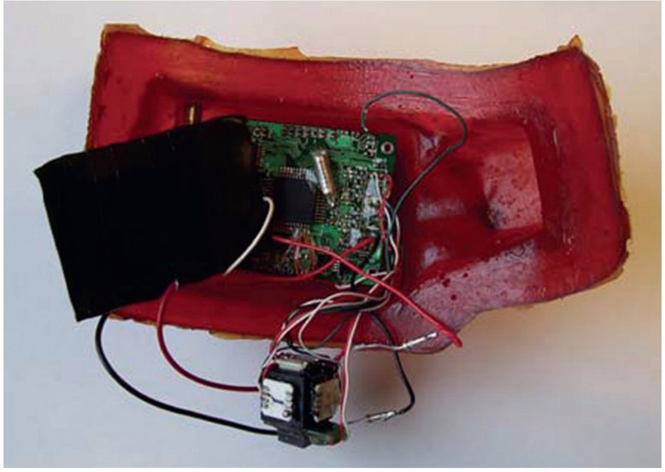

Fig 2.25 Electronics, accelerometers and power source shown with polyurethane housing for mounting on the hoof wall.

Reprinted from Ryan, C.T., Dallap Schaer, B.L., Nunamaker, D.L., 2006. A novel wireless data acquisition system for the measurement of hoof accelerations in the exercising horse. Equine Vet. J. 38, 671–674, with permission from the Equine Veterinary Journal.

Accelerometers measure acceleration of the surface to which they are attached. Sub-miniature accelerometers (mass <1 g) are available. They contain silicon beams that deform during acceleration causing changes in capacitance that are output as a voltage proportional to the applied acceleration. Tilt relative to the earth's gravitational field can also be measured using these accelerometers. Gravity deforms the silicon beam, changing the capacitance and associated voltage of the sensor.

Since each accelerometer measures acceleration in one direction only, two or three accelerometers are often stacked with their axes perpendicular to each other to obtain two-dimensional or three-dimensional accelerations. Interpretation of the output is subject to errors due to misalignment of the axes of the accelerometers with the body axes or to rotations of the instrumented body segments during locomotion. Orientation of the accelerations relative to the body's frame of reference can be achieved using optical motion capture or by integration of the angular velocity output of three orthogonal gyroscopes.

Gyroscopic sensors measure orientation based on the principle of conservation of angular momentum. The essence of the instrument is a spinning wheel on an axle that tends to resist changes to its orientation due to the angular momentum of the wheel. If two gyroscopes with their axles perpendicular to each other are mounted on a platform inside a set of gimbals, the platform will remain completely rigid as the gimbals rotate. Sensors on the gimbals' axes detect platform rotation. When used in combination with accelerometers, the direction of motion and changes in motion can be measured in all three directions. Miniature gyroscopes (mass <1 g) measure angular velocity through the phenomenon of Coriolis force, which is generated when a rotational angular velocity is applied to a vibrating element. It is a by-product of measuring coordinates relative to a rotating coordinate system.

Small, lightweight inertial-based sensors are generally robust and have some useful applications for recording data from a large number of consecutive strides, when the use of an optical motion analysis system may not be practical. In addition to providing accurate orientation data, inertially based systems can be used to calculate displacements (Pfau et al., 2005). The large volumes of data collected by systems based on inertial sensors necessitate automatic processing, especially if the system is to be used in a clinical setting, where results are needed rapidly for timely decision-making. One such technique involves the use of a hidden Markov model-based stride segmentation technique based on stochastic pattern recognition. It has been used to evaluate data from trunk-mounted, six degrees of freedom, inertial sensors in horses (Pfau et al., 2008). Other studies have evaluated center of mass movement and mechanical energy fluctuation in galloping Thoroughbreds (Pfau et al., 2006) and in horses moving on an incline (Parsons et al., 2008), and to compare movements of the left and right tuber coxae in horses with mild hind limb lameness (Pfau et al., 2007). Inertial motion tracking has inherently poor resolution and, over time, the readings drift.

A magnetometer measures the strength and/or direction of the magnetic field around it, which can be used to provide an absolute measure of orientation using the earth's magnetic field, as in a compass. A triaxial magnetometer with a tilt sensor can be used to sense absolute three-dimensional orientation.

In equine studies, accelerometers have most often been applied to the hoof wall, where they are used to detect initial ground contact and to measure the associated accelerations. In one design (Fig. 2.25), three accelerometers, a power source and the associated electronics were potted in a shock-attenuating silicon shell inside a semi-rigid polyurethane housing that was contoured to fit the dorsal hoof wall. The total mass of the assembly was only 148 g (Ryan et al., 2006).

By mounting accelerometers to the hoof wall and to the bones of the digit, Lanovaz et al. (1998) studied the attenuation of impact shock in the distal digit *in vitro*. Willemen et al. (1997) performed similar measurements both *in vitro* and *in vivo*. A hoof-mounted accelerometer is an effective tool for measuring certain characteristics of the footing (Barrey et al., 1991) and the efficiency of shock absorbing shoes and pads (Benoit et al., 1991). Hoof mounted accelerometers have also shown that impact accelerations increase with speed and are affected by the dynamic properties of the surface the horse moves over (Ratzlaff et al., 2005; Ryan et al., 2006).

A different application used two accelerometers secured beneath the horse's sternum to measure longitudinal and dorsoventral accelerations of the trunk segment (Barrey et al., 1994) with data transmitted telemetrically to a receiver connected to a portable computer. Analysis of the symmetry of the trunk acceleration patterns during trotting revealed subtle asymmetries in lame horses, though in some of these horses the side of hind limb lameness was identified incorrectly (Barrey & Desbrosse, 1996). The same device has been used to study accelerations of the trunk during jumping (Barrey & Galloux, 1997). Accelerometers attached to the saddle have been used to measure the acceleration at different gaits and the findings have been applied in the development of a mechanical horse that simulates the motions during walking, trotting, cantering and jumping (Galloux et al., 1994).

The output from vertically oriented, uni-axial accelerometers, one attached to the halter close to the poll and the other glued to the top of the croup, have been used to compute vertical displacements of the head and pelvis as the second integral of the accelerations. Movement asymmetries of the head or croup in lame horses are detected. When used in combination with gyroscopic transducers attached to one hoof to indicate the timing and duration of its stance phase, lameness can be partitioned between fore and hind limbs, then assigned to the left or right side (Keegan et al., 2001). Based on head movement data, the lameness is further assigned to the loading or push off phase. Comparison between this accelerometric-gyroscopic system and a video-based motion analysis system showed a high linear correlation for quantification of the degree of lameness in both fore and hind limbs (Keegan et al., 2004).

A three-directional gyroscopic transducer attached to the hoof has been used on a standalone basis to evaluate the effects of trimming and shoeing modifications on hoof motion and the direction of breakover (Keegan et al., 2005).

Combinations of accelerometers, gyroscopes and magnetometers have many applications, for example in virtual reality systems. With regard to motion analysis, combination of orientation data from gyroscopes with three-dimensional accelerations allows motion tracking with six degrees of freedom. As an example, an inertial orientation sensor that has been modified for equine use to provide a full set of movement parameters (displacement, velocity, acceleration) in three directions. The sensor was attached over the spine of horses exercising on a treadmill to measure orientation and relative position at the canter (Pfau et al., 2005). After high pass filtering to separate non-cyclical and cyclical components of the movement, the data were comparable with those from an optical motion capture system. This combination of sensors has been used to study movements of the center of mass and mechanical energy fluctuation during galloping (Pfau et al., 2006) and the effects of an incline on center of mass movement and mechanical energy fluctuation (Parsons et al., 2008). This technology has also been marketed as a clinical lameness evaluation tool (Keegan et al., 2004).

Pressure mats

Pressure mats contain an array of sensors used to map the pattern of pressure across a surface. The main applications in horses are to map pressure distribution beneath the hoof or beneath the saddle. In human gait analysis, ultra-thin, in-shoe sensors have been used to map pressure beneath the foot and force between the foot and the ground as a means of evaluating podiatric and orthopedic problems.

Hoof pressure mats

Pressures beneath the hoof are used to evaluate and compare farriery practices and in the detection of mild lameness. To perform these functions, the mat and the sensors must be sufficiently robust, accurate and reliable to measure relatively high forces and pressures. Larger mats (e.g. Matscan®, Tekscan Inc., Boston, MA) are placed on the floor or on top of a force plate. Some smaller mats can be cut to the appropriate shape and attached beneath the hoof or used inside a boot. The Hoof ™ System (Tekscan Inc., Boston, MA) displays contact area and color-coded pressure profiles (Fig. 2.26), average and peak pressures, center of pressure and its trajectory. The associated software displays force-time and peak pressure-time graphs, and allows the user to isolate and analyze data from specific regions of the hoof or to make side-by-side comparisons of pre- and post-treatment conditions.

In human studies, accuracy and precision of in-sole pressure mats have been shown to vary with manufacturer, levels of applied pressure, calibration procedure, duration of pressure application and length of time for which the insole has been used (Hsiao et al., 2002). Some types of pressure-measurement systems are particularly sensitive to calibration, with measurement errors being reduced when the sensors are calibrated within the range of pressures that they will be used to measure. An equine study suggested that sensors be used for a maximum of three trials before recalibration (Carter et al., 2001). Data recorded simultaneously from a force plate and a pressure mat have confirmed the value of the pressure mat for evaluating temporal variables and kinetic symmetry ratios but peak vertical force and vertical impulse values are lower than those recorded by the force plate (Oosterlinck et al., 2010). This problem can be overcome by calibrating the pressure mat dynamically using reference values from a force plate. In this method, the sum of the vertical forces applied to all the sensors in the pressure mat is adjusted to match the vertical component of the GRF (van Heel et al., 2004; Oosterlinck et al., 2012).

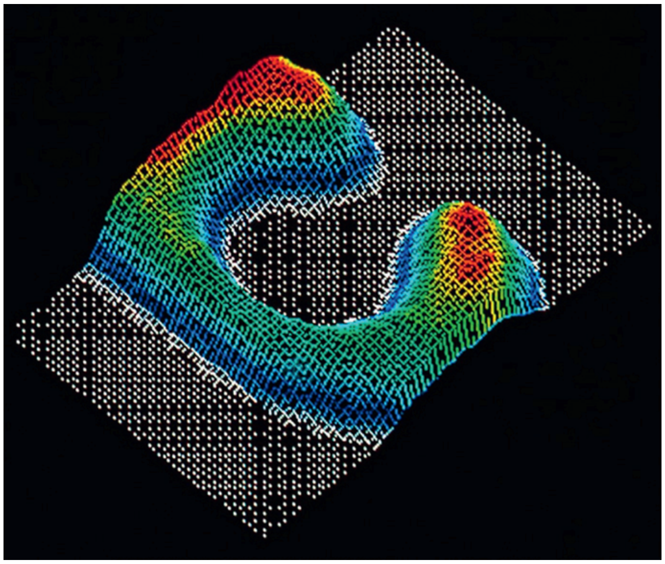

Fig 2.26 Pressure profile beneath the hoof collected with electronic pressure mat (RSFootScan, RSScan International, Olen, Belgium). *Photograph courtesy of Dr. W. Back.*

In horses, practical applications of the use of sensor mats beneath the hooves have focused on lameness detection (Carter et al., 2001; Perino et al., 2007) and evaluation of hoof dynamics and farriery (van Heel et al., 2004).

Sensor mats trimmed to the shape of the hoof have been attached using adhesive tape (Judy et al., 2001) or placed inside a hoof boot (Perino et al., 2007) to measure simple temporal variables, pressure distribution across the solar surface of the hoof and total force summed over all sensors. The total force recorded simultaneously by the pressure mat and a force plate (Perino et al., 2007) did not differ statistically, but there was an overall lack of agreement between the two sets of measurements (up to 1000 N or 20% of the total measurement) with higher coefficients of variation for the pressure mat (10.2%) than the force plate (6.6%). The authors suggested that shear forces may have interfered with the attachment of sensors around the periphery of the trimmed mat leading to greater variability in forces recorded from the trimmable versus untrimmable pressure mats.

An RSFootScan (RSscan International, Olen, Belgium) was embedded in an aluminum plate on top of a force plate. This combination allowed dynamic calibration of the force mat and provided force and pressure data that gave a more detailed analysis of the areas of contact between the hoof and the surface than was possible with the force plate alone, especially during loading and unloading (van Heel et al., 2004).

Saddle pressure mats

Knowledge of pressure beneath the saddle (Fig. 2.27) is potentially useful to evaluate saddle fit, rider position and riding technique. Pressure mats marketed specifically for this purpose have an array of sensors to measure forces acting normal (perpendicular) to their surface. Early models were hard-wired to a laptop computer via a long tether, which imposed limitations on the horse's mobility. The latest generation of pressure mats use wireless technology, allowing data to be collected on-board using a PDA or transmitted telemetrically to a computer, while the horse moves around freely.

Each sensor detects the force applied perpendicular to its surface (normal force) and the output on the computer screen is color-coded to represent bands of force. The operator sets the force range within each color band depending on the objective of the evaluation. If saddle fit is being evaluated without a rider, a smaller range of forces is required, whereas if the horse will be ridden, the added weight of the rider requires a larger range of forces. The output can be displayed as a sensor plot, a two-dimensional contour plot or a three-dimensional surface plot (Fig. 2.28). Total force summed over all sensors and maximal force in an individual sensor are also measured. The data can be partitioned into smaller areas for analysis and comparison: left and right sides; front and back halves; quadrants, etc. Small changes in position of the horse or saddle relative to the position of the mat affect the force distribution and the assignment of summed forces to different areas, so it is important to standardize the position of the mat relative to both the horse's back and to the saddle and to standardize the horse's position for standing measurements.

Fig 2.27 Pressure mat (Pliance, Novel GmbH, Munich, Germany) placed beneath saddle. Power source and transmitter are in the pack carried at the front of the saddle. The wires shown in loops on the horse's shoulder fit into the green bag during data collection.

As with all quantitative measurement devices, validity and reliability are important considerations. For a saddle pressure mat, there should be a high correlation between the sum of the measured forces and the mass of the riders and saddle. Pressure bench tests (Hochmann et al., 2002) indicate that the Pliance system (Novel GmbH, Munich, Germany) might be more reliable than the FSA (Vista Medical Ltd., Winnipeg, Canada), ClinSeat (Tekscan Inc., Boston, MA) and Xsensor (XSENSOR Technology Corporation, Calgary, Canada) systems. The Pliance mat has also been shown to be more reliable than the FSA device in equine practice (Jeffcott et al., 1999; de Cocq et al., 2006, 2009). Subsequently, the Pliance mat was proven valid for this purpose, but reliability measures indicate that the mat should remain on the horse's back when comparing different conditions (De Cocq et al., 2009). Pressure mats have been used in saddle fitting to compare different saddle brands (Werner et al., 2002) and tree width on saddle fit (Meschan et al., 2007). In ridden horses, they have been applied in studies of the horse's gait and movements and rider technique (e.g. Freuhwirth et al., 2004; Peham et al., 2004; Geutjens et al., 2008).

Electromyography

Muscle contraction is preceded by electrical activation, which can be detected and recorded as the electromyogram, to provide information on the state of activity of the motor neurons at rest, during reflex contraction and during voluntary contraction. Surface electromyography (EMG) is non-invasive, and can be performed on the conscious horse and used during locomotion (Korsgaard, 1982; Tokuriki et al., 1989; Jansen et al., 1992; Tokuriki & Aoki, 1995; Robert et al., 1999, 2000, 2001a, 2001b, 2002; Tokuriki et al., 1999; Colborne et al., 2001; Licka et al., 2004, 2009; Wickler et al., 2005; Wakeling et al., 2007; Zsoldos et al., 2010). Intramuscular EMG, in which the electrodes are inserted into the muscle tissue, is used to study normal (Schuurman et al., 2003) and pathological (Wijnberg et al., 2004; Macgregor & Graf von Schweinitz, 2006) muscular activity. The ability to investigate conditions, such as ataxia, myotonia, myositis,

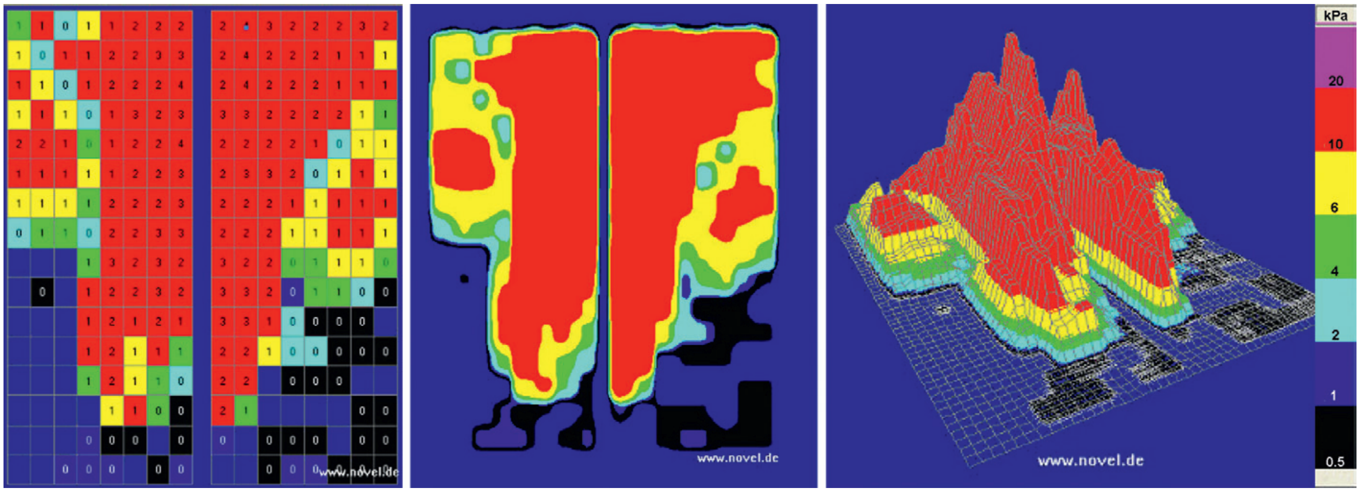

Fig 2.28 Output from Pliance force mat (Novel GmbH, Munich, Germany) shown as individual sensor map (left), two-dimensional planar view (center) and three-dimensional view (right). Pommel is toward top and left side is on the left for sensor map and two-dimensional planar view. The three-dimensional view has been rotated slightly counterclockwise. Pressures are color-coded according to the scale on the right.

shivers and stringhalt, and to diagnose neurologic disorders, such as equine motor neuron disease (EMND), hyperkalemic periodic paralysis, myotonia congenita and equine myotonic dystrophy, has resulted in EMG becoming a useful diagnostic tool.

EMG equipment

Myoelectric signals are collected by electrodes connected to a preamplifier located close to the muscle. Signal conditioning, consisting of data sampling, analog-to-digital conversion, multiplexing and coding are performed before transmission to the recording unit. Data are transferred from the receiving unit to the data recorder by cables, optical fibers or radio-telemetry. Further amplification of the signal, filtering and, in some cases, digital-to-analog conversion are performed by the receiver.

The electrodes function as the antenna to pick up the electrical signal. They may be placed on the skin surface, inserted percutaneously into the muscle or implanted surgically. Surface electrodes have the advantage of being non-invasive but they provide only a gross estimation of muscle activity in the large superficial muscle groups. Electrodes with higher spatial resolution are now available (Huppertz et al., 1997). Jansen et al. (1992) found surface EMG to be a reliable and reproducible technique. However, many locomotor muscles of the horse are deeply placed or lie beneath the thick cutaneous muscles, making them unsuitable for study by surface electrodes. Cross talk may be a significant problem when using surface electrodes (Schuurman et al., 2003).

The percutaneous technique involves using a hypodermic needle to introduce fine wires into the muscle belly to measure localized electrical activity in a small number of fibers close to the electrodes. Several electrode configurations are used. A unipolar electrode usually has a single strand of wire coated with an insulating material except for a small length at its distal end. The wire is inserted percutaneously through a small hypodermic needle and the end of the wire is bent back on itself to act as a barb. The potential is measured between the uninsulated tip of the wire and a reference electrode on the skin. Unipolar electrodes detect the time of activation of the muscle, rather than the amplitude of the contraction. Bipolar electrodes measure the voltage difference between two electrical contacts. A simple bipolar design has two hooked wires inserted through a hypodermic needle. Another type is the concentric bipolar electrode, which measures the potential difference between a point-like recording contact and an average of all the potentials in a ring surrounding it at some fixed distance. The advantages of this configuration are that the recording electrode is shielded by the outer needle from electromagnetic noise and the reference is kept as close to the electrode as possible. Concentric bipolar electrodes are often used in clinical applications (Wijnberg et al., 2003).

To ensure accurate placement in deeper muscles, the electrodes may be inserted under ultrasonic guidance. Surgical implantation of EMG electrodes is a more complex, time-consuming and potentially damaging procedure, but it provides the best results in terms of electrical and mechanical reliability, since the operator has direct visual control of the position of the electrodes.

Muscle potentials may be displayed on a computer with a data acquisition system using the convention that a positive potential is indicated by a downward deflection. Special software is used to process the information, to measure variables such as amplitude and frequency of the spikes, to rectify the output, to construct an envelope that touches the peaks of the spikes, and to measure the areas under the resulting curves.

The electromyogram

A resting muscle fiber has a 90 mV potential difference across its surface membrane, with the outer side being positive. During excitation the resting potential is temporarily reversed to 40 mV, with the outside being negative. As the action potential travels along the muscle fiber, the small electrical potential generated across the surface membrane is dissipated in the surrounding interstitial fluid, which is a good electrical conductor. The summation of the electrical changes in the interstitial fluid is recorded as the EMG.

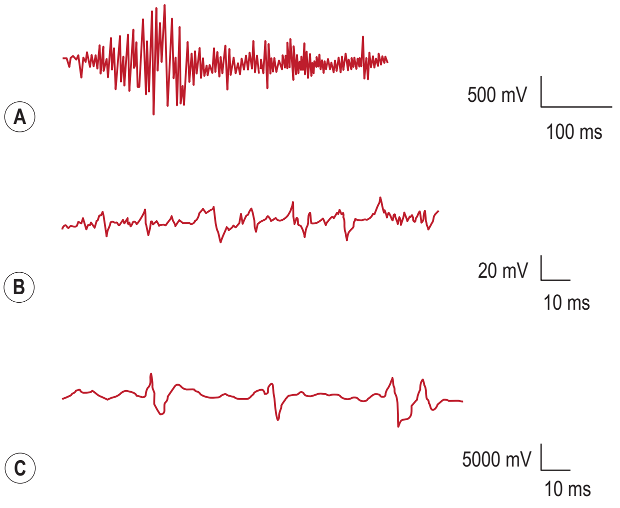

Fig 2.29 Normal electromyographic findings: (A) insertional activity; (B) endplate noise; (C) motor unit action potential (MUAP).

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Surface EMG is a non-invasive technique that gives a general picture of muscle activation in subcutaneous muscles, whereas intramuscular EMG measures localized electrical activity in a small number of fibers located around the electrodes. With the intramuscular technique, there are three phases of electrical activity: insertional activity, resting activity and activity during muscular contraction. The mechanical stimulation associated with insertion or movement of the EMG provokes spontaneous activity with positive or negative high frequency spikes in a cluster that may last for around 500 ms and are followed by electrical silence (Fig. 2.29) (Wijnberg et al., 2003). Abnormally shaped spikes or abnormal duration of electrical activity are signs of muscle pathology. Insertional activity tends to be short in duration when muscle fibers have been lost due to fibrosis or in ischemia, whereas neurogenic or myogenic problems induce abnormal muscular discharges and potentials (Wijnberg et al., 2003). Hyperirritability and instability of the muscle fiber membrane is usually a sign of early denervation atrophy but is also seen in myotonic disorders and myositis (Kimura, 1984) and in equine motor neurone disease (Podell et al., 1995).

Following the burst of insertional activity, relaxed skeletal muscle is electrically silent (Naylor et al., 1992), resulting in a fairly flat trace in the baseline electromyogram. When the electrode is positioned near an endplate it gives rise to endplate noise (Fig. 2.29) and endplate spikes, due to spontaneous release of acetylcholine. Repositioning the needle eliminates these signals. Irritation of nerve terminals in the vicinity of the electrodes may also induce electrical discharges (Wijnberg et al., 2003).

Motor unit action potentials (MUPs) are the summation of muscle action potentials from the voluntary or reflex contraction of myofibers in a motor unit. Approximately 50 muscle fibers around a needle electrode contribute to the observed potential. The waveform of the MUP is described in terms of its amplitude and duration and the number of phases and turns in the graph. Dedicated software is used to measure the amplitude and frequency of the MUPs, rectify the curves, construct envelopes, and calculate the area under the curves.

The duration, from initial elevation until return to baseline, is affected by the synchrony in firing of the individual muscle fibers and the conduction velocity. Discharges generated further from the electrode form the low amplitude areas at the start and end of the MUP. The amplitude of the MUP, defined from peak to peak, depends on the distance from the electrode tip to the center of maximal potential of the discharging unit. For example, fewer than 20 muscle fibers within a 1 mm radius of a concentric needle electrode contribute to the spike of the motor unit. Both amplitude and duration of the MUP may be affected by the horse's age and muscle temperature. The shape of the MUP is described in terms of the number of phases, with a phase being defined as the part of the curve between departure from and return to baseline, and turns, which are the changes in direction of the curve. Normal equine MUPs have been described as potentials that have two or three phases, a duration of 3–10 ms and an amplitude of about 1500 µV (Mayhew et al., 1978). More recently, MUP analyses have been reported in the horse for the subclavian muscle (Wijnberg et al., 2002a) and for the triceps and lateral vastus muscles (Wijnberg et al., 2002b).

The amplitude of the EMG signal depends on the dimensions of the electrodes, their electrical contact with the muscle, and the kind of electrodes: signals from indwelling wire electrodes usually are much lower than those obtained from surface electrodes. However, the major influence on the EMG signal amplitude is caused by the degree of activation of the muscle. When the muscle is completely activated, the EMG signal will reach a maximum. This relationship allows the EMG signal amplitude to be used as a measure of the degree of activation, and thus indirectly, of muscle force development (Hof, 1984). Recruitment is defined as successive activation of motor units with increasing strength of voluntary contraction (Kimura, 1989). In human subjects, it may be possible to estimate the number of active motor units at a given muscle contraction (Kimura, 1989) but in horses, it is difficult to judge the level of force and, therefore, the value of evaluating the recruitment pattern is limited (Wijnberg et al., 2002a, 2002b). This would require a more sophisticated muscle model that incorporates the muscle architecture, the force–length and force–velocity relationships of the muscle fibers, and the activation of the muscle, possibly from EMG signal analysis.

Electromyographic studies of athletic horses have described the activation pattern of various muscles during normal locomotion (Wentink, 1978; Korsgaard, 1982; Tokuriki et al., 1989; Tokuriki & Aoki, 1995; Robert et al., 1999) and have investigated the effects of speed and incline (Robert et al., 2000, 2001a, 2001b, 2002; Wickler et al., 2005) on muscle activation patterns. Over ground locomotion has been compared with swimming and walking in an underwater treadmill (Tokuriki et al., 1999) and the effects of fatigue on the EMG median frequency have been investigated (Colborne et al., 2001).

New technologies

The 21st century is an age in which technology is changing rapidly. Although the contents of this chapter are current at the time of writing, by the time the text is printed some of the information may be outdated and new methods and systems for locomotion analysis will undoubtedly have become available. It is recommended that the reader treat the information in this chapter as a framework from which to evaluate future developments in gait analysis methodologies.

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Signals from materials

Christian Peham

The concept of this chapter follows the signal beginning with measuring, then analog to digital conversion, signal processing and, finally, decision-making.

Introduction and definition of signals

In equine motion analysis a signal is a measured physical property of a movement presented as time-depended parameter or variable. It is acquired by different measurement methods, such as kinematic measurement (Fig. 3.1). This physical parameter can be a coordinate (distance from origin), a force, acceleration, an angle and so on. These signals are so-called bio signals. A bio signal presents a time series of a physical parameter of a living being (Shiavi, 1999), and appears naturally in time-continuous form. Figure 3.2 presents a typical signal in time-continuous form.

Due to the measuring technique (analog to digital converter (ADC)) today nearly every signal is detected as digital signal (Semmlow, 2004). The ADCs quantify the captured values. The effective range is always a power of 2. So a 12-bit ADC means that the effective range is divided into 2^{12} (4096) steps. A digital signal consists of values measured at given time points, in most cases time-equidistance. Figure 3.3 shows the sampling (measuring) process of a signal.

The sampling signal represents a camera, which takes a picture of the motion every 0.008 s (120 Hz sample rate). The result is a sampled signal with measured values on given time points.

Therefore in (equine) motion analysis, signal processing is digital signal processing (DSP). This knowledge is important for measuring (sampling frequency) and signal processing.

Normally noise and/or any other disturbances interfere with the desired signal (Semmlow, 2004). Sources of these disturbances may be errors of the measurement equipment, ADC (quantization error), influence of an electrical field in case of EMG or ECG, etc. DSP is necessary to get the most out of the measured data. The first step is to set up the measurement equipment in a way that the digital signal represents the measured signal sufficiently.

Choosing the sampling frequency (Nyquist – Shannon sample theorem)

Certain preconditions have to be fulfilled to represent a time continuous signal by a digital signal (time-equidistance sampled values). This characteristic is described by the Nyquist – Shannon sample theorem (Oppenheim & Willsky, 1996; Semmlow, 2004).

The last graph of Figure 3.3 shows a sampled signal. Now the question arises, is the sample frequency sufficient?

Motion of a wheel

A typical example of digital measurement equipment is a film camera. Let us consider an example when the camera takes 25 time-equidistant samples (pictures) of a motion every second. Depending on the speed of the moving object this sampling rate may or may not be sufficient.

In movies there is often a strange effect in moving stagecoaches. It is clearly visible that the stagecoach moves from left to right. But the wheels of the stagecoach appear to be revolving in the opposite direction (Figs 3.4 and 3.5).

This so-called 'alias effect' is the result of under sampling. The conclusion is that the sampling rate is too low.

Figure 3.6 shows another example of a turning wheel with more spokes. The conclusion is that in fast movements more than 16 pictures/turn (because there are eight segments) are necessary.

The conclusion of the wheel experiment is the Nyquist – Shannon sampling theorem, which states that the sampling frequency must be at least twice the signal frequency to avoid the alias effect (Werner, 2006):

$$F_{sample} > 2^{*}F_{signal} \quad \text{where F is the frequency}$$

Normally oversampling is used during the measurement. For instance, a sampling frequency that is five times higher than the theoretical minimum sample frequency is used.

Resampling and normalization

Often two different measurement systems are synchronized, e.g. a kinematic system with a force plate or EMG equipment. Both systems use different sampling frequencies. Since EMG measurements need a much higher sampling frequency than the kinematic measurements, the result is two different time scales, i.e. one for kinematic and one for EMG. To solve this problem, resampling is needed. If the sample frequency from EMG is reduced (Peham et al., 2001a,b; Licka et al., 2004), it is comparable to smoothing or low-pass filtering. If there is a whole-numbered relation between the two sample frequencies, it is very easy to reduce or add the samples. The simplest method to reduce the samples is for instance to take only every second or third sample and to add samples to calculate the values of the new samples by a linear relation between two neighboring samples. Usually the procedure of resampling is done in two steps. The first step is to fit the curve (e.g. cubic spline, Fourier series, etc.) in the second step; the new samples will be extracted from the fitted curve. If the sample frequency is to be reduced, it is necessary to limit the bandwith by a low-pass filter.

The effect of reducing the samples (resampling) can be demonstrated by the moving average. The moving average is one of the oldest and most popular technical analysis tools in motion analysis.

Fig 3.1 Horse on the treadmill during kinematic data acquisition.

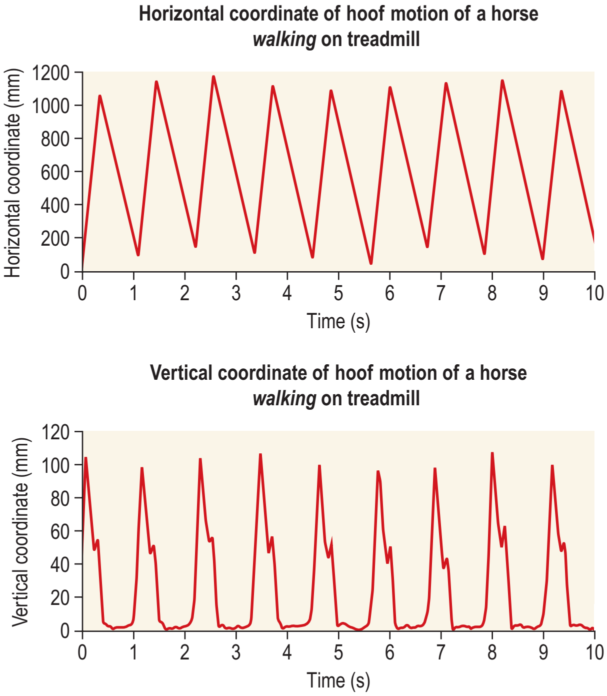

Fig 3.2 Typical example of bio signals; hoof motion of a horse in walk.

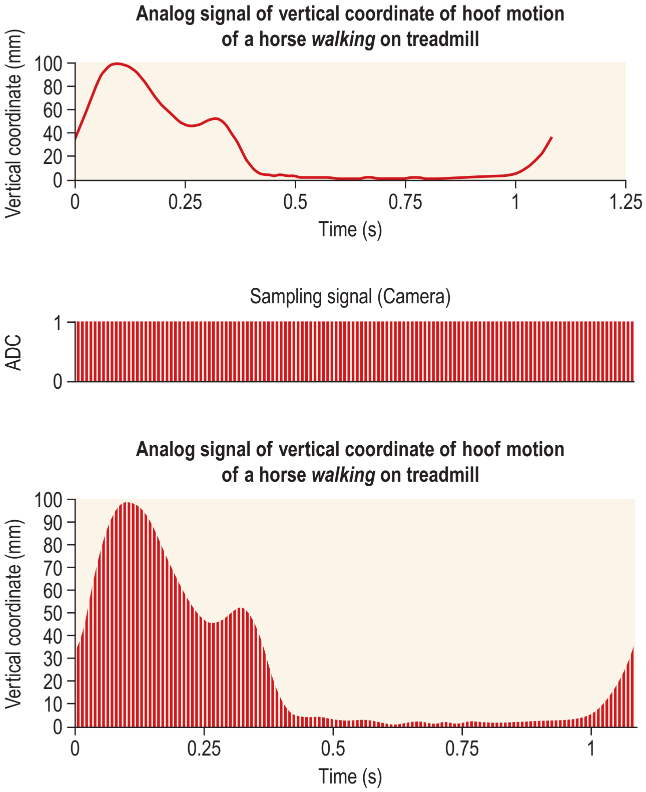

Fig 3.3 The sampling process.

A moving average uses a fixed number of samples. These samples will be averaged to give a new sample. Then the working window is shifted by one sample.

In case of a moving average of three, the mean is calculated from the first three samples ($(s_1 + s_2 + s_3)/3$) to give the first new sample. The next sample will be calculated by the mean of the samples shifted by one ($(s_2 + s_3 + s_4)/3$) and so on (Fig. 3.7). This is a kind of resampling with the reduction of the sampling frequency. The effect is a shift of the curve by one sample interval. If a moving average of five samples is used, the delay will be two sample intervals and so on. This combination of more samples is very similar to a reduction of the sample frequency. So if it is used, it must be realized that the signal is now low-pass filtered. A resampling is also evident when the duration of a motion cycle is normalized to 100%. Normalization or a relative time scale is used as it makes the comparison of different motion cycles easier, and allows averaging of multiple movement cycles into a single curve (a so-called 'ensemble average'). The disadvantage is that the absolute time scale is lost. Sometimes the information of the variation of the duration of motion cycle is needed, which is then done before normalization.

Figure 3.7 shows a signal and the smoothed signal with a moving average of three samples. It is obvious that the smoothing will shift the signal.

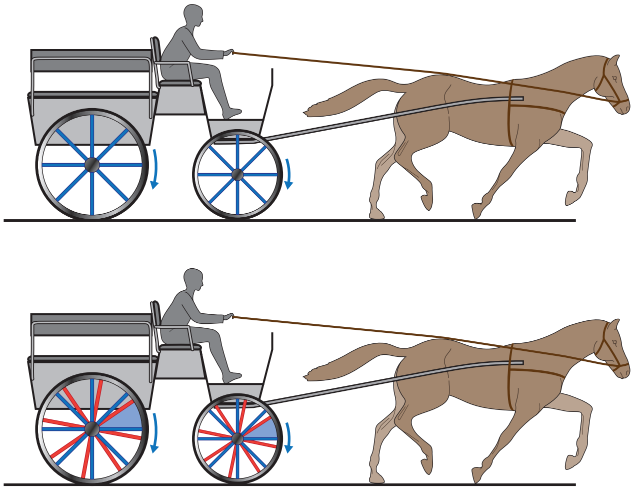

Fig 3.4 An example of a stagecoach moving from left to right. The sequence consists of two consecutive pictures. If the wheel turned clockwise for 30° (to the right) then to the viewer it may appear to have moved anticlockwise for 15° (to the left), as the two consecutive spokes are 45° apart. So we interpret (interpolate) a backward motion of the wheel. The actual turn of the wheel is shown by the blue-colored segment of the wheel. In the second picture the starting position is shown by red bars.

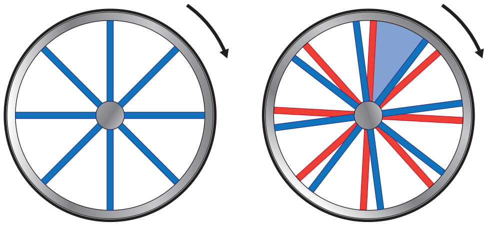

Fig 3.5 Turning wheel of a stagecoach.

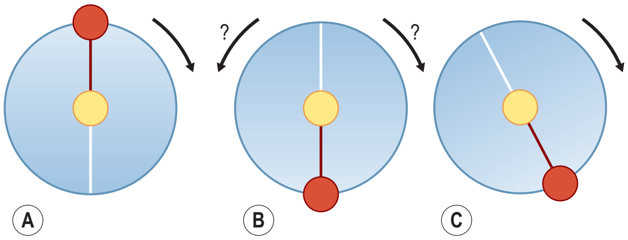

Fig 3.6 (A) An example of a wheel with only one spoke. (B) The spoke has moved 180°, but it is not clear in which direction the wheel has turned. (C) More than two pictures are necessary during a whole turn to show the direction of the rotation.

Aliasing – anti-aliasing filter

To avoid under sampling it is possible to use an anti-aliasing filter, which is a kind of low-pass filter. A low-pass filter limits the bandwidth (cuts off high frequencies) of the signal. The cut-off frequency is smaller than the half of the sample frequency.

$$F_{\text{sample}} > 2{*}F_{\text{cut-off}} = F_{\text{signal}}$$

So the sample theorem is fulfilled.

Signal processing

Signal processing is the analysis, interpretation and manipulation of signals. Signals of interest are biological signals such as motion, angles, EMG, ECG and many others. Processing of such signals includes storage and reconstruction, separation of information from disturbances and noise. We separate the signal processing in two steps, i.e. analysis of the time curve and analysis of the frequency domain.

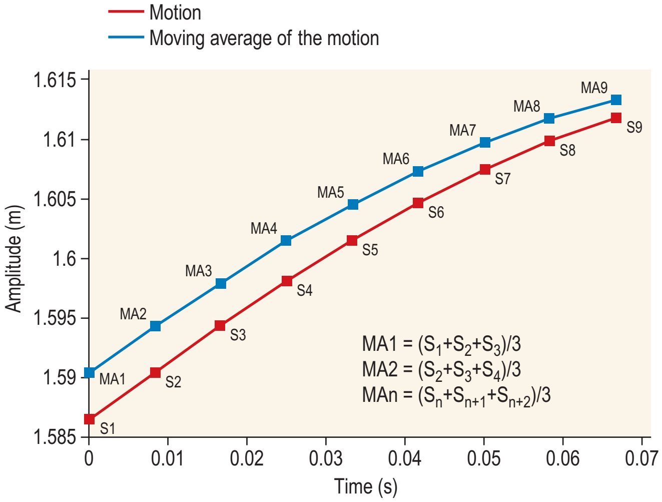

Fig 3.7 Moving average.

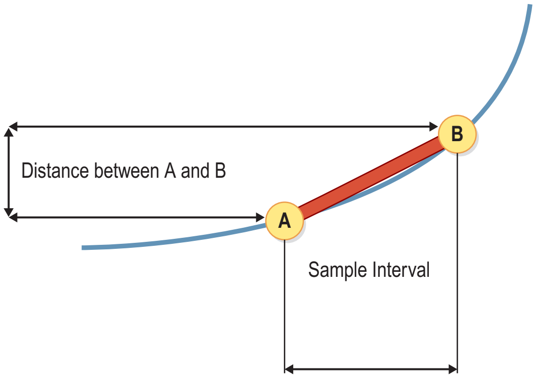

Fig 3.8 Derivation of a sampled signal.

Time curve analysis

Differentiation

Differentiation is often needed in motion analysis and biomechanics (e.g. to calculate velocity and acceleration from the motion). Furthermore, acceleration is needed to calculate the acting forces (force = mass × acceleration).

Definition of differentiation

The definition of the differentiation can be approached in two different ways. One is geometrical (as a slope of a curve), which was used by Leibniz, the other is physical (as a rate of change), which was the method of Newton. Historically, it was a struggle between Leibniz and Newton for being the pioneer of calculus. The approach of Newton was to calculate the velocity; therefore this method will be shown.

The physical concept of Newton

This approach was used by Newton in developing his 'Classical Mechanics'. The main idea is the calculation of velocity.

Figure 3.8 shows one sample interval of a coordinate motion. The sample rate gives us the time scale, whereas the coordinates give the distance from A to B. The velocity for each sample interval is calculated by dividing the distance between two samples by the duration of a sample interval. The mean velocity for each interval is the quotient of the distance and the elapsed time.

$$V_{\text{mean}} = \frac{\text{distance between two samples}}{\text{duration of a sample interval}}.$$

The motion is represented by the slope of a straight line between two points. If the sample rate is infinitive, the straight line is the tangent to this curve at a given time point. In the real world the sample rate is always finite. So in DSP it is possible to calculate the mean velocity between two consecutive measures. Time series of velocity can be calculated by repeating this step for all intervals.

Phase-plane analysis (practical use of differentiation)

Phase-plane analyses are used to show the stability of a system or a motion. Examples are stability of equine gait on a treadmill (Peham et al., 1998), harmony of horse and rider (Peham et al., 2001c) and stability of coupling via saddle of horse and rider (Peham et al., 2004). A phase-plane is a graph of a signal (motion) versus its derivative (speed).

Figure 3.9 shows the motion (first graph) and the velocity (second graph) of vertical motion of the head of the horse.

Increasing, decreasing and finding a local maximum or the minimum (extreme values)

The derivative of data or a function can provide information about any increase or decrease in the function and position of extreme values.

Since the differentiation is the local linearization, the curve can be replaced by tangents in every time point. We presented here only the simple linear method of differentiation (Fig. 3.8). More point methods (e.g. 5-point) based on the Taylor series are often used.

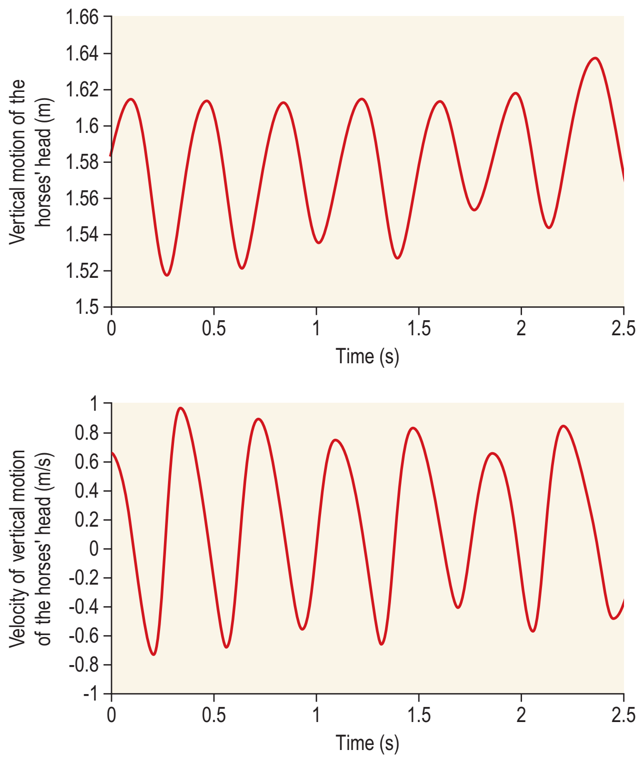

Fig 3.9 Differentiation of a signal.

When differentiation is applied to data that contains noise, results can be inaccurate. This will be discussed later.

Positive velocity indicates that the distance is increasing, whereas negative velocity stands for the decreasing distance.

In Figure 3.9, it can be seen that when the head goes up the velocity is positive. When the head goes down the velocity is negative.

At zero velocity, the motion reaches an extreme value, i.e. maximum or minimum. When the velocity changes from positive to a negative value, this indicates a maximum. Whereas, when it changes from negative to a positive value it indicates a minimum.

Integration

Integration is very important in motion analysis. Additionally, many powerful mathematical tools are based on integration, e.g. differential equations are the direct consequence of the development of integration. Calculation of impulse from the time curve of force (Osterlinck et al., 2009), integrated EMG (Wijnberg et al., 2009), and computation of speed from acceleration (Galloux et al., 1994) are a few examples of integration in motion analysis.

The integration of a function or data involves computing the area beneath the time curve. In most cases the time interval is constant, because of constant sample rate of measurement equipment, e.g. camera, force plate, EMG, and accelerometer, etc. It makes it very easy to determine the area under the expected curve between two sample values.

Figure 3.10 shows how the area under a curve can be calculated. The first step is computation of area of the square (side length = first sampled acceleration a_1, Δt_1 = sample interval) $A_1 = a_1 \times \Delta t_1$. The rest of the area is a right-angled triangle (side length a = difference between the first and the second sampled acceleration $a_2 - a_1$, side length b, Δt_1 = sample interval) $A_2 = (a_2 - a_1) \times \Delta t_1/2$.

$$A_{s,1} = A_{\textcircled{1}} + A_{\Delta} = a_1{}^*\Delta t_1 + (a_2 - a_1)^*\Delta t_1/2 = (a_1 + a_2)^*\Delta t_1/2$$

$$A_s = \sum_{i=1}^{n} (a_i + a_{i+1}) \cdot \frac{\Delta t}{2} + a_{begin} \text{ (= Sum area under the curve)}$$

ai … samples, Δt … time interval

The equation above shows the calculation of the area for one interval and then for n sampled values (n-1 intervals).

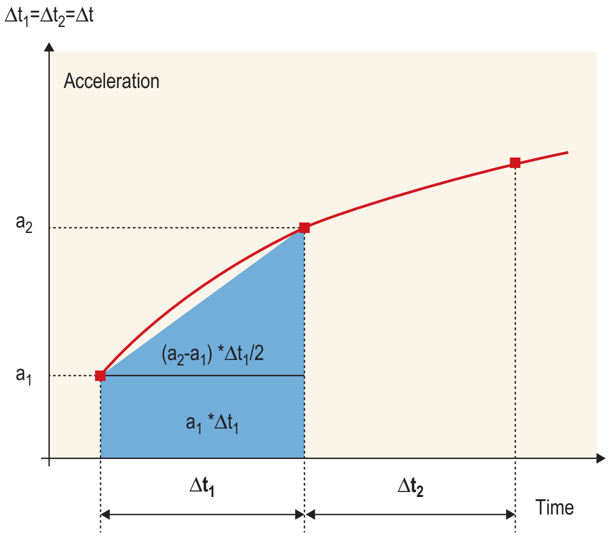

Fig 3.10 Calculation of the integral.

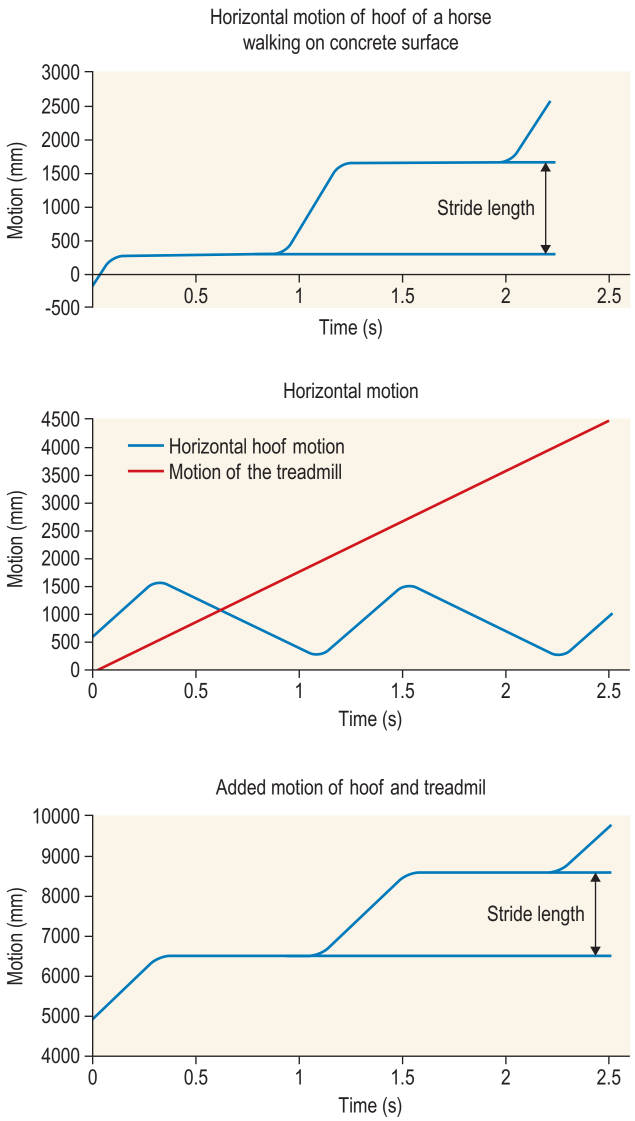

Fig 3.11 Difference between firm ground and a treadmill motion (coordinate transform).

Transformation of the coordinate system

A coordinate transformation is a conversion from one system to another to describe the same space. For example, in case of a comparison of data from a moving horse on firm ground to data from a horse moving on a treadmill a coordinate transformation is necessary. In this simple case, the horizontal excursions of the horse and the treadmill have to be added. Figure 3.11 shows the difference between the motion signal on firm ground (first graph) and on a treadmill (second graph). The third graph shows the transformed motion (from treadmill to firm ground).

The description of the skeletal-system movement involves the definition of specific sets of axes or frames that are either global or local (Cappozzo et al., 2005). The origin of the coordinate system has to be fixed on the belt where only the backward-movement is taken into account. It makes the trajectories of the fore and back movements comparable. This is a translation of the coordinate system. A universal translation includes translations in the direction of all the three coordinates (x, y, z) and two rotations, e.g. a coordinate system is fixed on the head of the horse to observe the chewing motion without the movement of the whole head (Niederl et al., 2006).

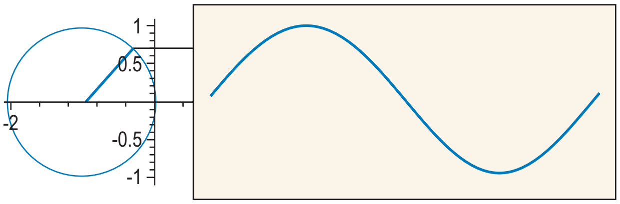

Fig 3.12 A rotating pointer giving a sine curve.

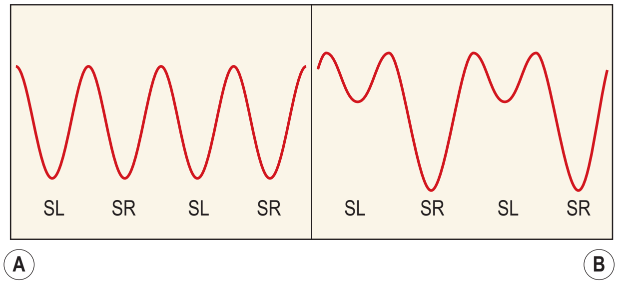

Fig 3.13 (A) Vertical head motion of a sound trotting horse. (B) Vertical head motion of a trotting horse with a supporting forelimb lameness of the left extremity. SL, stance left; SR, stance right.

Fourier analysis (time domain – frequency domain)

The Fourier transform is named in honor of the French mathematician Jean Baptiste Joseph Fourier. The Fourier analysis is the most important tool in signal processing. It is used in digital image processing, medical image processing (CT, MRI, ultrasound, etc.) as well as in engineering (communication, electrical and mechanical engineering) and physics (optics, mechanics, etc.). The Fourier transform separates a signal into sine waves with different frequencies, whereas the inverse Fourier transform composes the time curve from its frequency components. In other words the Fourier transform takes a signal from the time domain to the frequency domain and the inverse Fourier transform takes a signal from the frequency domain to the time domain (Nambu et al., 2000).

Gait is a periodic process, so it can be compared to the motion of a wheel. The motion of a wheel will be described by a sine function (Fig. 3.12).

A useful analogy is to interpret the Fourier analysis as a curve fitting tool, which uses only sinusoidal curves (sine and cosine). A very simple example is the vertical motion of the head, withers or sacral bone in walk and trot. Walk and trot are symmetrical gaits and therefore used for lameness or symmetry evaluation. Figure 3.13A shows the vertical motion of the head of a sound horse. The head is lowered during both stance phases, i.e. twice in a motion cycle. This curve can be represented by a sine wave twice the frequency of the motion cycle.

If the horse is severely lame on one of its front limbs, the head motion changes. The head is then lowered only during the stance phase of the sound limb and is less lowered during the stance phase of the painful limb (Fig. 3.13B). It is now evident that the vertical motion of the head of the horse can be represented by a sine wave with the frequency of the motion cycle.

Normally both frequency parts are included in the vertical head motion. So it is easy to calculate the symmetry index from this sinusoidal wave. The Fourier analysis decomposes the curve to these frequency parts (Peham et al., 1996, 1999, 2001d; Audigie et al., 2002). Sha et al. (2004) used Fourier series to determine the skin

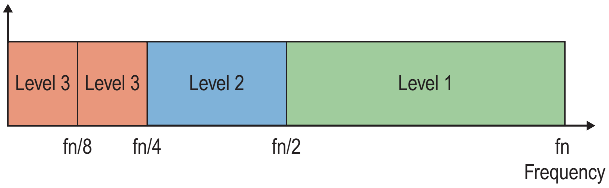

Fig 3.14 Frequency domain of a discrete wavelet transformation as shown in Figure 3.15.

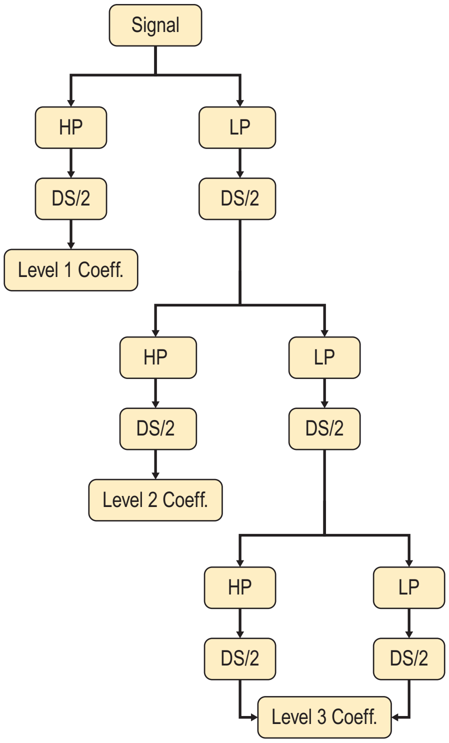

Fig 3.15 The wavelet decomposition of a signal via filter cascades. DS/2, down-sampling by a factor of two; HP, high-pass; LP, low-pass.

displacement over the radius. Back et al. (2006) showed changes in the frequency spectrum at impact between differently shod horses. It is necessary to know the concept of the Fourier transform to understand the following.

The Fourier transform is limited when the frequency is changed during the measurements, i.e. when a horse accelerates or changes the gait. In this case when the signals are non-stationary, Fourier transform is not sufficient. The first attempt to fix this problem was to use very short time windows, but it has the disadvantage that resolution of the frequency scale is very wide (frequency resolution = 1/duration of time window). The wavelet transform solves this dilemma of resolution to a certain extent (Fig. 3.14). Barrey and Galloux (1997) used the wavelet transform to analyze acceleration of jumping horses. Burn et al. (1997) decomposed the impact acceleration (instationary signal) of jumping horses.

In short, the wavelet transform uses variable time windows (Fig. 3.14) and therefore results in a time to frequency relation, a variable frequency scale and an efficient resolution in frequency domain (Meffert & Hochmuth, 2004; Strampp & Vorozhtsov, 2004; Polikar, 1995). Figure 3.15 shows the analysis process of the signal via wavelets. The signal will be low-pass and high-pass filtered and then the sample frequency will be reduced by a factor of two. This will be done iteratively (Fig. 3.15). Keegan et al. (2003) used the wavelet transform to detect lameness in horses.

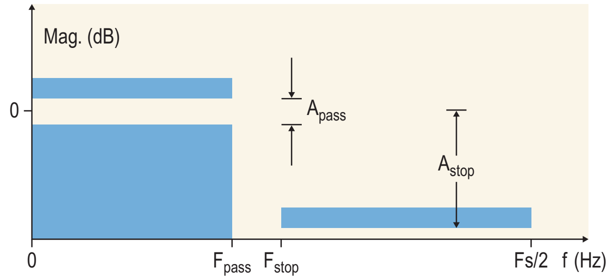

Fig 3.16 Shows the necessary filter parameters. A_{pass}, ripple range of the passband; A_{stop}, attenuation of the stopband; F_s, sample frequency; 0-F_{pass}, frequency range of the passband; F_{stop}-F_s/2, frequency range of the stopband.

Filtering

Filtering of the collected data is crucial in signal processing. The ideal filter will separate noise from the wanted signal, based on their different frequency content. In reality there is never a perfect separation between noise and signal. Filtering the collected data is, therefore, always a compromise between removing too much of the noise and too much of the signal (Strampp & Vorozhtsov, 2004; Meffert & Hochmuth, 2004; Werner, 2006).

As we will see in the following example, differentiation needs a low-pass filter, because of its characteristic to gain higher frequency parts (Giakas & Baltzopoulos, 1997; Bisseling & Hof, 2006). The frequency range of equine motion lies between 0 and the half of the sampling frequency. In walking humans with a stride frequency of 1 Hz, the highest harmonics were found to be in the toe and heel trajectories, and it was found that 99.7% of the signal power was contained in the lower seven harmonics (below 6 Hz) (Winter, 1990). In most cases sampling frequencies of 100 Hz are used. Clayton (1996) stated as a guideline that a digital low-pass filter with a cut-off frequency of 10–15 Hz is adequate for most videographic studies on equine gait.

It is generally assumed that raw surface EMG should be high-pass filtered with cut-offs of 10–30 Hz to remove motion artifact before subsequent processing to estimate muscle force (Potvin & Brown, 2004).

If peak values are detected (e.g. EMG signal processing determines the peak envelope), this will lead to an overestimate of the values. This can be avoided by the use of low-pass filtering. On the other hand the cut-off frequency of the low-pass filter influenced the peak values obtained with the largest changes occurring between 15 and 40 Hz. Typically, researchers using lower sample rates have to filter around 10 Hz and consequently are likely to underestimate peak angular velocities (Digby et al., 2005).

It is nearly impossible to determine the time occurrence in unfiltered EMG signals (Durkin & Callaghan, 2005; Ives & Wigglesworth, 2003).

The filter characteristic will be determined in the frequency domain. In motion analysis, filters with a special transfer function are used. Most of this transfer functions are named to honour the mathematicians who developed the transfer function or shape (polynomial) of the filter. The most popular are Butterworth (see Fig. 3.17), Chebyshev and Cauer.

The filters are defined by their type or polynomial (Butterworth, Chebyshev or Cauer), order of the polynomial (e.g. third order, fourth order, etc.) and cut-off frequency used.

The first step of filter design is to define the cut-off frequency. The cut-off frequency is the frequency where signal is attenuated by 3 dB (square root of two, i.e. 1.41). It is possible to construct low-pass, high-pass, band-pass and band-stop filters. See Figures 3.16 and 3.17. In motion analysis the most common type is the Butterworth filter.

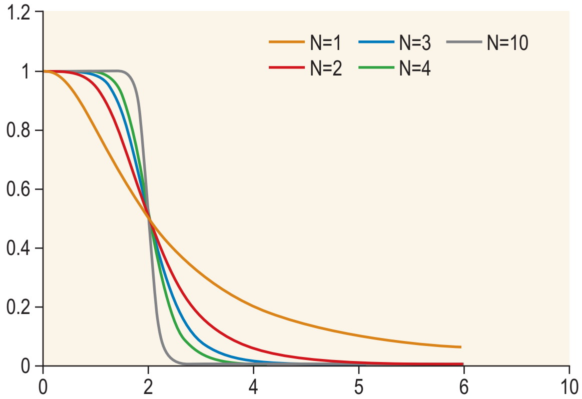

Fig 3.17 Shows the influence of the order N to the filter characteristic.

$$|H(\omega)|^2 = \frac{1}{1+\left(\frac{\omega}{\omega_c}\right)^{2N}}$$

where N is the order of the polynom, ω standardized frequency, ω_c standardized cut-off frequency.

In comparison to the other filter types the advantage of a Butterworth filter is, that the signal distortion is low (linear phase). Disadvantages are the relative wide transition range and the high order compared to Chebyshev and Cauer filters.

The term ‘spline’ stems from shipbuilding. A spline is a curve which connects given data points (samples) smoothly. So this method is very useful in motion analysis. It can be used to smooth data, then it is called smoothing spline, or as a curve fitting tool to fill gaps in the trajectories from incomplete measures (missing data), or to resample data (curve fitting, calculation of the new samples). In more detail, a function in most cases, cubic splines (polynom of the third order) will be fitted in the data by optimizing squared residuals (Vint & Hinrichs, 1996).

The following section will show the necessity of low-pass filtering when the differentiation is calculated.

Differentiation in time and frequency domain

How to calculate a derivative is explained earlier. Figure 3.18 shows real data of vertical motion, velocity and acceleration of the head of a horse. Noise increases with every derivation. The wanted signal has disappeared in the acceleration. What is the reason for this increase in noise?

In the time domain, the derivative is divided by time/interval. How are time and frequency related?

If the duration of the period of a cosine wave is one second, the frequency of this signal is one Hertz. If the duration is half a second, the frequency of this signal is two Hertz. The frequency is related to the reciprocal value of the time. If signal is divided by time in the time domain, the same operation in the frequency domain will be a multiplication by the frequency (see Fig. 3.19). A signal part, two times derivated at 1 Hz, is multiplied by 1 (1^2); a signal part, two times derivates at 2 Hz, is multiplied by 4 (2^2); and a signal part, two times derivates at 3 Hz is multiplied by 9 (3^2).

This behavior is similar to a high-pass filter. High frequency parts are amplified in comparison to low frequency parts. Noise is proportional to the bandwidth (frequency range). Now it is clear why noise is amplified. So we have to limit the bandwidth by a low-pass filter to get representative results (Uhlir et al., 1997). Figure 3.9 shows the same data as Figure 3.18 but band-limited by low-pass filtering.

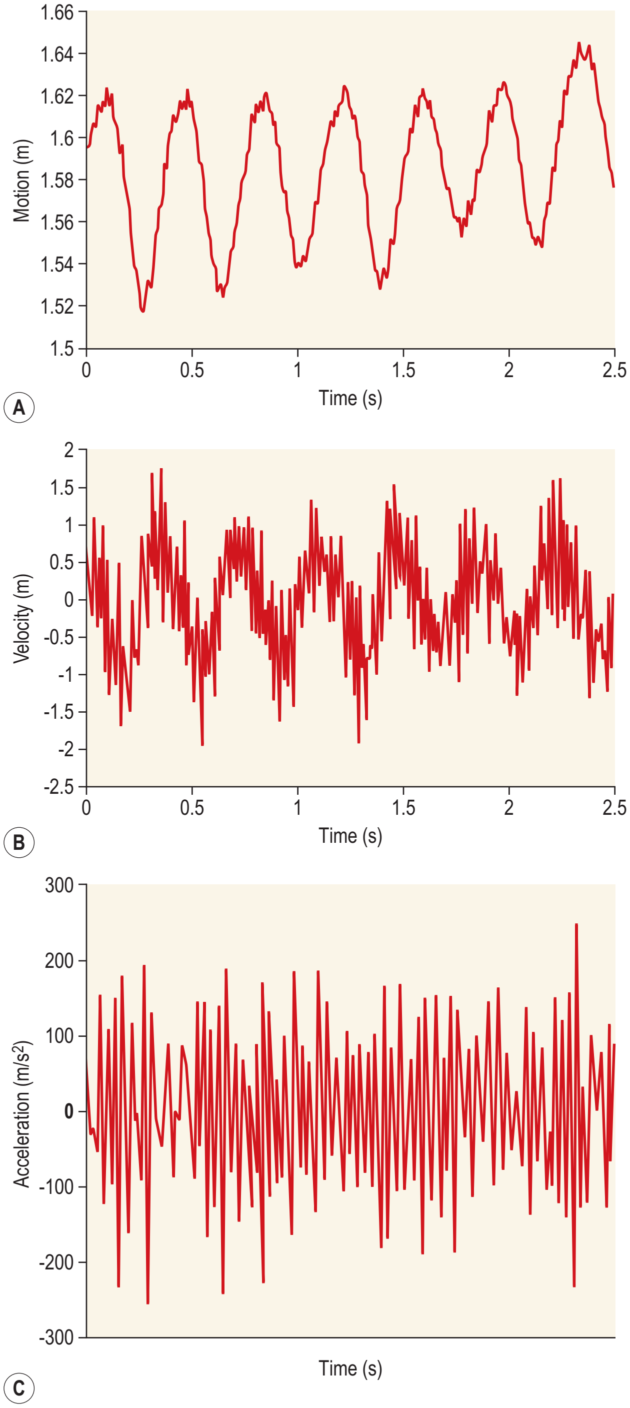

Fig 3.18 Effect of derivation of an unsmoothed signal. Noise is increasing. In the graphs of velocity and acceleration and the actual signal disappears.

Integration in time and frequency domain

The method of calculating an integration has been explained earlier. Figure 3.20 gives an example of an integrated EMG. See also resampling. It is obvious that the noise is reduced by calculating the integral of the EMG. What is the reason for this smoothing?

In the time domain, the integral was calculated by determining the area under the curve. This was done by a multiplication of time (amplitude × time). Now we know that time is related to the frequency by the reciprocal value. In the frequency domain, the frequency parts are divided by their entire frequency.

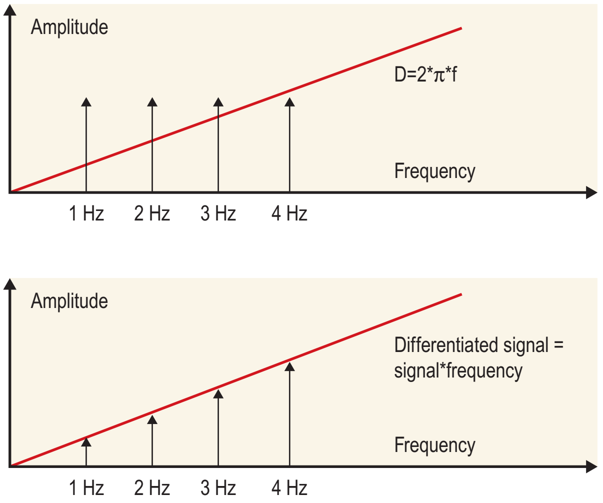

Fig 3.19 Effect of the derivation to the signal. Differentiation is a multiplication by the frequency. If the bandwidth is not limited, the noise of the higher frequencies will be amplified and the signal to noise ratio will be very low.

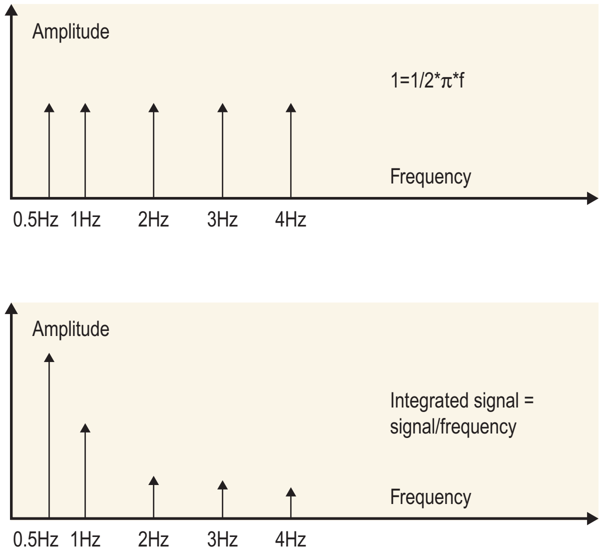

Fig 3.21 Effect of the integration. Lower frequency parts are amplified and higher frequency parts are dampened.

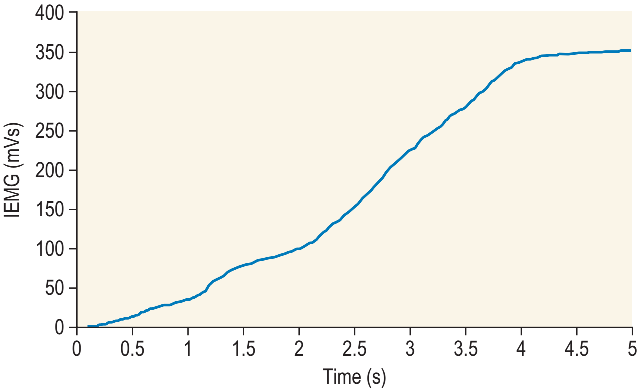

Fig 3.20 Integrated EMG signal of the long back muscle.

Figure 3.21 shows a signal in the frequency domain. The integrated signal part at 1 Hz is divided by 1; the integrated signal part at 2 Hz is divided by 2; and the integrated signal part at 3 Hz is divided by 3. This procedure gives us smoothed data and is comparable to the moving average using two neighboring data points. This is similar to a low-pass filter, because low frequency parts (below zero) are amplified and high frequency parts are dampened. In other words, a moving average reduces the samples by the number of data points that are included.

System analysis in time and frequency domain (convolution, special filters)

If special characteristics of the data are known, it is possible to develop a filter characteristic adapted to the wanted signal. Peham et al. (1996) used this to filter the vertical head motion. Peham et al. (2001b) filtered electromyographic signals of the left and right longissimus dorsi muscles, middle gluteal muscles and triceps brachii muscle of horses walking on a treadmill with a special signal adapted filter characteristic. In both cases, the transfer function was developed from the motion of the limb.

In the time domain, the convolution integral of the signal and the transfer function has to be calculated to get the filter signal. This is much easier in the frequency domain, because the convolution integral in time domain corresponds to a multiplication in the frequency domain. Therefore, in most cases the filters are developed in the frequency domain. Data are transformed in the frequency domain and then multiplied by the transfer function. See Figures 3.19 and 3.21.

This property can also be used to study the system behavior. See equations below.

Time domain:

$$\text{output}(t) = \int_{-\infty}^{+\infty} \text{transfer function}(t-\tau)\cdot \text{input}(t)dt$$

Frequency domain:

$$\text{output}(\omega) = \text{transfer function}(\omega)\cdot \text{input}(\omega)$$

In case of filtering, the transfer function and measured data (input) are given and filtered data (output) are calculated. In case of system analysis, input and output are available.

$$\text{transfer function}(\omega) = \frac{\text{output}(\omega)}{\text{input}(\omega)}$$

Peham and Schobesberger (2006) used the transfer function to calculate the elasticity of the equine back by relating the EMG of the long back muscle as input to the motion of the horses back as output. The transfer function was developed in a differential equation of second order and compared to the motion equation.

The convolution is similar in nature to the cross correlation (CC). The convolution calculates the CC of two signals whereas the reverse function of the second signal is used. The CC can be used to compare two different signals or find the content of one signal in the other signal. Strobach et al. (2006) used CC to show the limb coordination of ataxic, sedated and sound horses (by using the CC to compare the motion of different limbs). Peham et al. (1996) used CC to determine the wanted signal parts of vertical head motion, which were necessary for lameness evaluation.

The auto-correlation is the CC of a signal with itself. This can be used to find periodic elements in the signal or to determine, e.g. the stride frequency of a motion signal. Strobach et al. (2006) used the auto-correlation to show the differences in the gait pattern in ataxic, sedated and sound horses. If the auto-correlation was high, a stable motion pattern was present. Peham et al. (2001b) used the auto-correlation to calculate the signal to noise ratio.

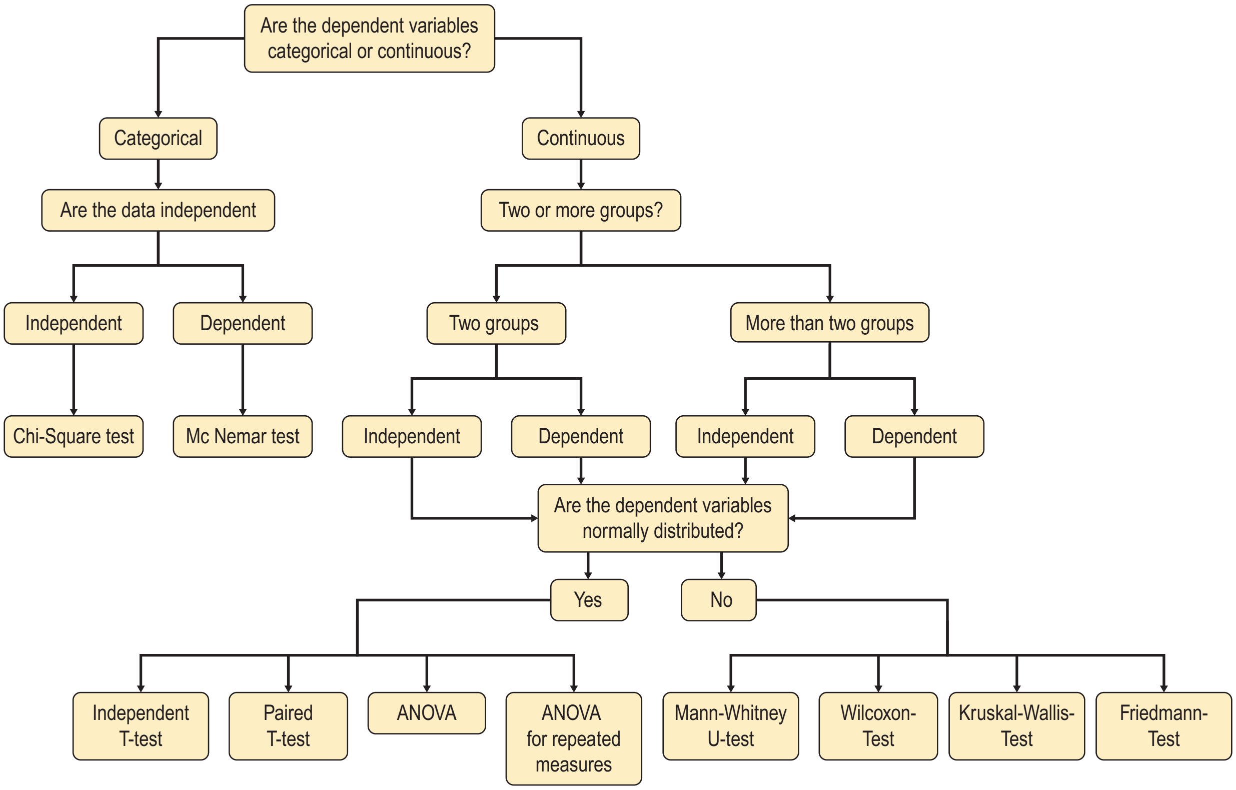

Fig 3.22 Basic guidelines for choosing a statistical test.

Kalman filters are used to estimate the dynamical behavior of linear systems. Halvorsen et al. (2008) used Kalman filtering to exclude skin-movement of the distal part of the limb of horse.

Decision-making

Signal processing is necessary to interpret the signal or characteristics of the signal. To get reliable information from the processed signal, statistics are needed to reflect trends, if any. Figure 3.22 shows a simple flow chart regarding selection of an appropriate statistical test. A more detailed discussion of statistical methods is given by Hopkins (2007).

Fuzzy logic

The classical (binary) logic distinguishes between two values 'black' and 'white'. This binary logic implies the law of the excluded middle, which states that for all propositions, either *black* or *white (not black)* must be true, there being no middle true proposition (*gray*) between them.

It was Jan Łukasiewicz who first proposed a systematic alternative to the bi-valued logic of Aristotle and described the 3-valued logic (black-gray-white), with the third value being possible (Jang et al., 1997).

Fuzzy sets have been introduced by Lotfi A. Zadeh (1965) as an extension of the classical notion of set. In classical binary set theory, two states (black and white) are possible. Other states are not elements of the set. By contrast, fuzzy set theory permits the gradual assessment of the membership of elements in a set (e.g. 50% of black and 50% of white gives us gray). Let us say, 'fuzzy logic is more adapted to the (bio-) logic of the real world, because in the real world (life) there are always more than two colors or a fixed number of solutions'.

Fuzzy clustering is used in clinical motion analysis to distinguish between sound and lame gait patterns. Keegan et al. (2004) used fuzzy clustering to detect spinal ataxia in horses.

Artificial neural network

Artificial neural network (ANN) is a method of highly sophisticated decision-making. ANN, often just called a 'neural network' (NN), is a mathematical model or computational model inspired from biological neural networks. It consists of a network of interconnected group of artificial neurons. The artificial neurons are in most cases switches that will be activated if a certain input threshold is reached. Combination, activation and weight of neurons are adapted to the problem. So an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase.

An overview of ANN in motion analysis is given by Schöllhorn (2004).

In more practical terms neural networks are non-linear, non-parametric statistical data modeling tools. They can be used to model a complex relationship between inputs and outputs or to identify patterns in data (Schöllhorn, 2004; Jang et al., 1997).

Savelberg et al. (1997a) used ANN as a tool for complex calculation to determine ground reaction forces in horses with hoof wall deformation. Further use of ANN was seen for computing tendon forces from EMG data in cats (Savelberg et al., 1997b) and for calculation of fore and back force from pressure data (Savelberg et al., 1999).

Use of ANN as a decisive statistical tool was shown by Schobesberger and Peham (2002). They used a multilayer feed forward ANN to quantify lameness in horses. The classification via ANN was correct in 78.6% of cases. They concluded that after proper training, ANNs were potentially capable of making a non-human diagnosis of equine lameness.

Schöllhorn et al. (2006) showed that a Kohonen map (a special type of ANN; it compares the input data with standard data by vector products) combined with a cluster analysis is sensitive enough to identify a specific motion pattern in the horse-rider interaction.

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CHAPTER 4

Locomotor neurobiology and development

Albert Gramsbergen

Introduction

The last decennia have seen an explosion of knowledge on the neurobiology of locomotion. Much research has been devoted to elucidating the basis of normal and disturbed locomotion in man. Investigations mainly in cats and rats and also in man have focused upon the steering of locomotion by central brain areas, upon central pattern generators (CPG), upon the recovery after brain damage or peripheral nerve lesions and a variety of other topics. It has been known for almost a century, that the neuronal assemblies called CPGs play an important role in rhythmic leg movements (and also in breathing and chewing movements). The research in lampreys, cats and developing rats into the neural organization of these CPGs, their wiring patterns and the transmitters involved has given an impressive momentum to studies into the neurobiology of locomotion in bipeds and in quadrupeds. Similarly, the cerebellum and motor learning, the basal ganglia and the planning of motor acts as well as the sensory-motor cortex and skilled movements in relation to posture and locomotion have seen a vivid research interest.

However, detailed knowledge is still lacking on the neuroanatomical and neurophysiological basis of locomotion in horses. Investigations into such neurobiological aspects generally require invasive procedures, and ethical considerations, the economical value and the size of this animal are the main reasons for a paucity of data. Non-invasive techniques such as transcranial magnetic stimulation with the recording of responses in the EMG or fMRI-techniques have not yet been adapted to equine research for a variety of reasons. On the other hand, research into the biomechanical aspects of walking, galloping and trotting in horses, and also into gait analysis with high-speed filming, have a long tradition. Results from this research have set standards which, in turn, inspired investigations in man and smaller laboratory animals. The ‘golden age’ of research into equine locomotion in the 1960s, (Van Weeren, 2001) developed a promising sequel by research in several laboratories in the USA, in Canada as well as in several European countries, most notably in The Netherlands and in France. The first edition of *Equine Locomotion* marked this interest and the results obtained so far were comprehensively summarized there.

Concepts on the neurobiological basis of locomotor movements in horses, therefore, necessarily mainly rely upon knowledge obtained in laboratory animals. Older textbooks on comparative neuroanatomy include only a few data on horses. These textbooks are mainly limited to comparing the gross anatomy of the brains in smaller mammals and man, with that of primitive vertebrates such as teleosts, reptiles, amphibians and birds. Larger mammals are rarely included in these comparisons (e.g. Ariens Kappers et al., 1967). Also, data on neural connections in the horse’s brain are scarce. Verhaart and Sopers-Jurgens (1957) described Bagley’s bundle by dissection of the horse’s brain. This projection runs from the cerebral cortex to the mesencephalic and pontine tegmentum and is considered to be the phylogenetic predecessor of the corticospinal tract (CST) which is present in other mammals.

In the last four or three decades of the 20th century a variety of neuroanatomical tracing techniques have been developed and these opened a multitude of new insights into brain circuitry. By the injection of retrogradely or anterogradely transported vital stains, terminals of neural projections or their site of origin can be studied. Such investigations, however, require surgical interference as well as, after a short survival period, post-mortem processing of the brain tissue. These studies have therefore not been performed in horses. For similar reasons, studies involving the implantation of depth electrodes for recording or stimulating central nervous structures have not been carried out in horses. Modern imaging techniques of the brain (as fMRI) have been widely applied in human research and results may indicate the brain areas involved in specific tasks. These studies require immobility of the skull in the scanner and that is one of the reasons why these techniques do not lend themselves to investigations in horses. Possibly, the newest advance in brain-imaging, MRI-diffusion tractography, which allows non-invasive identification of tracts in the CNS, might ultimately be applied to study neural projections in animals and possibly in larger animals (Behrens et al., 2007).

In horses, the recording of simultaneous EMG signals in collections of muscles have been performed with kinematic recordings to analyze coordination patterns during a variety of locomotion patterns. These studies are also important for diagnosing abnormalities in movement patterns and diseases of muscles and motoneurons.

This chapter bases itself upon research in laboratory animals and notions on neurobiological aspects of trotting and galloping in horses should be derived by the extrapolation of this knowledge. When extrapolating, it should be kept in mind that not only the size but also the behavioral competences of horses on the one hand, and laboratory animals such as rats, cats or monkeys on the other, differ widely. These differences are related to the ecological biotopes from which these animals stem. Behavioral competence is mutually interconnected with the neural organization of the nervous system and interspecies extrapolations therefore have to be interpreted with the greatest caution.

The relationships between the terminal projection patterns of the CST in a variety of animals in relation to their manipulative skills, is a case in point (Armand, 1982). In higher primates, the pyramidal neurons in the primary motor cortex are monosynaptically connected to the motoneurons of the hand and wrist muscles, located in the cervical spinal cord. By virtue of these direct connections, apes and man are able to independently move their fingers and toes, to manipulate objects and to use tools, while standing upright (Lawrence & Hopkins, 1976). In cats, however, fibers of the CST mainly end in the dorsal and medial laminae of the spinal cord and they connect to the so-called premotor neurons at cervical and lumbar levels. Indeed, cats cannot move their toes independently. Rats take an intermediate position between primates and cats as these animals do have a limited number of direct connections between cortical and spinal motoneurons and these do allow them to manipulate their food by independent toe movements. In rabbits and goats the CST only descends as far as the upper cervical segments and its fibers do not even reach the premotor neurones of the cervical and lumbar spinal cord. Horses most probably are similar to these animal species with respect to the descent of the CST or its analogon (Armand, 1982; Verhaart & Sopers-Jurgens, 1957).

In this chapter, current knowledge on locomotion and its neurobiological substrate will be briefly reviewed. The order which will be followed is from the peripheral elements to central structures, or, from the muscles via the spinal cord towards central motor systems. As developmental research into locomotor functions and structural changes in motor systems has made important contributions to our understanding of the neurobiology of walking and postural maintenance at adult age, these aspects will be discussed where appropriate.

Muscles, motors of movements

Leg and trunk movements are produced by skeletal muscles. Histological and neurophysiological aspects of muscles at adult age have been reviewed several times (Burke, 1981; Partridge & Benton, 1981; Kernell, 1998) and a few of these will be repeated only briefly here.

Muscles consist of hundreds or thousands of multi-nuclear muscle cells or muscle fibers and each of these contain many myofibrils. In addition, satellite cells occur which at later stages may transform into functional muscle cells. The myofibrils in the muscle cell consist of a chain of thousands of 'sarcomeres', the basic element of a striated muscle fiber. A sarcomere consists of longitudinal actin molecules with short troponin molecules attached and myosin molecules. The contraction of a myofibril is produced by the contraction of the actin and myosin-complexes in each of the sarcomeres. This contraction is produced by the formation of cross bridges between the actin and myosin molecules. This active process requires energy which is derived from ATP (which then degrades into ADP). The relaxation of the muscle by lengthening of the sarcomeres basically is a passive process.

The contraction of a muscle fiber is induced by an action potential in the motor nerve which arrives at the motor endplate. The release of acetyl-choline (ACh) in the motor endplate and the binding of ACh to nicotinic ACh-receptors, leads to the opening of ion channels in the muscle cell membrane. The net influx of Na^+ ions leads to a local depolarization of the cell membrane which spreads along the membrane. This depolarization, in turn, leads to the release of Ca^{++} via the sarcoplasmic reticulum. Ca^{++} binds to troponin which then induces the formation of the cross bridges between actin and mysin, producing the contraction of the muscle fibers. Both the spread of the depolarization along the membrane and the transport of Ca^{++} through the muscle cell is a relatively slow process and the delay between the arrival of the action potential and the onset of the contraction, the so-called 'action–contraction coupling', may last 200 ms.

Summary

Actin and myosin molecules shorten in the sarcomere by connecting troponin. This reaction is initiated by an action potential arriving at the muscle cell membrane which, in turn, releases the intermediary Ca^{++} ion.

Muscle fiber-types

Some muscles may appear dark-red on macroscopical inspection while other muscles are much paler. Examples of such dark-red muscles are the long back muscles and also the soleus muscles in the hind-legs. A large majority of the fibers in these muscles are of the so-called type I, and these fibers derive their energy (to regenerate ATP from ADP) from the aerobic oxidation of glucose (which takes place in mitochondria). Glucose enters the myocytes from capillaries and the extracellular space. These muscles appear dark-red because the type I myocytes contain high levels of the deep red myoglobin molecules, which bind oxygen, and also because of the many capillaries around the muscle fibers. Glucose is readily replenished from the blood vessels during muscle contractions and therefore these muscles are able to produce contractions for long periods of time.

Other muscles are much paler. These muscles mainly contain type II muscle fibers (and a minority of type I fibers). In type II muscle fibers, the ATP is regenerated by the anaerobic catabolism of glycogen which is stored in the muscle. This reaction is much faster but energetically less efficient than the aerobic metabolism of glucose. Moreover, the supplies of glycogen are limited. As the recovery of these supplies takes a considerable period of time, the contractions of the fibers in these myocytes can only be brief. Other fibers within the same muscle will take over but, obviously, this has its limits. Two subtypes of type II muscle fibers can be distinguished. Type IIb fibers derive their energy exclusively from the anaerobic metabolism of glycogen and type IIa fibers have a mixed metabolism; these make use both of the anaerobic as well as the aerobic route to generate energy.

The mechanical force of single muscle fibers has been recorded after briefly stimulating the motor nerve. Such stimulation induces a so-called muscle-twitch which is a single contraction of the fiber. It has been demonstrated that the force produced by a twitch of type I muscle fibers increases relatively slowly, has a low peak value and also decreases slowly. When stimulating for sustained periods and with such frequencies that the separate twitches fuse into a tetanic contraction, it appears that the tension in type I muscle fibers can be maintained for longer periods. In other words, these 'slow-twitch' muscle fibers are 'resistant to fatigue' and this is related to their oxidative metabolism (see above). On the other hand, the type II muscle fibers, after brief electrical stimuli, show a much faster increase in their tension and also the peak value of tension is much higher than that in the type I fibers. This increased tension is explained by the formation of alternative cross bridges between the actin and mysosin molecules. The tension after a twitch declines rapidly in these fibers. When stimulated with high, constant frequency leading to a tetanic contraction, the tension in these 'fast-twitch, fast-fatigable' muscle fibers diminishes after a relatively short period of time. After such contractions, these fibers need a considerable time to replenish their glycogen stores and to wash out the lactic acid, which is produced by the metabolism of glycogen. Type IIb fibers produce the highest tension, and these fibers show signs of fatigue most rapidly, while type IIa muscle fibers take an intermediate position between the type I and type IIb fibers. After stimulation their force rises and falls rapidly (though, less than that of the type IIb fibers) and because of a mixed aerobic and anaerobic metabolism, they are more resistant to fatigue than the type IIb fibers.

The different types of muscle fibers can be visualized histologically. Post-mortem studies allow the investigation of the distribution of fiber types in sections taken perpendicular to the longitudinal axis of the muscle at several levels. Multiple biopsies only allow an approximation of such data. In a classical method of processing (Dubowitz & Brooke, 1973), the muscle material is preincubated at different pHs and the ATPase staining technique then enables differentiation of the muscle fiber types. More recent methods apply myosin-related antibodies to identify several subtypes of muscle fibers (Schiaffino et al., 1986). Investigations with these methods have demonstrated that all muscles consist of a mixture of type I, type IIa and type IIb muscle fibers, but the relative proportions of these fibers differ greatly. Extremity muscles and particularly the flexor muscles may contain higher proportions of type IIa and IIb fibers and fewer type I muscle fibers. The antigravity muscles in the extremities, in contrast, contain increased proportions of types I and IIa muscle fibers. This is understandable when realizing that these muscles have to carry the weight of the animal for long periods of time. The proportions of type I muscle fibers are particularly pronounced in the soleus muscle in the hind legs, and portions of the flexor carpi ulnaris muscle in the forelegs. In these muscles, the type I muscles fibers may be as high as 100% (e.g. in rats). It is noteworthy that the type I fibers both in the extensors and the flexor-muscles are mostly concentrated in the deeper portions of the muscles, close to the skeletal elements (Wang & Kernell, 2001). Similar data have been obtained in horses (Grotmol et al., 2002).

The trunk muscles also contain elevated percentages of type I and IIa muscle fibers. This holds particularly for the multifidus and the longissimus muscles in the back (Gramsbergen et al., 1996). Similar results have been obtained in horses (Gellman et al., 2002). The high percentage of type I and IIa muscle fibers make these particular muscles fatigue resistant and therefore these muscles are ideally suited for postural functions, such as keeping the trunk straight and carrying the body weight (for a review on regional differences in the distribution of type I and type II muscle fibers, see Kernell (1998)).

Horse breeds differ in the size and composition of their muscles. Horses of some breeds are heavily built with bulky muscles that have a large cross-sectional area and these horses are kept in order to sustain enduring agricultural or transportation tasks. Their muscles contain large proportions of type I and type IIa muscle fibers which are able to produce forces for long-lasting periods (see Miyata et al., 1999). Horses of other breeds are characterized by a slender and athletic build that is appropriate for speed racing. Their muscles have increased proportions of type II muscle fibers that allow them to produce immense forces but only for relatively short periods of time.

Investigations in man with EMG recordings and, in addition, power spectral analysis of the EMG and the calculation of EMG-fatigue indices, indicated that loading for long periods induces the recruitment of satellite cells in the muscle (see below), their development into muscle cells and a relative increase in type II muscle fibers (Mileva et al., 2009). Investigations, e.g. in rats, have shown that per individual muscle the number of type I muscle fibers remains unchanged (or, is genetically determined; see Wilson et al., 1988; see also, Mileva et al., 2009) and Mileva's results, therefore, point towards an absolute increase in type II fibers. Other investigators suggest, in contrast, that training may influence the fiber type distribution of muscles by shifts in the numbers of both type I and type II fibers (e.g. Duclay et al., 2009).

Other training effects are hypertrophy of muscle fibers as indicated by an increase in their cross sectional area, increases in mitochondrial content (important for aerobic glycolysis) (Grünheid et al., 2009), changes in muscular architecture (which might be secondary to the muscle fiber hypertrophy) (Duclay et al., 2009), as well as vascular changes by angiogenesis and an increase in arteriolar density (for review, Laughlin and Roseguini (2008)). Short-term effects of training aim at increasing the storage of large quantities of glycogen for rapid use in type II muscle fibers.

Summary

Muscles are composed of type I muscle fibers (slow-twitch, fatigue-resistant) type IIA fibers (fast-twitch, moderately fatiguable) and type IIB (fast-twitch, fatiguable); intermediate types also exist.

Muscular development

Muscle cells or myocytes develop by the fusion of a longitudinal array of mesenchymal cells. The first generation of these multinuclear myoblasts, extending from tendon to tendon, are the primary myotubes. Each of these is soon innervated by a multitude of motoneuronal axons. At a later stage, a second generation of secondary myotubes develops in the vicinity of the middle region of the primaries. The secondary myotubes also are initially innervated by multiple motoneuronal axons (Ontell & Dunn, 1978; Goldspink & Ward, 1979; Bennett, 1983). During further development, the contractile proteins actin and myosin increase enormously in the myotubes of both types. The motor endplate develops its folded appearance and from a certain stage of development these cells have acquired the characteristics of the mature myocyte. It is generally accepted that the primary myotubes are the precursors of type I muscle fibers and the secondary myotubes of the type II muscle fibers (see Wilson et al., 1988).

Wilson and coworkers studied in rats the effects of severe under-nutrition from early gestation and through the lactation period on muscular development. The number of primary myotubes remained unaffected but they detected a dramatic decrease in the number of secondary myotubes. These and other results has led them to hypothesize that the development of primary myotubes is genetically determined while that of the secondary myotubes is susceptible to environmental factors, such as under-nutrition, hormonal factors and also training (Wilson et al., 1988). In addition, non-differentiated satellite cells develop and these cells may differentiate at a later stage into myocytes after damage to the muscle or after training.

The muscle-fiber type distribution within muscles is, to some extent, related to their topological origin. The muscles in the trunk arise from the segmentally arranged myotomes. The intercostal muscles (together with the rib and the spinal cord segment innervating these muscles) have clearly retained this segmental origin in all mammals. But, the long muscles in the neck and in the back, the abdominal muscles and the diaphragm are also of axial origin. These muscle are particularly important for the stabilization of the trunk and the head and, therefore, for postural control. At adult age, the trunk muscles contain high proportions of slow-twitch, fatigue-resistant muscle fibers.

The muscles in the four legs arise from limb buds. The limb buds develop at the ventrolateral aspect of the body axis and these originate from groups of mesenchymal cells which migrated from the trunk. The extensor muscles in the limbs (e.g. the gastrocnemius and the quadriceps muscles in the hind leg) develop from the ventral plates in the buds and they are involved in 'anti-gravity' tasks such as standing, and also in the heel strike phase of walking and running. These muscles later contain considerable percentages of type I muscle fibers. The flexor muscles develop from the dorsal plate in the limb bud, they are particularly active during the swing phase of the leg and these muscles contain increased proportions of type II muscle fibers.

Summary

Muscles develop, cytologically, from primary and secondary myotubes. Trunk and extremity muscles originate from myotomes and limb buds, respectively.

The motor unit and motoneurones

Groups of muscle fibers in a muscle are innervated by one motoneuron in the spinal cord (or in the brain stem) and the complex of an α-motoneuron, together with the muscle fibers, is called a 'motor unit'. All muscle fibers of a motor unit tend to have identical physiological properties (such as twitch speed and relaxation time) and these properties match the physiological and morphological properties of the motoneurons.

Research mainly in cats, has indicated that the small-sized motoneurons innervate the type I muscles fibers and in neurophysiological research, these units have been coined 'S-type units' (slow-twitch, fatigue-resistant). Motoneurons of intermediate sizes innervate type IIa muscle fibers and physiologists have distinguished 'FR-type units', fast-twitch, fatigue-resistant units and 'Fint-type units', with fast-twitch and intermediate fatigue-resistant units. The largest motoneurons are part of the 'FF-type units', innervating type IIb muscle fibers; these units are fast-twitch and fatigable (Burke, 1981).

The motorunits systematically differ in the numbers of muscle fibers which are innervated by the motoneuron. The smaller motoneurons innervate relatively small numbers of type I muscle fibers. Both the low tension produced by each of these fibers and the relatively small number of muscle fibers in each of these units, explain why these units produce relatively low forces. The larger motoneurons innervate larger numbers of (type II) muscle fibers. Each of these fibers produce higher tensions, and consequently these units produce relatively large forces (for a review see Kernell, 2006).

Summary

Small motoneurons innervate a group of slow-twitch, fatigue-resistant muscle fibers, producing low forces, motoneurons of intermediate sizes innervate groups of fast-twitch, intermediate-fatigable, and the largest neurons produce strong forces by their fast-twitch, fatigable muscle fibers.

Development of muscular innervation

At early stages of development, muscle cells are innervated by more than one axon (see above) and this is known as polyneural innervation. Later, and already in early development, this multiple innervation of muscle cells is replaced by mononeural innervation (for reviews, Bennett, 1983; Jansen & Fladby, 1990). Research from many groups has indicated that this regressive process is near completion when the behavioral function in which the muscle is involved has developed (Gramsbergen et al., 1997). Rats are a precocious species and they are born at an early stage of brain development. Still, mononeural innervation of respiratory muscles in this species has already been reached at birth when the animals start breathing continuously. On the other hand, in the psoas muscle in the hind leg, this regression of polyneural innervation is only completed around the 16th postnatal day (IJkema-Paasen & Gramsbergen, 1998). This is precisely the point at which they start the adult-like pattern of walking. Horses are a precocious species, born with a nervous system at an advanced stage of development. They are able to stand and walk shortly after their birth and, therefore, it is safe to postulate that most of their muscles are mononeurally innervated from birth.

It has been suggested that the great excess of axons innervating the primitive muscle fibers at early stages and the selective regression of supernumerary nerve fiber-endings thereafter plays a role in matching the properties of muscle fibers to those of the motoneurons (O'Brien et al., 1978; Greensmith & Vrbova, 1991). More recent research has indicated, however, that even at the earliest stages ingrowing axons follow a trajectory towards a specific muscular region with a preponderance of particular muscle fiber types (Wang et al., 2002). Therefore, the polyneural innervation at first and its regression thereafter should rather be regarded as a fine-tuning in the matching-process.

Summary

Muscle fibers initially are polyneurally innervated. Mononeural innervation develops by a regressive process before the muscle is involved in its adult functioning.

Size principle

The motoneurons within a motoneuronal pool differ in their sizes (see above). Henneman & Mendell (1981) have demonstrated that within a motoneuronal pool, the motoneurons are recruited in an orderly fashion from small to large, with increasing intensities of neuronal drive (e.g. from higher brain centers). During motor tasks which require only low muscle forces only the smallest motoneurons are activated (these motorneurons innervate groups of type I-muscle fibers). With increasing forces, additional motoneurones with larger sizes are recruited, first those with FR properties, later those with Fint properties and finally the FF units are activated with their large numbers of type IIb muscle fibers. This orderly recruitment of motoneurons is related to differences in the membrane properties of the smaller and larger motoneurons. Interestingly, the relative force-increase by recruiting additional motor units at adult age is more or less the same over a wide range of forces (Milner-Brown et al., 1973) and this leads to a smooth increase of force with increasing intensities of neuronal drive.

Summary

Motoneurons are recruited in an orderly fashion from small to large, with increasing intensities of neuronal drive.

Dendrite bundles

Apart from their size, motoneurons also differ in the morphology of their dendritic tree. The motoneurons in particular pools have their dendrites running in bundles both in a longitudinal direction as well as in transverse directions, while in other motoneuronal pools such organization is absent. Motoneurons with dendrite bundles have been described in cats (Scheibel & Scheibel, 1970), in rats (Gramsbergen et al., 1996) and in the human spinal cord (Schoenen, 1982) and because of their wide occurrence it seems highly likely that dendrite bundles also occur in the horse's spinal cord. Dendrite bundles consist of up to 15 dendrites in close vicinity for several hundreds of millimeters (Fig. 4.1), and connected via long-stretched gap-junctions (Matthews et al., 1971; van der Want et al., 1998). Dendrite bundles specifically occur in pools of axial muscles in the trunk and neck as well as in pools of anti-gravity muscles in the extremities (notably, the soleus and the gastrocnemius muscles in the hind limb and the flexor carpi ulnaris muscle in the forelimb). Interestingly, these are the very muscles that contain high percentages of type I muscle fibers.

The physiological significance of dendrite bundles is not known but one possibility is that they serve to electrotonically couple motoneurons in pools stretching over several spinal cord segments which innervate long muscles, e.g. in the back or abdomen. Our study into the development of the dendritic tree of motoneurons innervating the soleus muscle (mainly consisting of type I muscle fibers) revealed that, until the 14th postnatal day in rats, the dendrites of these neurons run in a seemingly disorganized fashion. From that age, however, the dendrites reorganize into prominent bundles. This fast development coincides with the occurrence of the adult-like walking pattern in rats. On the other hand, the dendrites of the motoneurons innervating the tibialis anterior muscle (a flexor muscle, and the antagonist to the soleus muscle) do not

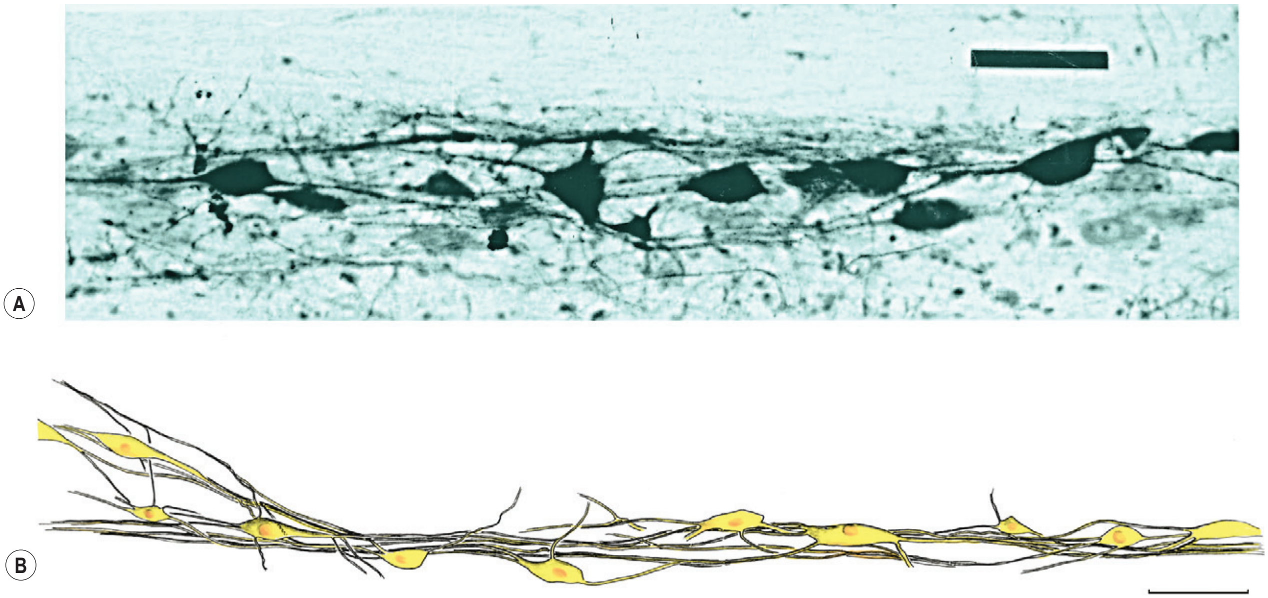

Fig 4.1 Motorneuronal pools of the longus capitis muscle: (A) microphotograph and (B) reconstruction of another pool. Bars: 100 μm.

Reprinted from Gramsbergen, A., Ijkema-Paassen, J., Westerga, J., Geisler, H.C., 1996. Dendrite bundles in motoneural pools of trunk and extremity muscles in the rat. Experi. Neuro. 137 (1), 34–42, with permission from Elsevier.

develop dendrite bundles at any age (Westerga & Gramsbergen, 1992). The organization of dendrites into bundles depends on the ingrowth of descending projections from higher levels as (in rats) a spinal cord transection at early age prevents these bundles from developing (Gramsbergen et al., 1995). In cats, such interference at adult ages leads to their hypotrophy or even atrophy (Reback et al., 1982).

Summary

Dendrite bundles are typical for motoneuronal pools of muscles with an important postural function.

Central pattern generators

Walking, trotting or galloping is produced by rhythmic and alternating leg movements in varying patterns. Graham Brown (1914) was the first to demonstrate that such rhythmic and alternating extremity movements can occur even after several dorsal roots of the lumbar spinal cord have been severed. This demonstrates that proprioceptive feedback is not essential for these movements to occur. A few years earlier, Sherrington (1910) had demonstrated that rhythmic limb movements also remain after severing descending projections in the thoracic spinal cord. These results together indicate that local neuronal networks in the spinal cord are able to autonomously generate rhythmic movement patterns. Brown has coined these assemblies ‘half-centers’ and later they became know as ‘central pattern generators’ (CPGs). Von Holst in 1935 similarly described that rhythmic swimming movements in teleosts remain after transection of the spinal cord and Weiss reported such results in salamanders after partial deafferentation of the limbs (Weiss, 1936). These results provide strong counterevidence against the concept of rhythmic limb movements being a chain of reflexes.

Most of the studies on CPGs for extremity movements have concentrated on the hind limb. Grillner and Zangger (1975) demonstrated that adult cats with a low thoracic spinal cord transection maintained a delicate pattern of orderly starting and stopping of EMG activities in the hind limb flexors and extensors during walking on a treadmill. Forssberg et al. (1980) demonstrated after spinal cord transection that the coordination patterns in the limbs follow the increasing speed of the treadmill, provided that the limb afferents are left intact. At higher speeds they even observed a gallop-like coordination. Shik and Orlovsky (1976) studied cats after spinal cord transection when walking on a treadmill with two belts, driven at different speeds. When the speed differences became too large, the frequencies of the CPG stepwise shifted to a 1 : 2 relationship and on this basis and other evidence it is considered that each limb has its own CPG (Fig. 4.2).

The neural principles involved in CPGs have been elucidated in a series of investigations in the lamprey, a primitive fish which has a less complex spinal cord than mammals and no extremities. Here, each spinal cord segment along the trunk has a CPG which subsequently and with a short phase lag become active. This leads to the rhythmic curving of the trunk which produces the swimming movements. Grillner and coworkers demonstrated that each spinal cord segment has two networks on the left and right side, each consisting of excitatory and inhibitory interneurons and with motoneurons as the output elements (Grillner et al., 1991). The networks on both sides are connected via inhibitory connections functioning as coupled oscillators with an output of alternating activation on the right and the left side. Networks in adjacent spinal cord segments are connected via propriospinal interneurons.

Based on neuroanatomical and neurochemical data derived from studies in the lamprey, the network was modeled and computer simulations indicated that increases in the frequency of the most rostral segment are spread along the spinal cord and this leads to higher swimming speeds (Grillner et al., 1991). Such increases in speed in natural life are induced by supraspinal influences.

The CPGs for extremity movements in tetrapods obviously are more complex and probably consist of a series of coupled oscillators for the different muscle groups. In experiments performed in the isolated spinal cord of newborn rats by Cazalets et al. (1995) fictive locomotion was recorded from electrical activity in the ventral roots (see also Kjaerulff & Kiehn, 1996). Cazalets and co-workers showed that the CPG for hind limb movements in the rat is located in the first lumbar segment. They also identified the neural transmitters which are involved such as the excitatory amino acids L-glutamate and aspartate as well as 5-HT, dopamine and

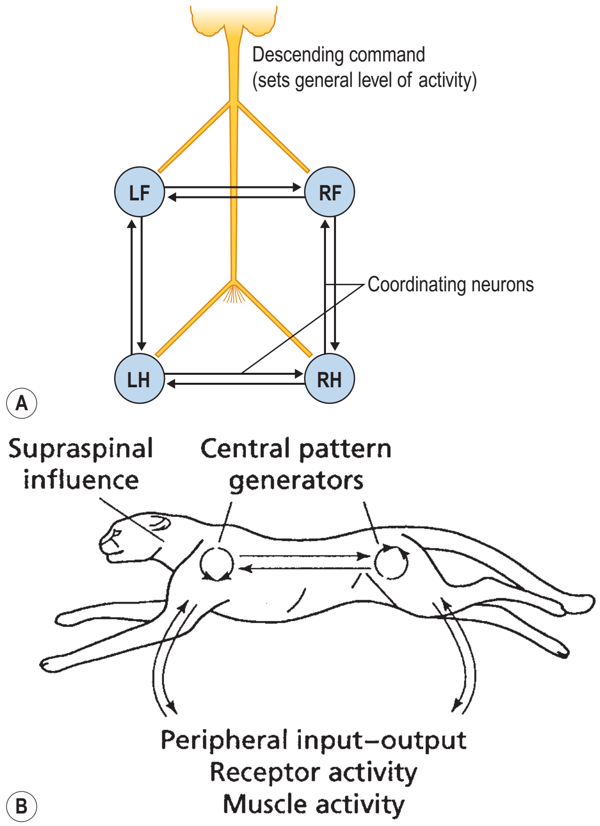

Fig 4.2 Schematic representation of the neural control of locomotion. (A) Dorsal view. Interlimb coordination is achieved by interaction of the central pattern generators (CPGs) of each of the four limbs. The general level of activity in the different generators that are capable of rhythmic activity is set by a supraspinal descending command, whereas actual coordination is due to interaction between the four different generators via coordinating neurons. (B) Lateral view. The CPG of each limb is influenced by peripheral input from a variety of somatosensory receptors as well as descending influence from supraspinal centers. Through peripheral output pathways, appropriate muscles are contracted to perform their task and result in intralimb coordination.

(A) Reprinted from Grillner, S., 1975. Locomotion in vertebrates: central mechanisms and reflex interaction, 55 (2), 247–304, with permission from The American Physiological Society. (B) Reprinted by permission of the publisher from FUNCTIONAL VERTEBRATE MORPHOLOGY, edited by Milton Hildebrand, Dennis M. Bramble, Karel F. Liem, and David W. Wake, p. 339, Cambridge, Mass.: The Belknap Press of Harvard University Press, Copyright © 1985 by the President and Fellows of Harvard College.

GABA. However, the neural elements and the circuitry of these CPGs for rhythmic alternating limb movements in higher vertebrates are still unknown.

Obviously, locomotion in intact animals is adapted to environmental constraints. Avoiding an object in the trajectory, walking on a slope or anticipating an unevenness in the path lead to adjustments of the limb excursions or their rhythmicity. Exteroceptive and proprioceptive information influences the extension and flexion phases of the step cycle via segmentally arranged circuitry. Stumbling over unexpected objects on the trajectory leads to adjustments of the step cycle (Rossignol et al., 1988) and other experiments have demonstrated that increasing the load on the extended limb and input from Golgi-tendon organs via group II afferents also leads to adjustments of the step cycle (Duysens & Pearson, 1980).

The CPG itself, in turn, influences the input from proprioceptive afferents. This probably is affected by activating the inhibitory interneurons mediating the reciprocal Ia inhibition (Hultborn, 1972). Input from the visual and the vestibular system is relayed along descending projections and cerebellar circuitry probably plays an important role in adjustments (see below).

An intriguing problem with respect to locomotion in horses, other animals and man is how the fluent postural adjustments in the trunk muscles are effected during locomotion at various speeds. It is well known from kinematic studies that the activation and coordination of trunk muscles differ importantly between walking, trotting and galloping. Theoretical possibilities are, that the trunk muscles are rhythmically activated via the CPG for limb movements, that the rhythmic activity in the trunk muscles is produced by separate CPGs (perhaps similar to the chain of CPGs in fish) and that the activity in these CPGs is coupled to the CPG for limb movements, and, thirdly, that the trunk muscle activity is adjusted separately via supraspinal influences.

Our own experiments involving EMG recordings of limb muscles and dorsal trunk muscles in adult rats indicated that at low walking speeds tonic activation without modulation prevails in the back muscles. At higher speeds, and particularly during accelerations, stronger and more uniform activation patterns occurs in the long back muscles and shortly preceding the stance phases of the extremities at the ipsilateral side (see below; Gramsbergen et al., 1999). As vestibular deprivation from the 5th postnatal day in rats leads to long-lasting abnormalities in the coordination between extremity movements and trunk control (Geisler & Gramsbergen, 1998) we proposed that supraspinal influences play a decisive role in the control of the back muscles (Gramsbergen, 1998).

Summary

CPGs in the spinal cord are able to autonomously generate rhythmical locomotor patterns in the trunk muscles in fish and amphibiae and in the extremities in quadrupeds and bipeds. Afferent feedback and CPGs mutually influence each other. In rats, the CPG for hind limb movements is localized in the first lumbar segment. Postural adjustments during walking might be governed largely by supraspinal influences.

Descending projections

In vertebrates, the topography of the descending projections in the spinal cord to the motoneurones innervating the trunk and extremity muscles reflect to some extent their phylogenetical descent. Axial muscles in the trunk (the ‘oldest’ muscles from an evolutionary perspective) are innervated by medially descending motor projections as the reticulospinal and vestibulospinal tracts. On the other hand, the motoneurones innervating the ‘newer’ extremity muscles are located laterally in the ventral horn and these are innervated by laterally descending tracts.

The medially descending projections, such as the vestibulospinal, reticulospinal and tectospinal projections, are particularly important for the innervation of the muscles in the neck and trunk and also muscles in the proximal segments of the extremities. Anatomical investigations in rats demonstrated that these projections descend early during neuro-ontogeny.

In quadrupeds, the rubrospinal tract (RST) is particularly important in the innervation of the motoneurones of the extremity muscles. This projection has not been studied yet in horses but it seems safe to speculate that in this species this will be the main tract involved in adjusting the excitation of motoneurons and in steering non-rhythmic extremity movements (such as jumping, etc.). The RST arises from the red nucleus and descends contralaterally. In rats and cats, this tract arises mainly from the most caudally located magnocellular part and to a lesser extent from the rostral parvocellular part. It crosses in the ventral tegmental decussation and descends via the lateral funiculus. The axons terminate upon excitatory and inhibitory interneurons in the spinal cord. The red nucleus receives its major input from the deep cerebellar nuclei and possibly also from the motor cortex, both via direct connections (and in horses possibly via collaterals from Bagley's bundle). The cerebellum and the vestibular complex play an important role in the regulation of locomotor movements and the regulation of postural maintenance.

The CST will be less well expressed in horses (Verhaart & Sopers-Jurgens, 1957) and horses may, in this respect, resemble the expression of the CST in rabbits. In rabbits, the unmyelinated fibers of the CST terminate at the 2nd cervical segment (Hobbelen et al., 1992; for review see Nudo & Masterton, 1988). Verhaart and Sopers-Jurgens demonstrated Bagley's bundle by dissection of the horse's brain and concluded that this tract only descends as far as upper spinal cord levels. In horses, transcranial magnetic stimulation on the skull and the recording of muscle activation in extremity muscles might help in future research to elucidate the nature of the descending projections (see Nollet et al., 2003).

Parallel to the projections of the (three) so-called somatic motor systems referred to above (the vestibule- and tectospinal tracts, the RST and the CST), another system of diffusely projecting monoaminergic fibers, the 'fourth motor system' plays an important role in modulating motor activities. This was termed the limbic motor system (LMS) by Kuypers (1982) and the emotional motor system (EMS) by Holstege (1991, 1995). The LMS originates in the medial portions of the hypothalamus and the mesencephalon. Its medial components modulate the excitatory state of interneurons and motoneurons via diffusely projecting noradrenergic and serotonergic fibers. An increased excitatory state induces motoneurons being more readily activated by a neuronal drive (e.g. from suprasegmental levels). The LMS is the earliest of the descending projections to develop. At birth in the rat, its fibers have descended already to lumbar levels where they have established 5-HT containing synapses (Rajaofetra et al., 1989); in comparison, the CST in the rat has descended to lumbar levels only around the 10th postnatal day. As the terminals are initially widespread, but at later stages restricted to the dorsal and ventral horns, Rajofetra hypothesized that an initial role during early stages of these 5-HT containing fibers might be to stabilize the innervation patterns of other projections to the spinal cord.

Summary

The medially descending vestibulospinal and reticulospinal tracts, project upon motoneurons of axial muscles and these phylogenetically old systems are functional from early stages. The laterally descending projections project upon motoneurons of extremity muscles. The cerebellum, via the crossed rubrospinal tract starts its adult-like functioning at a late stage.

Central brain mechanisms and locomotion

The mesencephalic locomotor region

Strong evidence has been collected from research in cats that the rhythmic leg movements in locomotion are 'initiated' by activity in a group of cells in the mesencephalic brain stem. Electrical stimulation of this area in intact cats induced the leg movements on a moving treadmill (Shik et al., 1966). Since then this area has been termed the mesencephalic locomotor region (MLR). Anatomically, its neurones are localized around the pedunculopontine tegmental nucleus (Spann & Grofova, 1989). Descending fibers probably course via the reticulospinal tract and impinge upon the CPGs where they start the rhythmical activity.

The experiments indicated also that by increasing the stimulus intensity the walking speed increased (by an increase in the CPG-frequency) and eventually the animals made a transition to trot or gallop (indicating an alternative phasing-pattern within the CPGs) (Shik et al., 1966; Shik & Orlovsky, 1976). The speed 'increases' and the transitions into other coordination patterns probably are mediated by indirect activation, via noradrenergic projections arising from the locus coeruleus and adjacent cell groups. These nuclei are located close to the MLR and the fiber-projections are part of the LMS (see above).

The cerebellum

The cerebellum plays important roles in adjusting motor commands during locomotion. Cerebellar lesions in cats and rats (e.g. Brooks, 1975; Gramsbergen, 1982) or cooling of the cerebellum (Udo et al., 1979) lead to atactic gait and irregularities in foot placing, and, for this reason, it is generally considered that the cerebellum plays a key role in finely adjusting the limb movements during the step cycle.

The cerebellum receives massive information from spinal sources both from a direct and indirect nature. The projections convey information on the 'ongoing movements' (by input from premotor neurons, interneurons adjacent to the motoneurons) as well as information on the 'position of limbs and the tension in muscles' (by input from muscle spindles and tendon organs). The information from both these sources reaches the cerebellum along the ventral and dorsal spinocerebellar tracts respectively. Indeed, Arshavsky and coworkers (1972, 1986) have recorded rhythmic activity in the ventral spinocerebellar in phase with rhythmic activity in the limbs and this is in agreement with the anatomical data. The projections terminate on the parallel fibers in the cerebellar cortex (with collaterals, e.g. on neurons in the deep cerebellar nuclei). The parallel fibers contact the Purkinje cells. The axons of the Purkinje cells are the sole output of the cerebellar cortex.

Another important input which is highly relevant for steering locomotor activity stems from the vestibular nuclei and these give information on the position as well as the movements of the head.

An important indirect input to the cerebellum is via the inferior olivary nucleus. The inferior olivary nucleus receives indirect (multisynaptic) information from the spinal cord and several areas in the CNS. Axons from these neurons reach the Purkinje cells in the cerebellar cortex as climbing fibers, each of which has thousands of synaptic contacts with one Purkinje cell (e.g. Ruigrok & Cella, 1995). The physiological significance of the input from the inferior olivary nucleus to the cerebellum is still unclear. In one theory, the climbing fiber system, together with the parallel fiber system (see above), is considered to be decisive in motor learning (Marr, 1969). A more recent theory suggests that the ION plays an important role in regulating a distributed processing of afferent information in the cerebellar cortex (Llinas & Muhletaler, 1988).

The outflow of cerebellar processing is transported via the deep cerebellar nuclei to the red nucleus and thalamic nuclei and from there along descending tracts to pre-motoneurons of extremity muscles. This input is crucial for postural adjustments and postural control during walking and running.

Our own experiments in rats indicated that the cerebellum plays an important role in adjusting postural control to limb movements during walking. This postulate is based upon the finding that vestibular deprivation in rats retards the development of postural control and this, in turn, leads to a delay in the development of the adult-like walking pattern (see, above; Gramsbergen, 1998, 2001, 2005a, b).

Summary

Locomotion is initiated by activity in the MLR, which in turn might be activated by higher centers. The LMS plays a role in the acceleration or deceleration of walking speed. Cerebellar circuitry plays a role in adjustments of postural control during walking.

Walking in adult animals

During walking, limbs are in contact with the ground during the stance phase and are moved forward during the swing phase. The foot placement sequence during walking at low speeds typically is LH–LF–RH–RF, with the body always being supported by three limbs. The extension phases of the two hind limbs are phase shifted by 0.5, which implies that when one limb is starting its stepcycle the other limb is halfway through its cycle. When walking along irregular trajectories, these phase shifts change. This alternating gait pattern (Grillner, 1975, 1981) applies not only to rats but also to many quadrupeds, including horses, during walking at lower speeds.

When walking speed increases and when the footfall pattern indicated above is maintained, the stride length increases and the stance phase decreases, but the duration of the swing phase remains more or less constant (Westerga & Gramsbergen, 1990). During further increases in speed, e.g. in horses, walking changes into a trot and then to a gallop, which are characterized by different footfall patterns. Transitions between gaits during acceleration or deceleration occur at variable speeds (Grillner, 1975, 1981).

The kinematic and neurophysiological aspects of these patterns in rats have not been studied in detail but abundant data are available on horses (see other chapters in this book). The few studies that have been performed aimed at investigating the energy expenditure and force production by muscles during such patterns (e.g. in mice: James et al., 1995; in rats: Sullivan & Armstrong, 1978; Taylor et al., 1982; Perry et al., 1988).

An important difference between smaller and larger animals during fast locomotion is that in species such as rats, cats and dogs the hind limbs are used for acceleration and maintenance of speed and the forelimbs for braking, while in larger animals such as horses, the hind and forelimbs promote similar functions during acceleration and braking (Heglund et al., 1982). These differences most probably are reflected in neural circuitries as well as in muscular and skeletal specializations of the hind and forelimbs.

Summary

Walking, trotting and galloping are characterized by different footfall patterns and transitions between these patterns occur at variable speeds. In horses, the hind and forelimbs are both used for accelerating and braking.

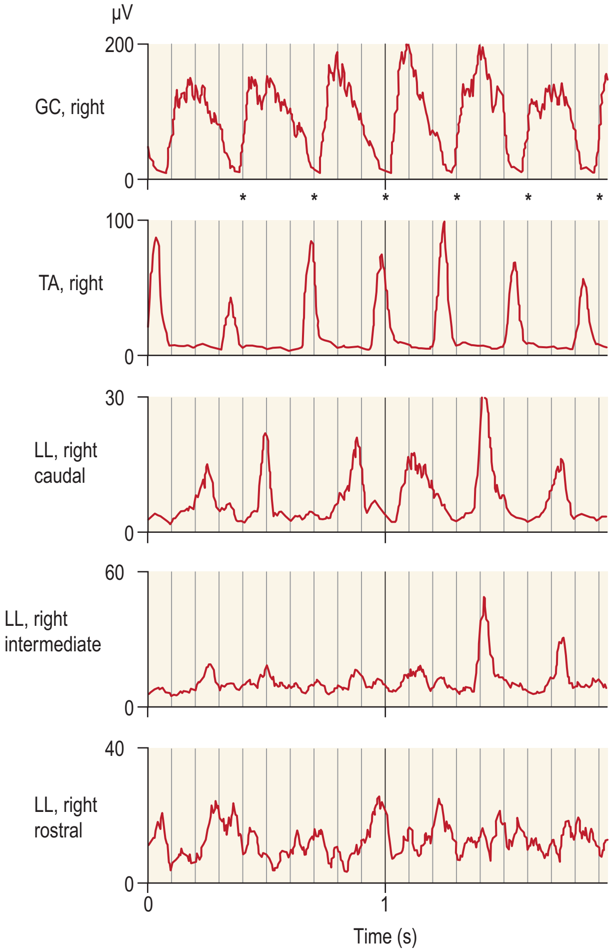

Fig 4.3 Averaged EMG records of a rat aged 32 days. Recordings from the gastrocnemius (GC) muscle at the right side, the tibialis (TA) muscles at the right side, and the longissimus (LL) muscles at caudal, intermediate and rostral levels. Asterisks indicate the onsets of the stance phase in the hind limb at the right side.

Reprinted from Gramsbergen, A., Geisler, H.C., Taekema, H., van Eyrken, L.A., 1999, The activation of back muscles during locomotion in the developing rat. Developmental Brain Research 112 (2), 217–228, with permission from Elsevier.

EMG recordings during locomotion in adult animals

Most of the investigations into electromyographic activity of leg muscles during walking in rats and cats have been performed in the hind limb (for reviews, Grillner, 1975, 1981; Grillner et al., 1991). Globally, the extensors of the hip, knee, ankle and digits are activated during the stance phase and the flexors are active during the swing phase (Fig. 4.3). EMG patterns in the forelimb have been studied less frequently. In the newt, extensors and flexors of the forelimb are activated rhythmically and reciprocally but the EMG patterns are more complex and co-contractions are often observed (Szekely et al., 1969).

In the literature on kinematic and electromyographic aspects of the step cycle in cats, the 'extension phase' generally is subdivided into an E1 phase indicating the onset of limb extension before contacting the ground, the E2 phase during the midphase of ground contact and the E3 phase with the foot still in contact with the ground but shortly before toe-off. The swing phase thus consists of the F (flexion) and E1 phase, and the stance phase consists of the E2 and E3 phases.

In the hind limbs of freely moving rats, the tibialis anterior (ankle flexor) and the semitendinosus muscles (knee flexor) are activated shortly before the onset of the swing phase. Bursts in these muscles are characterized by a short 'attack' phase and the bursts generally only last during the first part of the swing phase (the F phase). Between the bursts EMG activity generally is absent. Remarkably, the onsets of the EMG bursts in these muscles coincide, despite the fact that they move different limb segments and that slight phase shifts in joint angle trajectories occur (Westerga & Gramsbergen, 1990). During increases in speed, the burst durations in these flexor muscles remain unchanged, but the EMG amplitudes increase (Westerga & Gramsbergen, 1993; Gramsbergen et al., 1999). In cats, EMG recordings in the iliopsoas and the extensor digitorum longus muscles as well as in the tibialis anterior muscle showed similar results (e.g. Engberg & Lundberg, 1962, 1969).

The gastrocnemius, the soleus (ankle extensors) and the quadriceps femoris (knee extensor) muscles are activated shortly before the onset of the stance phase (during the E2 phase) and EMG activity lasts until shortly before the onset of the next swing phase (Westerga & Gramsbergen, 1993, 1994; Gramsbergen et al., 1999). The bursts in these extensor muscles start simultaneously (as occurs in the flexors) and the profiles of the EMG bursts are more or less identical. During increases in speed, the burst amplitudes in these muscles remain the same but in the extensors the burst

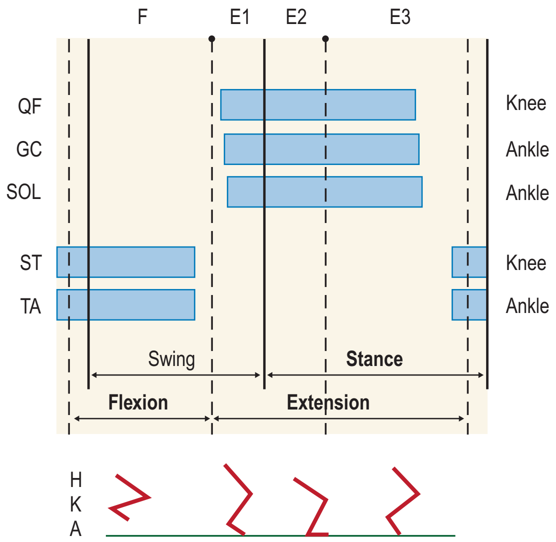

Fig 4.4 Schematic representation of EMG activity in a few hind limb muscles in relation to extension and flexion phases and swing and stance phases. QF, quadriceps femoris muscle; GC, gastrocnemius muscle; SOL, soleus muscle; ST, semitendinosus muscle; TA, tibialis anterior muscles (extensors and flexors of the knee and ankle, respectively). Blocks indicate burst activity: E1, extension of hind limb before stance phase; E2, midstance phase; E3, extension shortly before toe-off; F, flexion. Stick diagrams are derived from video recordings: H, hip; K, knee; A, ankle.

durations decrease (Fig. 4.4), which agrees with data obtained in cats (Grillner, 1981).

EMG activity in the postural muscles in the back is related in a complex way to the activity in the hind limb extensors and flexors. In adult rats, EMG patterns were recorded in the medially located multifidus muscles and the laterally located longissimus muscles (Geisler et al., 1996b; Gramsbergen et al., 1999). The multifidus muscle is tonically active during all movements that require stabilization of the trunk, and during locomotion the activity in this muscle modulates slightly with the frequency of the left and right hind limb. The EMG in the longissimus muscle, on the other hand, is more phasic in character. EMG bursts in these muscles are phase-linked to bursts in the gastrocnemius muscles during the stance phase (Gramsbergen et al., 1999). This is remarkable because intuitively, it seems that a swing phase in one of the hind limbs induces a relative instability of the trunk which should be counteracted by activity in the trunk muscles. During one step cycle of both hind limbs two bursts in the longissimus muscles occur. The burst with the 'higher' amplitude accompanies extension of the 'ipsilateral' hind limb and that with a 'lower' activity the extension of the 'contralateral' leg. EMG activity at more rostral levels in the longissimus muscle is variable in amplitude, duration and phasing of the bursts (with reference to the stance phases in the hind legs). In horses, similar results were obtained by recordings of the multifidus muscles during trotting on a moving belt (Licka et al., 2004).

During rapid acceleration and fast walking, simultaneous contractions may occur over the entire length of the muscle but at slow speeds the rostral portions of the longissimus muscles only show tonic activity without modulations in amplitude (Fig. 4.4).

These data on adult rats are in agreement with results from adult cats. Carlson et al. (1979) reported a similar coupling in the activation of back muscles with the vastus lateralis muscle in the hind limb during treadmill walking. Their data, however, indicate that the two bursts-per-step cycle in both hind limbs and in the longissimus muscles are more or less identical in amplitude, which might point to a peculiarity of treadmill walking.

Summary

Flexors in the hind limb are activated simultaneously, shortly before the swing phase of the hind limb and extensors are activated shortly before the stance phase. The longissimus muscles in the back are activated during extension of the hind limbs and EMG activity in this muscle is strongest during the stance phase of the ipsilateral hind limb.

Development of postural control

Adequate postural control is an important factor in the development of standing and locomotion. Posture may be defined as the relative positions of the head, trunk and the extremities as well as the orientation of the body in space. In adult animals, both feedback ('static'; e.g. during standing) and feed-forward ('dynamic'; during locomotion and head movements) control mechanisms play a role (Massion, 1992). Although it is impossible to distinguish the walking movements from postural adjustments from a behavioral point of view, it should be remembered that the neural systems governing posture and movement are organized differently and have a different evolutionary descent (see above). On the one hand, specific central motor areas, specialized sensory systems and medially descending spinal projections are involved in postural control. On the other hand, neural systems with laterally descending fiber projections are involved in governing extremity movements. Obviously, intimate connections exist between these systems at adult age (and the cerebellum is crucial in that coupling).

Horses are born at an advanced stage of brain development and within hours of birth they are able to stand and to walk. This indicates that postural mechanisms and vestibular reflexes must have matured before birth in this species. Experiments in guinea pigs (guinea pigs are (as horses) a precocial species and neural development for an important part has occurred intra-uterinely) have shed light on the development of the vestibulum. The structural development of the vestibulum in guinea pigs is completed before birth but its functioning is inhibited prenatally possibly due to low levels of oxygen content in the placental blood (Peter Schwartze, University of Leipzig, Germany, pers. commun.). This active inhibition is most useful as it prevents the occurrence of vestibular reflexes of the fetuses before birth (e.g. during vigorous movements of the mother, such as during walking). In horses this might be similar. Immediately after birth, the inhibition is relieved because of a fast rise in the oxygen content in the arterial vascular bed. This, in turn, leads to sudden development of vestibular reflexes (which enables an upright stance).

Experiments in rats by Geisler et al. (1996a) showed that the development of postural control is the limiting factor for walking development. She demonstrated that vestibular deprivation by plugging the semicircular canals from the 5th postnatal day selectively induces a retardation in postural development. Motor patterns which specifically require high levels of trunk control such as grooming (self-cleaning behavior) were retarded by 1–2 days. Rearing (standing on the hind limbs without support from the wall) was even delayed by as much as 5 days. Movements of the extremities were essentially normal, but the adult-like type of smooth walking (with the body free from the floor – indicating control of the trunk muscles) was retarded by 3–4 days. These experiments demonstrate that postural development is the limiting factor for the development of walking (Gramsbergen, 1998, 2001, 2005a, b).

Summary

In rats, around the end of the 2nd week after birth, the immature walking pattern is replaced by a smooth adult-like walking pattern. The development of postural control probably is the limiting factor for this transition.

Synthesis

Control of the postural muscles in the trunk and the neck on the one hand, and that of the extremity muscles on the other are governed by different neural motor systems. Neural control of axial muscles in the trunk and neck is provided by old structures from an evolutionary point of view. On the other hand, the neural control of the extremities is from a more recent evolutionary stage. From this perspective it is remarkable that postural control, by the older system, is the limiting factor for the development of the adult pattern of fluent and swift locomotion. This has been demonstrated in rats and also data on the development of standing and free walking in human infants are congruent with this conclusion. As horses are born at an advanced stage of brain development, this maturational order is less obvious. The cerebellum plays important functions, not only in finely tuning muscle forces during movements and acquisition and performance of skilled movement patterns but also in making postural adjustments during extremity movements. As to this latter function, the data available suggest that the cerebellum is the key structure in coupling and adjusting the activities of the evolutionary newer structures, i.e. the muscles in the legs and their control with those of the older structures, i.e. the axial muscles along the trunk and their neural control. Trunk muscles and particular extremity muscles, the so-called anti-gravity muscles are specialized to subserve postural tasks. They contain large proportions of type I muscle fibers which are specifically able to sustain force-loads for long periods. These muscles are innervated by motoneurons which, in part, are connected by dendrite bundles (possibly an evolutionary older type of interneuronal connectivity; Gramsbergen et al., 1996; Gramsbergen, 2005b). These muscles, containing large proportions of type I muscle fibers are innervated by motoneuronal pools with conspicuous dendrite bundles (as in the soleus muscle and the trunk muscles), or in other cases by motoneuronal pools with a few regions of dendrite bundles (as the gastrocnemius and vastus medius muscles). Other extremity muscles and particularly the flexor muscles are composed of large proportions of type IIa and IIb muscles. These muscles are particularly involved in heavy exercises which they can, however, can only sustain for relatively short periods.

The basic rhythmicity in alternating limb movements (even at varying footfall patterns) is produced by neuronal circuits, localized at spinal levels, CPGs (Fig. 4.5).

Walking starts by activation from the MLR in the mesencephalic brain stem. It is supposed that also in horses (like in cats and in rats) a locomotor region in the mesencephalon exists. This cell group, in turn, is activated by other brain areas, and most probably by the sensory-motor cortex (or it's analogue in horses). The speed of walking is adjusted by the LMS. In situations of fear or strong activation during races, the LMS may induce the CPG to switch to increased rhythms and incidentally to other coordination patterns.

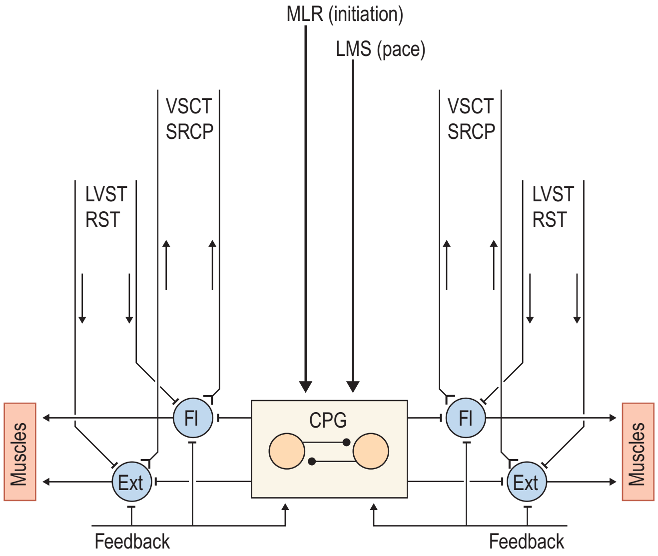

Fig 4.5 Diagram representing CPG in relation to motorneurons (Fl, flexors; Ext, extensors) and ascending and descending tracts. CPG, central pattern generator; Feedback, proprioceptive feedback from muscles, tendons and joint receptors; RST, rubrospinal tract; LVST, lateral vestibulospinal tract; VSCT, ventral spinocerebellar tract; SRCP, spinoreticulocerebellar tract; MLR, mesencephalic locomotor region; LMS, limbic motor system.

Training procedures in horses aim at optimizing muscular sizes and muscular properties. EMG-recordings and advanced automatic analysis techniques such as the computation of power density spectra and the recording of shifts in these spectra during exercises and training or fatigue in conjunction with kinematic recordings and analysis will prove to be important tools in devising the most effective training schemes.

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CHAPTER **5**

Gaits and interlimb coordination

Eric Barrey

Introduction

The locomotor apparatus is a complex set of systems including muscle, bone segments and joints, which are controlled by the central nervous system to produce well-coordinated locomotion. Biomechanically, locomotion involves moving all the body and limb segments in rhythmic and automatic patterns, which define the various gaits. A great diversity exists in equine gait patterns because quadrupedal locomotion allows many combinations of inter-limb coordination. Furthermore, horse breeds have been genetically selected for different occupations: draft, riding, driving and meat production. Sport horses compete in a variety of sports, including pacing, trotting and galloping races, eventing, show jumping, dressage, endurance and western disciplines. Consequently, a large range of gaits and gait variations can be observed in horses, including the walk and its many variations, trot, pace, canter and gallop. These gaits can be analyzed and classified according to their linear, temporal and dynamic characteristics using the measuring techniques that have been described in Chapter 3. The variety and complexity of gaits have always created difficulties in defining a terminology that is, at the same time, broad enough and also sufficiently specific to describe the locomotor phenomenon. Some efforts have been made to define a standard terminology for describing equine locomotion (Leach et al., 1984a; Clayton, 1989; Leach, 1993) The gait terminology used in this book is defined in the glossary (p. xix).

Classification and description of gaits

A gait can be defined as a complex and strictly coordinated, rhythmic and automatic movement of the limbs and the entire body of the animal, which results in the production of progressive movements. In horses, a two-, three- or four-beat gait corresponds to the number of footfalls that can be heard during each stride of trot, canter and gallop, respectively. The sounds are related to the footfall pattern of the gait but, when the interval between footfalls is very short, the human ear is not able to perceive the separation.

One method of classifying gaits depends on the symmetry between the left and right sides. In a symmetric gait, the left and right footfalls of the fore and hind limbs are evenly spaced in time. In an asymmetric gait, the footfalls of the fore and/or hind limbs occur as couplets. The first limb of a couplet to contact the ground is the trailing limb; the second is the leading limb:

- symmetric gaits: walk, trot, running walk, rack, toelt, fox trot, paso, stepping pace
- asymmetric gaits: canter, transverse and rotary gallop, half bound.

Another type of gait classification distinguishes between stepping or walking gaits that have no period of suspension (there is always a contact with the ground) and running gaits that have one or more suspension phases in each stride (no foot in contact with the ground). The main characteristics of equine gaits are described in Table 5.1. Within each gait there exist continuous variations, from a collected type of gait with a slow speed, to an extended type of gait with a higher speed.

Many types of illustrations have been proposed to describe the limb movements more precisely in time and space: drawings, chronophotographs, bar diagrams, phase diagrams and pie diagrams (Fig. 5.1). Some of the methods are only descriptive and show either temporal or linear characteristics of gaits:

- Drawings of the footfall sequence (Barroil, 1887) (Fig. 5.1A).
- Gait or bar diagrams and hoof imprints which shows tracks and linear distances (Lenoble du Teil, 1893) (Fig. 5.1B). Gait and bar diagrams can also describe temporal footfall sequence (Marey, 1873) (see Fig. 5.4B).
- Pie gait diagram showing the footfall sequence and relative durations of the suspension phase, stance phases and overlaps (Deuel & Lawrence, 1984) (Fig. 5.1D).

Two other methods represent and classify the gaits in a more functional way using phase lag or advance between the footfalls:

- The continuum of symmetric gaits was described by a diagram proposed by Hildebrand (1965) (Fig. 5.2). The stance duration of the hind limb was plotted against the lateral advanced placement. On the x-axis, the stance duration of the hind limb indicates if the gait is classified as walking (no suspension phase) or running (two suspension phases per stride in the symmetric gaits). On the y-axis, the lateral advanced placement quantifies the phase lag of the lateral fore and hind limbs. The two-beat gaits are at the top and bottom of the diagram, with the four-beat gaits between them. A similar diagram has been proposed for illustrating and comparing the diagonal gaits by plotting the hind stance phase duration against the diagonal advanced placement (Clayton, 1997).
- A group of methods describe the type of coupling between the four limbs. All the running gaits can be modeled using the relative phases of the limb cycle (Alexander, 1984) (Fig. 5.1C). However, this diagram describes only the footfalls sequence but does not give any linear or temporal characteristics of the stride. A more sophisticated method based on a series of coupled oscillators has been proposed to describe and simulate both symmetric and asymmetric gaits (Collins & Stewart, 1993). This model has the advantage of being able to describe gait transitions and abnormal gaits like the aubin, in which the hind limbs trot while the forelimbs gallop, and traquenard, in which the hind limbs gallop while

Table 5.1 Classification and main characteristics of equine gaits

Classification	Gait	Gait variations	Footfall sequence	Rhythm (beat/stride)	Type of symmetry	Speed (m/s)	Stride length (m)	Stride frequency (stride/s)	Limb stance phase (s or % stride)	Suspension phase (s or % stride)
Walking gaits	Walk	Collected, medium, extended, free	RH, RF, LH, LF	4	Right/left bipedal	1.2–1.8	1.5–1.9	0.8–1.1	65–75%	0
	Toelt, paso, rack, foxtrot		RH, RF, LH, LF	4	Right/left lateral	3.4–5.3	1.7–2.3	2.23–2.36	40–55%	0
Running gaits	Trot	Piaffe, passage, collected, working, medium, extended, flying-trot	RH-LF, susp, LH-RF, susp	2	Right/left diagonal	2.8–14.2	1.8–5.9	0.9–2.52	26–53%	0–9%
	Pace		RH-RF, susp, LH-LF, susp	2	Right/left lateral	9.1–16.0	4.5–6.3	1.8–2.4	0.130–0.138 s	0.081–0.094 s
	Canter	Collected, medium, extended, disunited	Trail.H, lead.H-trail.F, lead.F, susp	3	Asymmetry with a phase lag between limb pair	2.9–9	1.9–4.6	1.6–2.0	0.28–0.30 s	0–0.013 s
	Gallop	Transverse, rotary	Transverse: trail.H, lead.H, trail.F, lead.F, susp	4	Asymmetry with a phase lag between limb pair	9–20	4.5–7.2	2.27–2.92	0.085–0.09 s	0.063–0.114 s 16–28%

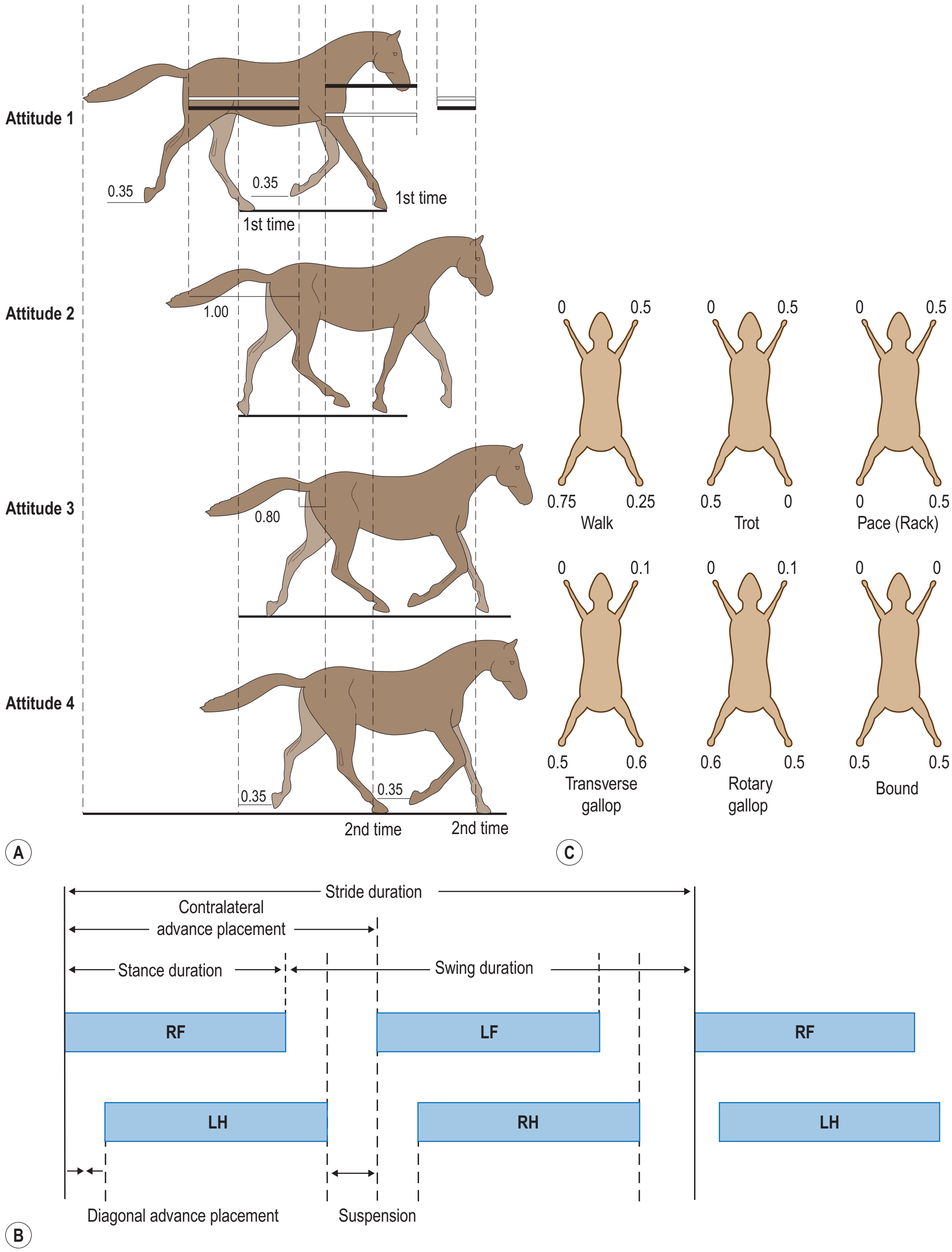

Fig 5.1 Methods for representing the footfall sequences and temporal characteristics of the gaits. (A) Drawings of the footfall sequence observed at the flying trot. (B) Gait and bar diagram of the trot. The bars represent the stance phase duration of each limb. (C) Drawings of the relative phases between the limbs in various quadrupedal gaits.

the forelimbs trot. The model consists of four coupled oscillators that simulate the cyclical patterns of the four limb movements. It is possible to generate all types of equine gaits using five ways of coupling the oscillators. This type of functional model can be useful for understanding locomotor control by the central nervous system. Experimental results in neurophysiology demonstrated that the rhythmic activity of the skeletal muscles of each limb comes from the central nervous system (Barbeau & Rossignol, 1987). There are four distinct rhythm generators (CPG) for the two hind limbs and for the two forelimbs (Forssberg et al., 1980a, b). Such a generator has been identified in the lumbar spinal cord of the newborn rat (Cazalets et al., 1996). In horses, the characteristics of these rhythm generators should determine the stride frequency and its variability. Great stability is required in dressage while rapid changes are nessary for jumping or racing horses.

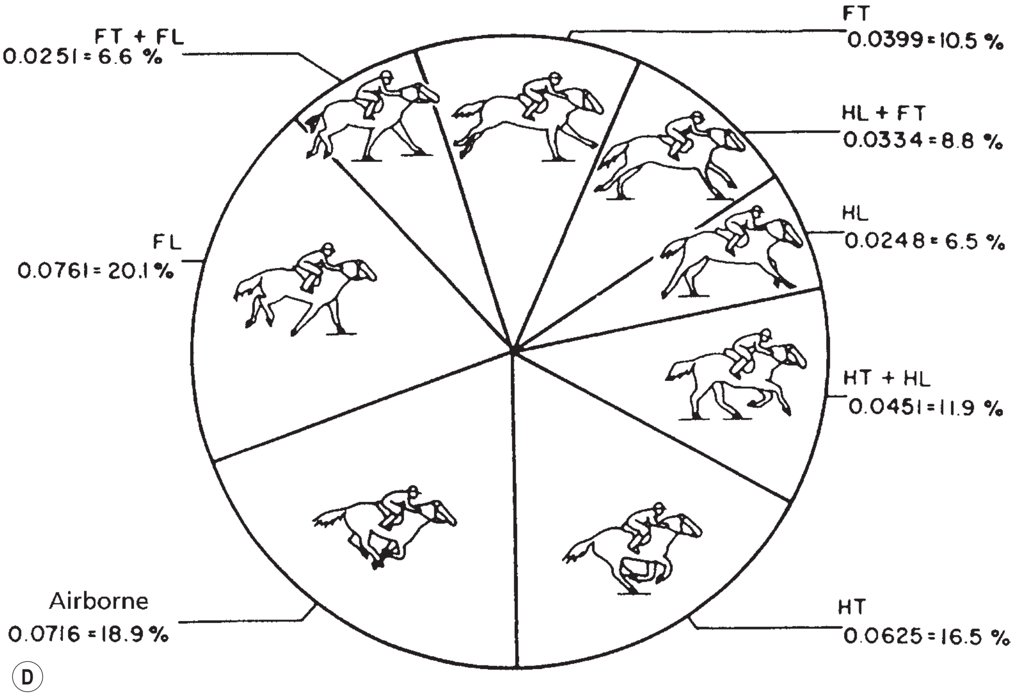

Fig 5.1 *Continued* (D) Pie gait diagram of the gallop in Quarter Horses showing the footfall sequence and the durations of the suspension phase, stance phases and overlaps expressed in seconds and as a percentage of stride duration. The sequence rotates counterclockwise.

(A) Reproduced from Barroil (1887). (C) From Alexander, R. McN. The gait of bipedal and quadrupedal animals. Int. J. Robotics Res. 3, 49–59, Copyright ©1984, reprinted by permission of SAGE. (D) Reproduced from Deuel & Lawrence (1987).

Walk

The walk is a four-beat gait with large overlap times between stance phases of the limbs and no period of suspension. It is the slowest equine gait but probably one of the more complex gaits because of the variability in the overlap and lag time between limbs. In a lameness examination, the variability in the regularity and symmetry of the stride measured at the walk was higher than at the trot (Barrey & Desbrosse, 1996). In dressage horses, the speed of the walk increased from the collected walk (1.37 m/s) to the extended walk (1.82 m/s) with only a small increase in stride frequency (Clayton, 1995). The speed change was mainly the result of lengthening the stride by increasing the over-tracking distance. Even in highly trained dressage horses, a regular four-beat rhythm of the footfalls was observed in only one of the six horses.

For a breeding purposes, the calculation of heritabilities of the gait parameters are interesting in order to know if the measurements of these traits could be useful for genetic selection. Heritability (h^2) of a quantitative trait, like a gait parameter, estimates the genetic component vs. non-genetic components (breeding management, nutrition, environment, training), which may influence this quantitative trait. Heritability is expressed as a percentage of the genetic variance against the total variance including all the other effects. Table 5.2 shows the heritabilities obtained in French saddle horses for the walk in hand. Walk heritabilities were rather low (mean heritability, $h^2 = 0.15$) except for vertical activity, longitudinal propulsion and percentage of four-beat walk which were highly heritable (Barrey, 2004). The low heritabilities could be explained because the walk is a complex four-beat gait which can be slightly modified by many factors: rider actions, environment.

Other walking gaits

Icelandic horses, Paso Finos, and certain other gaited breeds exhibit a four-beat symmetric gait in which the footfalls are coordinated as lateral or diagonal couplets (Fig. 5.3) (Nicodemus & Clayton, 2003). Gaits with these characteristics are called toelt, paso, running walk, rack, stepping pace or slow gait. These gaits are comfortable for the rider because the amplitude of the dorsoventral displacement is lower than at the trot, which is a consequence of not having a period of suspension. Furthermore vertical movements of the fore and hind limbs are out of phase, allowing a smoother gait (Biknevicius et al., 2006). The speed ranges between 1.7–2.3 m/s for the toelt and the natural gait transition sequence is walk-toelt-canter (Grasselli et al., 1991).

Trot

The trot is a two-beat, symmetric, diagonal gait (Fig. 5.4). The variations of the trot of saddle horses are the collected, working, medium and extended trots, with the speed of the gait increasing from collected to extended trot. A positive, hind first diagonal advanced placement has been measured at the collected trot in elite dressage horses (Holmström et al., 1994; Clayton, 1997), with the hind limb contacting the ground about 20–30 ms before the diagonal forelimb. Passage and piaffe are diagonal exercises derived from collected trot. From trot in hand to passage, the speed (−2.18 m/s) and stride length (−1.18 m) are reduced while the stride duration (0.279 s) and diagonal advanced placement (9.7 ms) increase (Holmström et al., 1995). Dressage finalists at the Olympic Games in Barcelona showed differences between the temporal variables of the collected trot, passage and piaffe (Clayton, 1997). The stride duration is longer for piaffe (1.08 s) and passage (1.09 s) than for collected trot (0.84 s), which means that passage and piaffe have a lower stride frequency. For most of the other temporal variables, collected trot and passage were similar to each other except that the suspension phase was short in passage.

Heritabilities of the trot parameters have been calculated in French saddle horses using the same method as for the walk (Table 5.2). Most of the trot variables had a moderate to high heritability (mean heritability, $h^2 = 0.24$) (Barrey, 2004). The trot

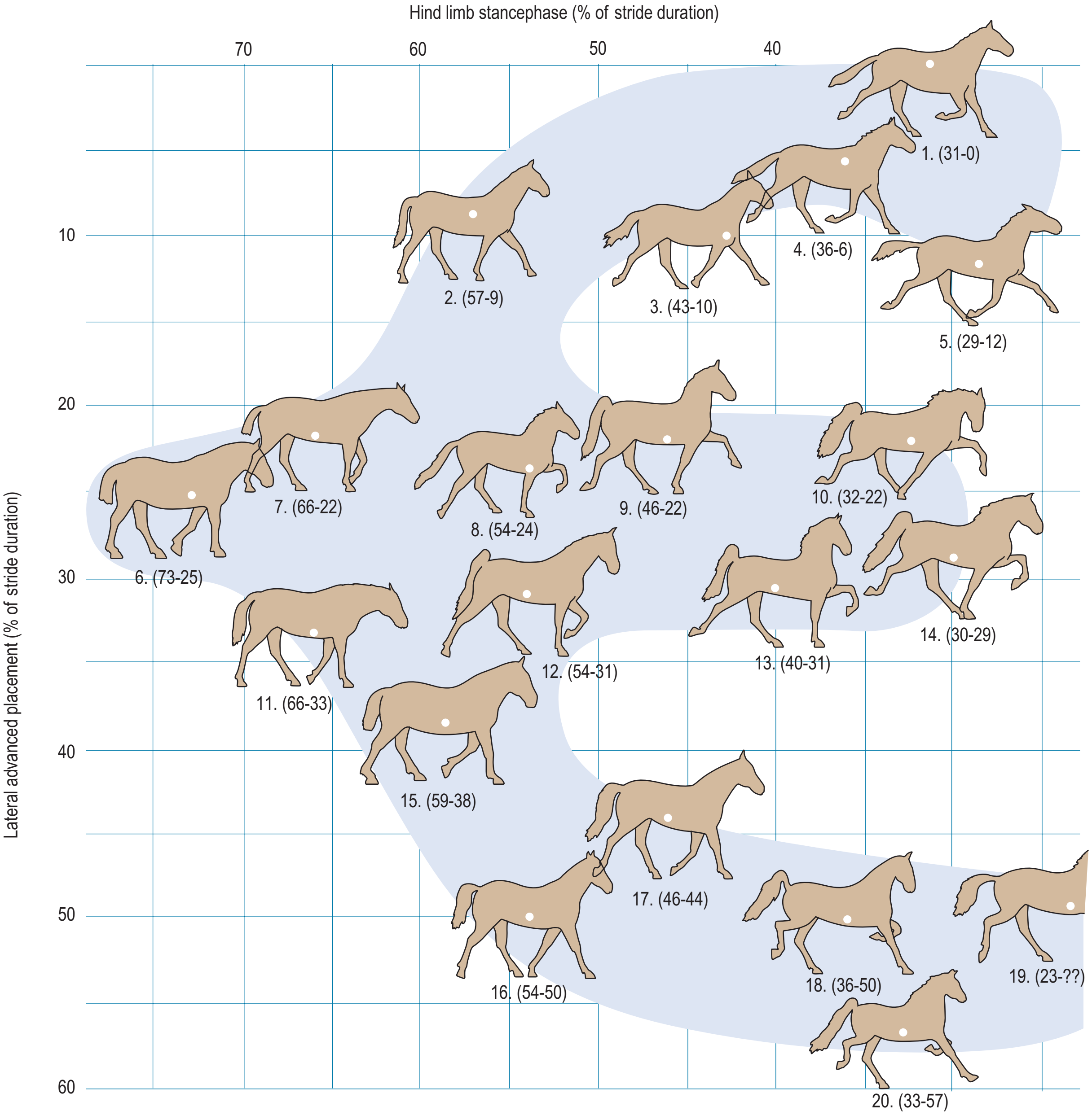

Fig 5.2 Classification of symmetrical gaits according to the temporal characteristics of the gait.
From Hildebrand, M., 1965. Symmetrical gaits of horses. Science 150 (3657), with permission from AAAS.

characteristics are very important for dressage ability and should be used for early selection at 2 or 3 years old. Slow stride frequency, high dorsoventral activity and high propulsion acceleration vector and longitudinal activity are the trot characteristics required for performing in dressage. The heritabilities were higher at trot than at walk.

Because of the heritabilities of the gait parameters, it was assumed that some of these traits could be genetically selected and contributed to dressage performance. Several breeds have been specifically selected for dressage. In Spain, Andalusian horses have been bred for dressage since the 15th century. The Andalusian horses were used for military work at several royal riding academies in Spain, Italy, France and Austria from the 15th to 18th centuries. According to the international competition results, several German breeds or crossed breeds (Hannoverian, Oldenburger, Westphalian and Dutch Warmblood) are today the best performers. In these studbooks, the dressage ability was the main objective of genetic selection. In France, the French saddle horses were mainly selected for jumping. However, a new breeding program for dressage was set up at the end of the 20th century. It has been shown that specific conformation and gait characteristics in German breeds can explain their higher ability for dressage competition (Barrey et al., 2002). For dressage performance, the trot characteristics and variations are very important because they form the basis of passage and piaffe which should be performed at the top level. According to the FEI rules, the trot should be a two-beat gait with free, active and regular steps; the regularity and elasticity of the steps, and engaged hind quarters, should be the main qualities of the trot. The same cadence and rhythm should be maintained during trot variations. The trot characteristics of the German horses showed good similarities with the FEI rules: a slow stride frequency, high regularity, large dorsoventral displacement and activity, which means elasticity and good propulsion (see Table 5.3). Spanish horses have a shorter stride length, a higher stride frequency and a lower dorsoventral displacement and

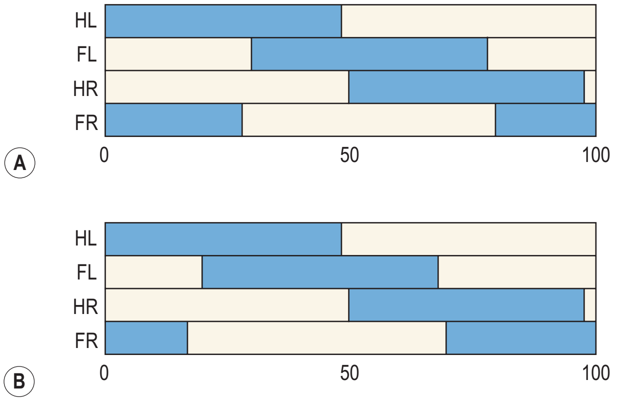

Fig 5.3 Bar diagrams illustrating two types of footfall sequences of the toelt in Icelandic horses: (A) diagonal couplets and (B) lateral couplets. HL, left hind limb; HR, right hind limb; FL, left forelimb; FR, right forelimb.

(B) Grasselli, A., Grasselli, R., Iotti, P., 1991. Quantitative analysis of 4-beat leral gaits. In Proc. 42nd Annual meeting of the EAAP, 8–12 September, Berlin, H4-2, pp. 558–559, reprinted with permission.

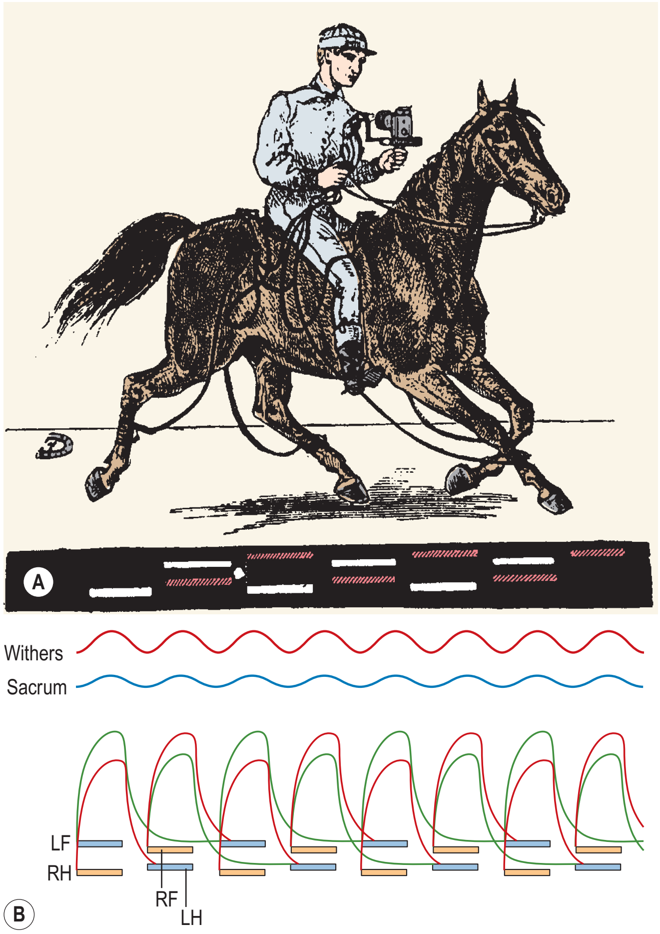

Fig 5.4 Footfalls sequence recorded at the trot using a pneumatic gait recorder. (A) Horse equipped with pneumatic accelerometers attached to the limbs, saddle and tuber sacrale for measuring temporal gait parameters. The white spot indicates the suspension phase as shown on the figure. (B) Time-related changes in the pressure obtained from the pneumatic accelerometers at the trot (LF, left forelimb; RF, right forelimb; RH, right hind limb; LH, left hind limb). The shaded bars indicate the stance phase durations of each limb. The gaps between the shaded bars are the suspension phases between the diagonal supports.

Reproduced from Marey (1873).

Table 5.2 Genetic components (heritabilities estimates h^2 <1) of the gait parameters measured in French saddle horses using an acclerometric gait analysis device (Barrey, 2004)

Gait variables	h^2 (SE) for walk	h^2 (SE) for trot	h^2 (SE) for gallop
Stride characteristics			
Speed	n/a	0.30 (0.14)	n/a
Stride length	n/a	0.29 (0.13)	n/a
Stride frequency	n/a	0.20 (0.15)	0.32 (0.19)
Dorsoventral motion			
Symmetry	0.10 (0.08)	0.12 (0.08)	n/a
Regularity	0.10 (0.13)	0.12 (0.09)	n/a
Displacement	0.16 (0.12)	0.14 (0.08)	n/a
Dorsoventral activity	0.41 (0.12)	0.22 (0.10)	0.50 (0.13)
Gait tempo	0.29 (0.10)	0.05 (0.07)	n/a
Longitudinal motion			
Mean propulsion vector	0.19 (0.07)	0.20 (0.11)	n/a
Propulsion duration	0.69 (0.13)	0.38 (0.15)	n/a
Longitudinal activity	n/a	0.44 (0.14)	0.46 (0.20)

h^2, heritability; n/a, data not available.

Table 5.3 Changes in trot variables with the stage of training

Trot parameters	4 years	5 years	6 years	7 years and older
Stride frequency (stride/s)	1.34^a	1.32^a	1.26^b	1.27^b
Stride regularity (/200)	186^a	185^a	185^a	179^b
Dorsoventral activity (W/kg)	7.8	8.3	8.7	10.4
Longitudinal activity (W/kg)	1.14	1.62	1.55	2.1
Propulsion acceleration vector (g)	2.3	2.2	1.4	3
Dorsoventral displacement (m)	0.11^a	0.13^b	0.135^b	0.13^b

Values followed by different superscript letters are significantly different ($p < 0.05$).

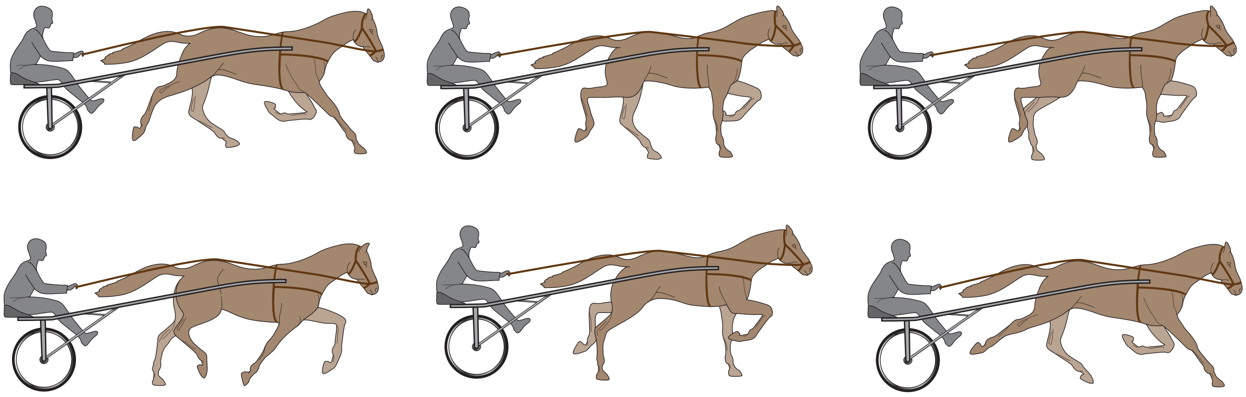

Fig 5.5 Flying trot of a Standardbred.

Drevemo, S., Dalin, G., Fredricson, I., Hjerten, G., 1980. Equine locomotion 3: the reproducibility of gait in Standardbred trotters. Equine Vet. J. 12, 71–73, reused with permission from the Equine Veterinary Journal.

activity than German horses. Spanish horses exhibited elevated movements (large flexion of carpus and tarsus) rather than extended movements of the limbs. Spanish and German groups have a high propulsion and longitudinal activity, which should be an advantage for collecting the trot to passage and piaffe. The German horses had gait characteristics more adapted for dressage competition and that could already be measured in 3-year-old horses.

In harness trotters, the trot is so extended that it can reach a maximum speed of 14.2 m/s with a maximum stride frequency of 2.52 strides/s and a maximum stride length of 5.92 m (Barrey et al., 1995). The diagonal sequence usually changes to a four-beat rhythm due to asynchrony of the impact (and lift-off) of the diagonal limb pairs (Drevemo et al., 1980). This particular gait is named the flying trot (Fig. 5.5). The hind limb touches the ground first (positive advanced placement), and the dissociation at lift-off is greater than at impact.

Various irregularities in the rhythm of the trot can occur during a harness race, which may result in the horse being disqualified by the gait judges. Irregular gait patterns that occur relatively frequently are called the aubin and the traquenard in French. At the 'aubin', the forelimbs gallop and the hind limbs trot, while, at the 'traquenard', the forelimbs trot and the hind limbs gallop. A trotter is also disqualified for pacing or galloping. With increasing speed, the stride length increases linearly but interference between the hind limb and the lateral forelimb becomes a limiting factor. A large amount of overreaching by the hind limbs is possible only if the hind limbs move outside (lateral to) the forelimbs during the swing phase. Heritabilities of the trot parameters measured in harness trotters (French totters) at high speed are moderate to high (stride frequency, 0.40 stride/s; stride length, 0.36 m; longitudinal activity, 0.23 W/kg (Leleu, 2004)). The heritability of the trot symmetry index is zero and the regularity of the stride in time is very low (0.09), which demonstrate that these coordination parameters are more trained than inherited.

The foxtrot is a four-beat symmetric gait in which the footfalls of the diagonal limbs occur as couplets. The interval between footfalls of the fore hoof and the diagonal hind hoof is 15% of stride, compared with 35% of stride between footfalls of the hind hoof and the lateral fore hoof. During a complete stride, the overlap periods were tripedal with two hind limbs and one forelimb (8.9%), diagonal bipedal (60.6%), tripedal with one hind limb and two forelimbs (8.9%) and lateral bipedal (21.7%) (Clayton & Bradbury, 1995).

Pace

This lateral symmetric gait is used in harness racing mainly in North America and Australia. The maximum speed is higher than at the flying trot. At racing speed, the pace, like the trot, becomes a four-beat gait, with dissociation of the lateral limb pairs at impact and lift-off. The hind limb contacts the ground about 26–30 ms before the lateral forelimb (Wilson et al., 1988a). In comparison with the flying trot, there is less problem of limb interference at the pace because the lateral sequence avoids any contact between the ipsilateral limbs. Consequently, there are fewer coordination problems and it is easier for the horse to increase stride length. These differences may explain the higher speed records obtained by pacers 9.4–16.0 m/s (Wilson et al., 1988b) than by trotters 11.8–14.2 m/s (Barrey et al., 1995).

Canter and gallop

Canter and gallop refer to the same gait performed at different speeds: the canter is a slow speed, three-beat gait and the gallop is a four-beat gait performed at a higher speed. At the canter, the stance phases of the diagonal limb pair (leading hind and trailing fore) are synchronized while at the gallop the footfalls of the diagonal are dissociated, with the leading hind limb contacting the ground before the trailing forelimb. The gallop is the fastest equine gait, and is the racing gait of Thoroughbreds and Quarter Horses. Canter parameters are highly heritable (mean heritability, $h^2 = 0.43$) and could also be used for genetic selection (Table 5.2) (Barrey, 2004).

The canter and gallop show asymmetric movements of both the hind and forelimbs. There are two possible footfall sequences: right lead canter or gallop and left lead canter or gallop. Horses at liberty prefer to canter or gallop through a turn with the inside limbs leading.

The 'lead change' is the transition between the footfall sequences of the right and left leads. Racehorses usually change the forelimb lead before the hind limb lead. However, in dressage the rider can elicit the canter lead change during the suspension phase so the change is initiated in the hind limbs (Clayton, 1994). In racing, horses change leads eight or more times per mile to avoid excessive muscular fatigue due to the asymmetric work of the limbs and also to minimize the centrifugal forces as they accommodate to the curve (Leach et al., 1987).

At the gallop, there are two ways of coordinating the hind or fore footfalls. These are called the 'transverse gallop' and the 'rotary gallop' (Fig. 5.6). The transverse gallop is used more frequently by horses than the rotary gallop but the rotary sequence is observed temporarily during a lead change initiated by the forelimbs or when muscular fatigue occurs during racing. The disunited canter has the same footfall sequence as the rotary gallop except that stance phase of the lateral limbs is synchronized. It can be observed for one or

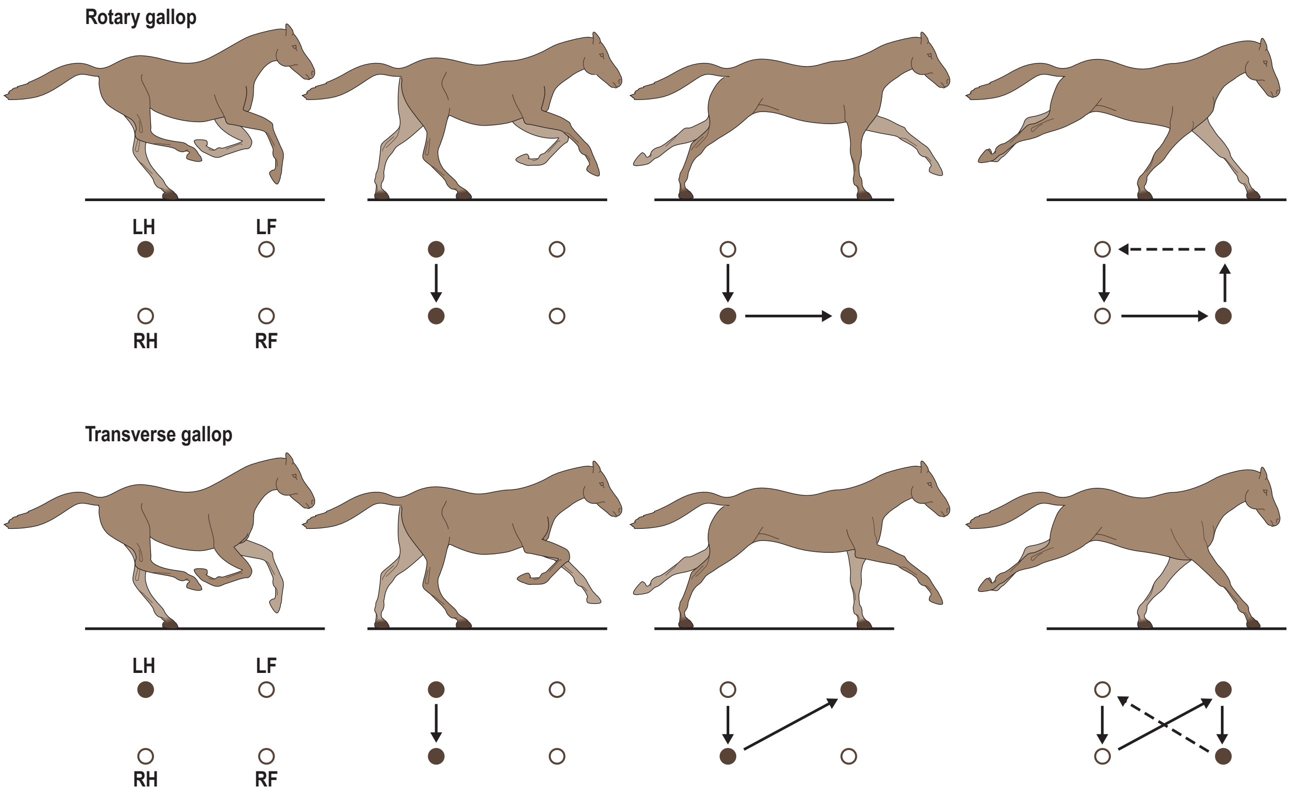

Fig 5.6 Differences of the footfall sequences of transverse and rotary gallops.

Reprinted from Leach, 1984. Stride characteristics of horses competing in Grand Prix jumping, with permission from the American Journal of Veterinary Research http://avmajournals.avma.org/loi/ajvr.

more strides after a bad lead change in dressage or landing after jumping.

Jump

The jump is a gallop stride in which the airborne phase is a long dissociation of the diagonal. The footfalls of the jump stride are: trailing hind and leading hind at lift-off, jump suspension, then trailing fore and leading fore at landing. At lift-off, the hind limb stance phases are more synchronized than in a normal gallop stride to produce a powerful push-off. The footfalls of the forelimbs at landing are not synchronized (Leach et al., 1984b). A lead change can take place during the airborne phase and, in this case, the change of forelimb placement order occurs before that of the hind limbs. A disunited canter can be observed after the jump if the lead change of the hind limbs does not occur immediately after the landing phase.

Gait transitions

In order to increase its velocity, the horse can switch gaits from walk to trot, from trot to canter and then extend the canter into a gallop. Each gait can be extended by changing the spatial and temporal characteristics of its strides. Ponies were shown to have a preferred speed for the trot to gallop transition and this particular speed was related to an optimal metabolic cost of running (Hoyt & Taylor, 1981). However, another experiment demonstrated that the trot-gallop transition was triggered when the peak of ground reaction force reached a critical level of about 1–1.25 times the body weight (Farley & Taylor, 1991). Carrying additional weight reduced the speed of the trot-gallop transition.

The footfall sequence of various gait transitions has been described by Marey (1873), Barroil (1887) and Lenoble du Teil (1893) (Fig. 5.7). Kinematic studies have described alternative footfall sequences observed in dressage horses during transitions between the walk and trot transition (Argue & Clayton, 1993a) and during the transitions between trot and canter (Argue & Clayton, 1993b).

The combination of gait analysis by accelerometry and wavelet analysis allows quantitative description of some temporal and kinetic characteristics of gait transitions (Biau et al., 2002). Transition duration, dorsoventral activity and frequency were specific for each transition. Training improved smoothness of braking deceleration and frequency changes with a long transition duration. The walk-halt transition was characterized by the largest transition duration, the lowest dorsoventral activity, and a low braking deceleration. The change of the vertical activity during this transition was smooth but the decrease of stride frequency was sudden. The trot-walk transition was characterized by a short duration with a large braking deceleration and a great change of vertical activity. An increase of transition duration allowed a smooth transition with lower braking deceleration. Canter-halt, canter-walk and canter-trot transitions were characterized by a great dorsoventral activity and a middle braking deceleration. It was explained by progressive decrease of dorsoventral activity before the gait change, which minimized the braking deceleration at the end of the canter, especially for experienced horses. The transition duration increased significantly with training for trot-walk, canter-halt and canter-trot transitions. The lengthening of the transition duration allowed a slow decrease of stride frequency (canter-trot transition) and a smooth decrease of vertical activity (canter-halt and trot-halt transition). The rider adapted his technique to the locomotion and level of the horse. By lengthening transition duration, experienced horses could perform a smooth deceleration. In contrast, young horses could not

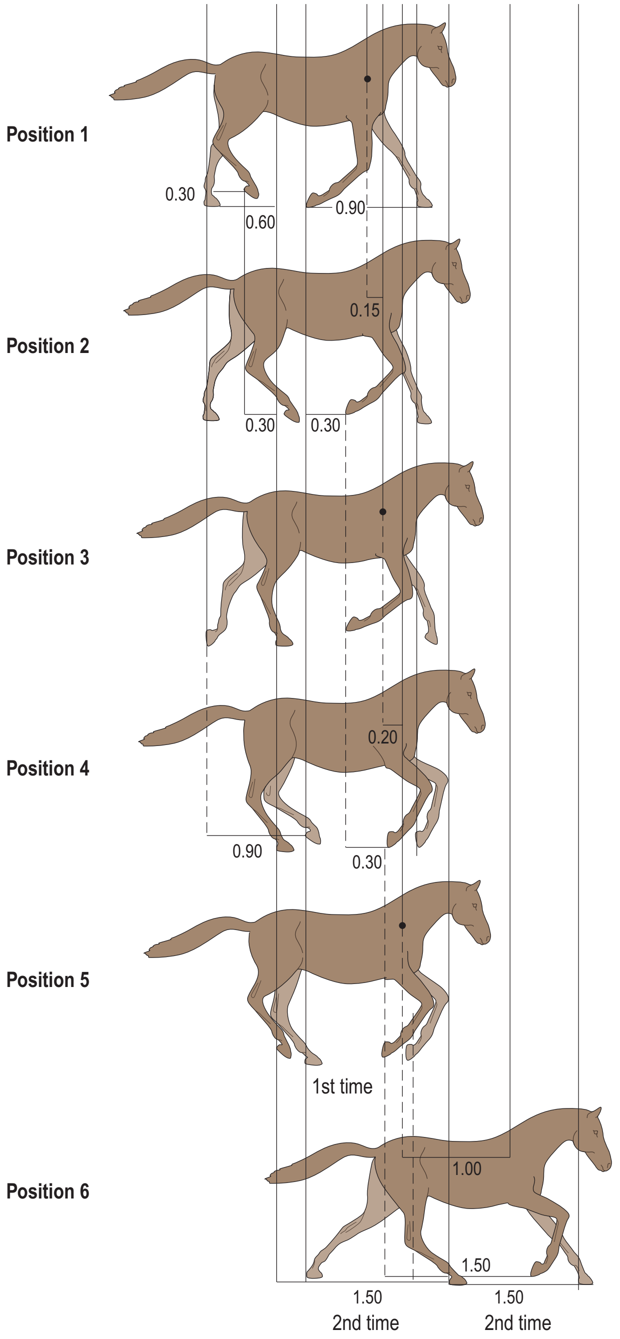

Fig 5.7 Example of limb placement sequence during a transition from walk to canter.

Reproduced from Barroil (1887).

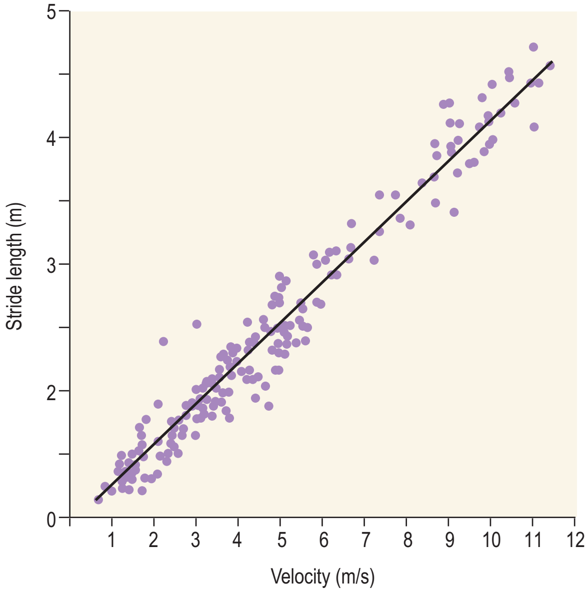

Fig 5.8 Linear relationship between the stride length and velocity of the gaits. Data are from 6-month-old Quarter Horse foals.

Reprinted from Leach, 1984. Stride characteristics of horses competing in Grand Prix jumping, with permission from the American Journal of Veterinary Research http://avmajournals.avma.org/loi/ajvr.

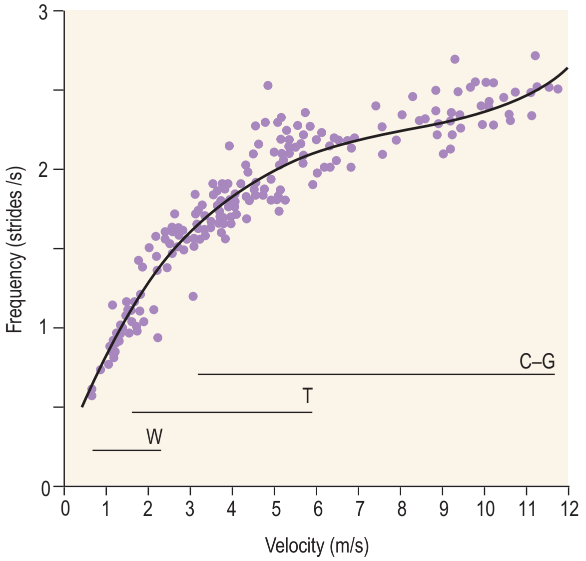

Fig 5.9 Non-linear relationship between the stride frequency of the gaits.

Reprinted from Leach, 1984. Stride characteristics of horses competing in Grand Prix jumping, with permission from the American Journal of Veterinary Research http://avmajournals.avma.org/loi/ajvr.

prepare their gait transition and would suddenly brake which produced a high peak of deceleration. The amplitude of frequency change during the gait transition decreased with training for all transitions, especially for canter-halt and trot-walk transition.

Velocity-related changes in stride variables

To increase speed at a particular gait, the amplitude of the steps becomes larger and the duration of the limb cycle is reduced in order to repeat the limb movements more frequently. The stride frequency (SF) and stride length (SL) are the two main components of speed. The mean speed can be estimated by the product of the stride frequency and stride length: speed = SF × SL. The speed-related changes in stride parameters have been studied in many horse breeds and disciplines. Stride length increases linearly with the speed of the gait (Fig. 5.8).

Stride frequency increases non linearly and more slowly (Dusek et al., 1970; Leach & Cymbaluk, 1986; Ishii et al., 1989) (Fig. 5.9). During rapid acceleration, such as that occurring at the start of a gallop race, the stride frequency reaches its maximum value very

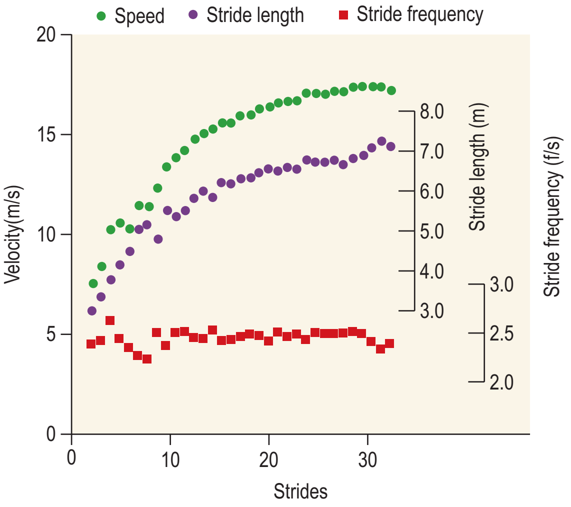

Fig 5.10 Changes in velocity, stride frequency and stride length at the start dash in a galloping horse.

Reprinted from Higara, A., Yamanobe, A., Kubo, K., 1994. Relationships between stride length, stride frequency, step length and velocity at the start dash in a racehorse, J. Equine Sci. 5, 127–130, with permission of the Japanese Society of Equine Science.

rapidly to produce the initial acceleration, while the maximum stride length increases more slowly to its maximum value (Hiraga et al., 1994) (Fig. 5.10).

In Thoroughbred racehorses, the effects of fatigue include increases in the overlap time between the leading hind limb and the trailing forelimb, the stride duration and the suspension phase duration (Leach & Springings, 1979). The compliance of the track surface can also influence the stride parameters when the horse is trotting or galloping at high speed. At the gallop, the stride duration tends to be reduced on a harder track surface (Fredricson et al., 1983). There is a slight increase in the stride duration on a woodfiber track in comparison with a turf track at the same speed.

When the rider stimulated the horse with a whip, there was a reduction in the stride length and an increase in the stride frequency corresponding to a reduction of the forelimb stance phase duration. However, the velocity was not significantly influenced (Deuel & Lawrence, 1987b).

Gait development and training effects

Gait patterns are influenced by the age of the horse, but little is known about gait development. Studies in different breeds of foals have analyzed the relationship between conformation and stride variables in foals aged 6–8 months. In Quarter Horse foals, speed increases were obtained by a longer stride length in heavier foals and a higher stride frequency in taller foals (Leach & Cymbaluk, 1986). In Dutch Warmblood foals, the elbow, carpal and fetlock joint angle flexions were the most significant differences between the stride kinematics of individual foals (Back et al., 1993). The stride and stance durations increased with age as a consequence of the increase in height but the swing duration and the protraction and retraction angles were consistent over time. The joint angle patterns recorded at 4 months and 26 months of age were very similar. The duration of the trot swing phase, the maximal range of protaction-retraction of the limbs and the maximal flexion of hock joint were well correlated between 4 and 26 months of age (Back et al., 1994a). The good correlations between the kinematic parameters measured in the foals and adults make it possible to assess these parameters in young horses in order to predict the gait quality of adult horses. According to the correlations with the judged scores, there are some objective indicators of good trot. A slow stride frequency with a long swing phase, a large amplitude of scapular rotation, maximal forelimb retraction and maximal hind limb protraction lead to a long stride length with a good trot. The vertical elasticity of the trot was associated with maximal fetlock extension, and maximal stifle and tarsal flexion (Back et al., 1994b).

In racehorses, the influence of training has been investigated in Standardbreds and Thoroughbreds. After 3 years of training, Standardbreds showed increases in stride length, stride duration and swing phase duration (Drevemo et al., 1980). In Thoroughbreds, stride duration and stride length increased (Leach & Springings, 1979). After 8 weeks of high intensity training on a treadmill, the stance phase duration of the Thoroughbred gallop stride was reduced by 8–20% (Corley & Goodship, 1994).

In young saddle horses (2.5 years old), some kinematic changes were observed on a treadmill at trot after a 70-day training period for dressage and jumping (Back et al., 1995). The protraction and retraction range of the forelimbs decreased and the stance duration and the flexion of the hind limbs decreased. The engagement increased with a maximal protraction of the hind limbs that took place earlier in the stride cycle. The stride frequency stayed constant. During the same 70-day period, the stride frequency in the control group (in pasture day and night) was reduced with a longer swing phase. The trained horses were trotting with impulsion ‘on the bit’ with the same stride frequency while the pastured horses were trotting in a more relaxed way with a lower stride frequency.

Dressage requires a high level of locomotor control by the rider, which is obtained progressively through exercise and collecting the gaits. A horse’s ability for collection seems to be one of the main limiting factors for dressage because it is impossible to execute the more complex exercises correctly without having attained a good collected gait at trot and canter. Some locomotor parameters were identified as favoring collection ability, extended gaits and the expressiveness of the gait (Holmström et al., 1994b; Back et al., 1994b). A slow stride frequency including a long swing phase is required for good trot quality. The elapsed time between the hind limb contact and the diagonal forelimb contact defines the diagonal advanced placement and should be positive and high at the trot. The diagonal hind limb should touch the ground about 30 ms before the diagonal forelimb. In space, a good engagement is required; the hind limb footfall should be placed as far as possible under the body for a good propulsion activity.

Dressage horses should be trained to improve their coordination, their suppleness and their gait collection. The collection of the gait means that the forward movements become more upward movements and the stride frequency decreases. A group of horses competing in dressage has been tested from 4 to 7 years old to determine the training-related changes in locomotion variables (Barrey & Biau, 2002). The changes of the trot (Table 5.3) were more pronounced than the changes in the walk and canter. At the trot, the stride frequency decreases between 5 and 6 years old. In the same time the walk and gallop stride frequencies stay the same. At the trot, the dorsoventral displacement increases after the 1st year of training. The increase of dorsoventral activity with age corresponded to an increase of muscular power and an increase of the dorsoventral displacement in the collected gaits. The stride regularity and symmetry increase initially, but then decrease after 6 years old.

Influence of the treadmill on gait characteristics

Under laboratory conditions it is possible to study the locomotion of horses running on an experimental track or on a treadmill. The latter provides an excellent means of controlling the regularity of the gaits because the speed and slope of the treadmill belt are determined by the operator. In order to analyze the gaits without

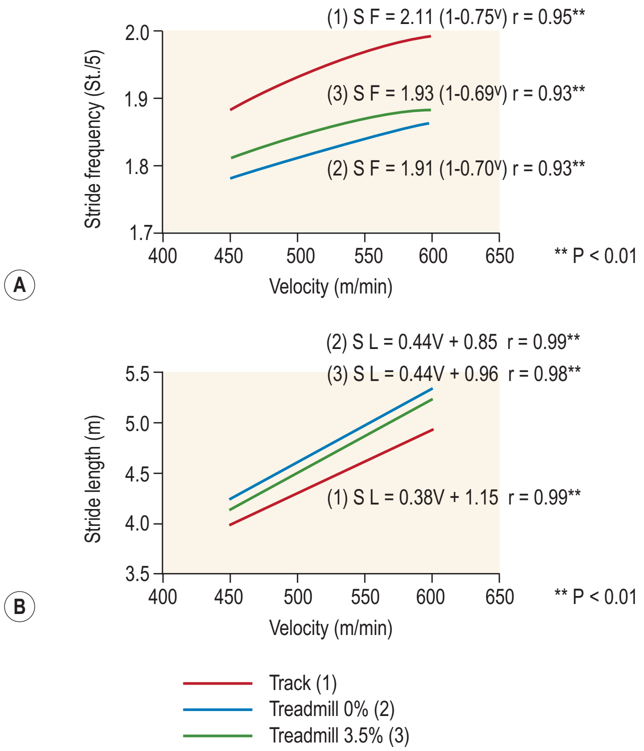

Fig 5.11 Relationship of velocity with (A) stride frequency and (B) stride length for locomotion on a track, a flat treadmill and a treadmill with a 3.5% inclination.

Reprinted from Barrey, E., Galloux, P., Valette J.P., Auvinet, B., Wolter, R., 1993a. Stride characteristics of overground versus treadmill locomotion in the saddle horse. Acta Anatomica 146, 90–94, with permission from S Karger AG.

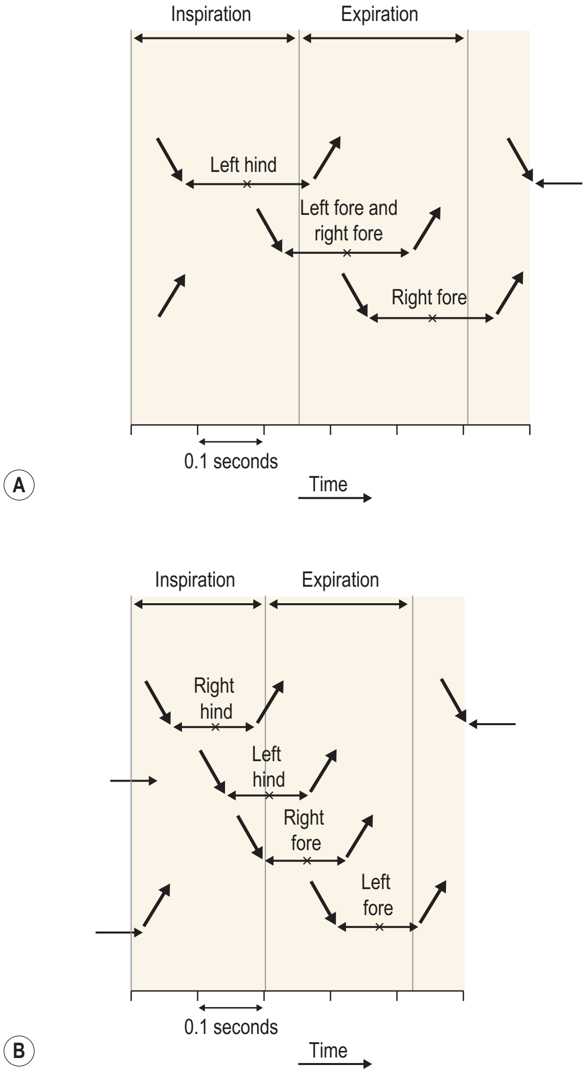

Fig 5.12 Schematic diagrams showing the relationship between the limb cycle and the respiratory cycle at (A) the canter and (B) gallop.

Reprinted from Attenburrow, D.P., 1982. Time relationship between the respiratory cycle and limb cycle in the horse. Equine Vet. J. 14, 69–72, with permission from the Equine Veterinary Journal.

stress, some pre-experimental exercise sessions are required to accustom the horse to this unusual exercise condition (Buchner et al., 1994). The horse adapts rapidly at trot, and stride measurements can be undertaken at the beginning of the third session. For the walk, however, adaptation occurs more slowly and many stride parameters are not stable even after the nineth training session. Within a session, a minimum of 5 min of walking or trotting is required to reach a steady state of locomotion.

Many locomotion studies have been performed on high-speed treadmills, since the development of the first installation of this type of machine at the Swedish University of Agricultural Science in Uppsala (Fredricson et al., 1983). However, it was demonstrated experimentally that the stride length was longer on the treadmill at the trot and canter than at the same speed on a track (Barrey et al., 1993a; Couroucé et al., 1998) (Fig. 5.11).

The mechanical reasons for these differences are not entirely known, but some explanations have been suggested by the experimental and theoretical results. The speed of the treadmill belt fluctuates in relationship to the hoof impact on the belt (Savelberg et al., 1994). The energy transfer between the hooves and the treadmill belt are not exactly the same as in overground locomotion because the belt and the hooves are driven backwards by the engine of the treadmill. During level treadmill exercise, the horse receives some mechanical energy from the treadmill. This assumption is based on the fact that the heart rate response and blood lactate concentration, which reflect the horse's workload, were lower on a treadmill than overground during a standardized exercise test (Valette et al., 1992; Barrey et al., 1993b). At a slow trot, a treadmill inclination of 6% tended to increase the stride duration and significantly increased the stance duration, more so in the hind limbs than the forelimbs (Sloet et al., 1997). Maximal fetlock extension was reduced in the forelimbs and increased in the hind limbs on the incline, which indicated that the hind limbs generate more propulsion on the inclined than on the flat treadmill. The inclination of the treadmill did not change stride length nor did it change the stance, swing or stride duration in a cantering Thoroughbred (Kai et al., 1997).

Locomotion and respiratory coupling

Some relationships have been established between stride parameters and other physiological variables. At the canter and gallop, the respiratory and limb cycle are synchronized. Inspiration starts at the beginning of the suspension phase and ends when the trailing forelimb contacts the ground. Expiration then occurs during the forelimb stance phases (Attenburrow, 1982) (Fig. 5.12). Expiration is facilitated by compression of the rib cage between the weight-bearing forelimbs. This functional coupling of respiration to the stride cycle might be a limiting factor for ventilation at maximal exercise intensity. At the gallop racing speed, less than 50% of the stride duration is available for the expiration. At 16 m/s, the expiration during the trailing and leading forelimb support represents 45% of the stride duration (Barrey et al., 2000). At high speed on a treadmill (11 m/s), the respiratory and stride cycles are exactly synchronized with one inspiration/expiration per stride in Standardbreds. The inspiration takes place during the support phase of one diagonal and most of the preceding and following suspension phases. About 57% of the stride duration was available for inspiration and only 43% for expiration. Hypercapnia, acidosis and muscular fatigue onset may occur quickly at high speed because of this decrease in expiration duration, which is mechanically linked to the stride cycle both at the trot and gallop.

At the walk, trot and pace there is no consistent coupling between the locomotor and respiratory cycles. At trot, the ratio between locomotor and respiratory frequency ranged between 1–3 depending on speed, duration of exercise and breed of horse (Hörnicke et al., 1987; Art et al., 1990). A similarly variable coupling mechanism was observed at the pace where the ratio between the stride and respiratory frequencies ranged from 1–1.5 (Evans et al., 1994).

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CHAPTER 6

Forelimb function

Hilary M. Clayton, Henry Chateau, Willem Back

Terminology

This chapter reviews the structure and functions of the equine forelimbs in relation to locomotor activity, including kinematics (movements) and kinetics (forces) during the stride. A stride is regarded as the unit of measurement. The stride starts and ends with consecutive occurrences of the same event, which is often a specific footfall. Within a stride, each limb has a stance phase when the hoof is in contact with the ground, and a swing phase when the hoof is swinging through the air. The stance phase starts at the moment of initial ground contact, after which the hoof is decelerated during the impact phase. In the middle part of the stance phase the limb is loaded by the horse's body weight then unloaded. Breakover is the terminal part of stance when the heels leave the ground and rotate around the toe, which is still in ground contact. The various gaits are defined by the sequence and timing of the limb movements during the stride.

Forelimb kinematics are described in terms of temporal (timing), linear (distance) and angular variables. In order to interpret data describing segment and joint angles, it is important to know where the angles were measured. For example, joint angles may be measured between the proximal and distal segments on the anatomical flexor aspect or as the angle by which the distal segment deviates from alignment with the proximal segment, or some combination of these methods (Fig. 6.1). Furthermore, the angle may be expressed in absolute terms or it may be normalized to the standing angle, the angle at ground contact or the average angle during the stride (Mullineaux et al., 2004).

The ground reaction force (GRF) vector is usually resolved into vertical, longitudinal and transverse components to facilitate interpretation of its effects. Due to their proximity to the horse's center of mass, the forelimbs carry more weight (57–58%) than the hind limbs (42–43%) and have proportionately higher vertical forces and impulses. This supportive function is reflected in the pillar-like alignment of the antebrachial and metacarpal segments.

GRF data can be combined with kinematic data using a link segment model to calculate internal forces within the limb that cannot be measured directly (see Chapter 19 for details). Briefly, in a two-dimensional link segment model, each segment is represented as a solid bar and the location of its center of mass is known relative to the coordinates that define the segment. The input for the model comprises kinematic and force data that are synchronized in time and space, together with segment morphometric data (Fig. 6.2, Table 6.1). An inverse dynamic solution is used to compute net joint moments and net joint powers (Colborne et al., 1997a,b). The net joint moment represents the net torque acting around a joint, which is produced primarily by the soft tissues (muscle, tendon and ligament). Net joint power, calculated as the product of the joint moment and that joint's angular velocity, measures the rate of mechanical energy generation and absorption across a joint. Discrete bursts of positive and negative work can be quantified as the areas under the positive and negative phases, respectively, of the power curve. Positive work is done when the net joint moment acts in the same direction as the angular velocity of the joint, indicating that the muscle shortens as it generates tension (concentric contraction). Negative work is done when the net joint moment acts in the opposite direction to the angular velocity of the joint, so the muscle lengthens as it generates tension (eccentric contraction) and acts to restrain joint movement in opposition to gravity or some other external force.

This chapter describes the structure of the forelimb musculature, the movements of the forelimb and the role of specific muscle groups in causing and controlling those movements. These concepts are important in understanding how the muscles of the forelimb work to cause or control segmental and joint motion. The role of the forelimb joints and musculature as determined by inverse dynamics analysis will be described later in this chapter.

Musculotendinous architecture

In small, non-cursorial mammals, the forelimb is attached to the trunk via a shoulder girdle, in which the clavicle articulates with the sternum and scapula, imposing some constraints on forelimb motion. Horses do not have a clavicle or shoulder girdle. Instead, the articulation between the forelimb and the trunk is a synsarcosis, consisting of a substantial group of extrinsic muscles and their associated soft tissues. The absence of a clavicle allows the scapula more freedom to rotate and translate relative to the ribcage, which may contribute to an increase in stride length. As a consequence of this translational motion, the instantaneous center of rotation of the scapulothoracic joint changes throughout the stride.

Locomotor muscles account for about 42% of the horse's body mass (Gunn, 1978) with the large, powerful muscles concentrated in the proximal limb, while the distal forelimb makes use of long, elastic tendons to reduce the metabolic cost of locomotion. The bulk of the musculature is in the proximal limb, which reduces the moment of inertia of the limb as a whole. The functions of the musculotendinous system of the equine forelimb include connecting the forelimb to the trunk; supporting the body mass; stabilizing the joints in opposition to the force of gravity during the stance phase; generating forces that are used for propulsion, braking and turning; and flexing the joints to lift the hoof clear of the ground during the swing phase. At first glance, there appears to be considerable redundancy in muscular function but muscles with

Fig 6.1 Two methods of measuring joint angles of the forelimbs with the measured angles being represented by black arcs. Left: measurement of the angle between the proximal and distal segments on the anatomical flexor aspect. Right: measurement of the angle by which the distal segment differs from alignment with the proximal segment; deviation toward the flexor aspect is negative (–), deviation toward the extensor aspect is positive (+).

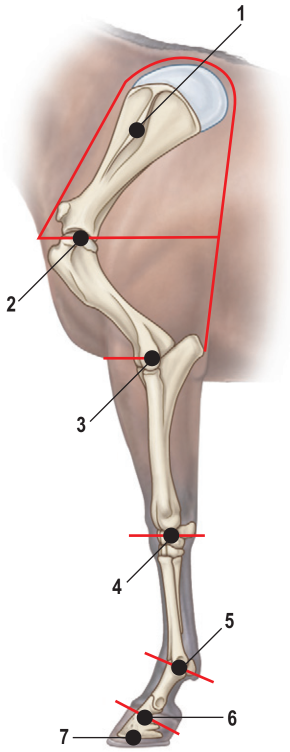

Fig 6.2 Skin markers used to locate the centers of mass of the forelimb segments in Table 6.1, which are separated according to the incision lines shown in red.

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Table 6.1 Forelimb segmental masses, densities, reference lines for division of segments (see Fig. 6.2 for key to marker locations), and position of segmental centers of mass in the sagittal plane*

Segment	Mass (kg)	Density (g/cm^3)	Proximal and distal markers	Distance as % segment length	
				x-axis	y-axis
Scapula	11.5 ± 0.9	1.04 ± 0.01	1–2	27 ± 4	−12 ± 5
Brachium	8.6 ± 1.5	1.05 ± 0.01	2–3	51 ± 8	−5 ± 3
Antebrachium	6.7 ± 0.6	1.12 ± 0.03	3–4	35 ± 3	−2 ± 2
Metacarpus	1.6 ± 0.1	1.29 ± 0.04	4–5	44 ± 4	−1.0 ± 0.3
Fore pastern	0.73 ± 0.03	1.25 ± 0.03	5–6	46 ± 4	−11 ± 4
Fore hoof	1.08 ± 0.01	1.18 ± 0.01	6–7	29 ± 6	−20 ± 4.0

*Position of center of mass is expressed along the x-axis (longitudinal, positive distally from the more proximal marker), then along the y-axis (perpendicular to x-axis, positive cranially). Distances are expressed as percentage segment length between the two reference markers. Location along the x-axis is measured first from the proximal reference marker toward the distal reference marker, then shifted along the y-axis. Data are mean ± SD for 12 forelimbs of 6 Warmblood horses.

Reprinted from Willemen, M.A., Savelberg, H.H.C.M., Barneveld, A., 1997, The improvement of the gait quality of sound trotting warmblood horses by normal shoeing and its effect on the load on the lower forelimb, Livestock Production Science, 52 (2), 145–153, with permission from Elsevier.

similar attachments may, in fact, have quite different functional responsibilities. Evaluation of the geometry and architecture of the musculotendinous units is helpful in understanding whether their function is to produce rapid movements or generate large forces to stabilize the joints.

Muscle size is expressed in terms of its mass and volume, which are closely correlated. Muscle density, calculated as mass divided by volume, has been determined to be 1.075 g/cm^3 over a range of muscles, with different muscles varying by only a small amount (Brown et al., 2003). Fiber length and pennation angle affect the range of motion through which the muscle contracts and its ability to generate force. Long fibers arranged in parallel with the long axis of the muscle belly have the greatest capacity to shorten the muscle. Thus parallel fibers impart the largest range of motion and the most

Table 6.2 **Architectural properties of the extrinsic muscles of the equine forelimb**

Muscle	Mass (kg)	Volume (cm^3)	MFL (mm)	PCSA (cm^2)	Force (kN)	Power (W)
Pectoralis transversus	1.54	1434	200	77	2310	231
Pectoralis descendens	2.84	2649	461	60	1800	415
Pectoralis ascendens	21.0	1954	292	72	2160	315
Serratus ventralis cervicis	29.9	2781	49	577	17310	424
Serratus ventralis thoracis	24.3	2349	693	62	1860	644
Brachiocephalicus/Omotransversarius	13.0	1217	519	23	690	179
Subclavius	0.68	631	191	42	1260	120
Trapezius	1.83	1705	378	53	1590	301
Rhomboideus cervicis	0.55	503	311	15	450	70
Rhomboideus thoracis	0.43	409	139	24	720	50
Latissimus dorsi	1.83	1705	378	53	1590	301

MFL, mean fiber length; PCSA, physiological cross-sectional area; force, maximal isometric force generation capacity estimated by multiplying muscle PCSA by the maximal isometric stress of skeletal muscle, taken as 0.3 MPa; power, maximal power output calculated as one-tenth of the product of force and maximal contraction velocity, which was estimated based on published values of equine muscle fiber-typing.

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rapid shortening velocities. These characteristics are associated with muscles that act as prime movers. When fibers insert into the tendon at an angle (pennation angle), the amount of force transmitted to the tendon is determined as force developed in the fiber multiplied by the cosine of the pennation angle. Thus, fibers with a pennation angle of 40° transmit only 77% of the force generated by the muscle fiber to the tendon. In the equine antebrachial muscles, a close inverse relationship between muscle fiber length and pennation angle has been demonstrated (Brown et al., 2003), and this relationship may be true for other anatomical areas.

Physiological cross-sectional area (PCSA), which is a determinant of the maximal isometric force that can be generated by a muscle, is calculated from muscle volume divided by fiber length. For muscles with equal volumes, PCSA is larger in muscles with short, pennated fibers because a larger number of fibers can be contained within the volume. These characteristics, which confer an increase in passive stiffness to the muscle, are typical of the anti-gravity muscles that support the body during the stance phase. Short, highly pennated fibers in combination with a long, elastic tendon are characteristic of muscles involved in elastic energy storage and release.

The force of contraction of a muscle can be estimated in a Hill-type model based on four parameters: fiber length, maximal fiber shortening velocity, pennation angle, and peak isometric muscle force (Zajac, 1989). In general, muscle size (volume and mass) and fiber length decrease in a proximal to distal direction within the equine limbs. Muscles in the proximal forelimb tend to be large and powerful with long fibers arranged parallel to the muscle belly to move the joints through a large range of motion. By comparison, muscles in the distal limb are smaller and less powerful with short, pennate fibers that are not capable of a large amount of shortening but are well suited to contract isometrically. When muscle length is controlled by an isometric contraction, the long tendons are loaded elastically as the limb accepts weight in early stance, then recoil to release the stored elastic energy at the end of stance. Large, cursorial animals use this musculotendinous arrangement to move at high speeds with a relatively economical metabolic cost (Alexander, 2002).

Extrinsic muscles of the forelimb

The extrinsic muscles of the forelimb, which have an attachment to the bones of the limb and an attachment to the trunk, are responsible for suspending the trunk between the forelimbs and for moving the forelimbs relative to the trunk. In general, these are large muscles with long fibers arranged parallel with the long axis of the muscle belly (Table 6.2) that insert on the bones via short tendons or aponeurotic sheets (Payne et al., 2004). This internal architectural style favors the ability to contract rapidly through a wide range of motion at the expense of the ability to generate high forces. The exception is *serratus ventralis thoracis*, which has short, pennate fibers and is encased in a strong aponeurotic sheath. These features suggest that *serratus ventralis thoracis* bears primary responsibility for antigravitational support of the trunk, whereas the other extrinsic muscles move the forelimb relative to the trunk during the swing phase or advance the trunk over the grounded limb during the stance phase.

Serratus ventralis thoracis (Fig. 6.3, Table 6.2) is the largest extrinsic muscle of the forelimb both in mass and volume and has the shortest mean fiber length. It is a broad flat muscle covered medially and laterally by broad aponeurotic sheets. The shortness of the muscle fibers (49 mm) relative to the length of the aponeurosis (500 mm) offers limited ability for muscular contraction to compensate for stretching of the aponeurosis, which implies that this muscle would not be effective in moving or positioning the limb. The elasticity of the aponeurosis may contribute to the overall elastic properties of the limb by acting in series with the spring-like tendons in the more distal part of the limb and may support protraction of the scapula (Smythe et al., 1993). Pennation of the fibers and the consequent increase in cross-sectional area gives the muscle considerable passive stiffness and allows it to generate sufficiently high forces to withstand gravitational loading of the limbs during galloping. *Serratus ventralis thoracis* is the primary muscular component of the thoracic sling, which suspends the trunk between the forelimbs and controls the position of the thorax and withers relative to the scapulae when the forelimbs are weight-bearing. During standing, the trunk is supported passively by elongation of the muscle fibers and the series

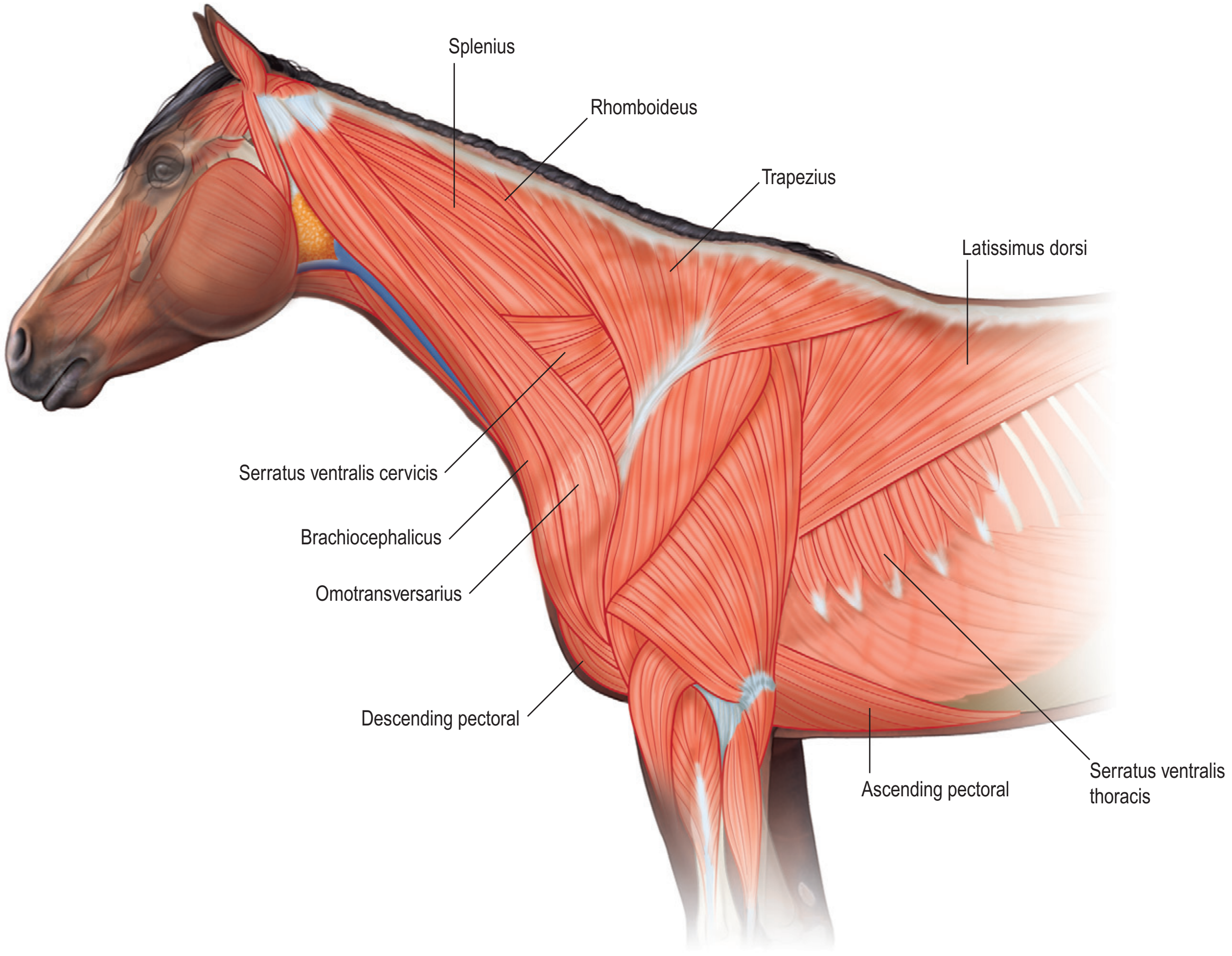

Fig 6.3 Extrinsic muscles of the forelimb.
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elastic elements. Much higher forces must be resisted during locomotion when gravitational and inertial loads on the limbs produce peak vertical forces of at least 8 kN per limb for a 500 kg horse (McGuigan & Wilson, 2003). Loading during locomotion is easily resisted by the maximal isometric force-generating capacity of *serratus ventralis thoracis,* which is estimated to exceed 17 kN. This muscle is more variable in its mass than the other extrinsic muscles, which may reflect adaptation in response to the amount and type of training.

Serratus ventralis cervicis (Fig. 6.3, Table 6.2) is somewhat smaller than the thoracic part of the muscle and differs in having relatively long fibers and a smaller cross-sectional area (Payne et al., 2004), that confer the ability to support the base of the neck or to retract the limb by rotating the proximal scapula cranially. In dogs, it has been suggested that the primary function of *serratus ventralis cervicis* is to stabilize the position of the fulcrum about which the forelimb rotates in a craniocaudal direction during active retraction of the forelimb, thus ensuring that the GRF vector passes close to the center of scapular rotation (Carrier et al., 2006).

The pectoral muscles (Fig. 6.3, Table 6.2) are large with relatively long fibers that suggest a primary role in adducting the forelimb (Payne et al., 2004). The deep pectoral (*pectoralis ascendens*) is a large, powerful muscle with long fibers. It is active through most of the stance phase when it may assist in moving the trunk forward over the grounded limb. The superficial pectorals (*pectoralis descendens* and *pectoralis transversus*) are smaller muscles with medium length fibers (Payne et al., 2004).

Subclavius (Table 6.2) has long fibers (519 mm) that allow generation of large forces to assist in adduction and retraction of the forelimb or stabilization of the scapula (Payne et al., 2004).

Trapezius (Fig. 6.3) and *rhomboideus* are the smallest extrinsic muscles of the forelimb and have medium-length fibers (Table 6.2) (Payne et al., 2004). Both muscles insert on the dorsal scapula and have fiber orientations ranging from vertical in the middle of the muscle to almost longitudinal towards the extremities. The orientation of the vertical fibers suggests that their function is to hold the proximal scapula against the trunk (preventing winging of the scapula) by opposing the action of the pectoral muscles that adduct the distal scapula and humerus. The longitudinal fibers likely contribute to forelimb protraction, retraction and stabilization.

Brachiocephalicus (Fig. 6.3) and *omotransversarius* are considered together since their fibers cannot be separated close to their origins in the shoulder region. They form a large, powerful muscle, with long fibers oriented parallel to the muscle belly (Payne et al., 2004). Fiber lengths in Table 6.2 represent a mean of the two muscles, though *brachiocephalicus* has longer fibers than *omotransversarius*. The fiber direction suggests a primary role in forelimb protraction.

Latissimus dorsi (Fig. 6.3, Table 6.2) is a moderately large and powerful muscle with fairly long fibers (Payne et al., 2004). It is enveloped by an aponeurotic sheath that is part of the thoracolumbar fascia. The fiber orientation suggests a primary role in forelimb retraction. Compared with the primary limb protractors, *brachiocephalicus* and *omotransversarius*, *latissimus dorsi* develops similar amounts of force but less than half as much power. Electromyographic studies indicate that this muscle is active in late swing and at hoof contact (Preedy, 1998), when it may act to retract the limb in preparation for ground contact and stabilize the trunk during the impact phase.

Intrinsic muscles of the forelimb

The intrinsic muscles of the forelimb are characterized by being smaller in volume than the extrinsic musculature with short, highly pennate fibers and long tendons relative to muscle length. Total mass of the intrinsic musculature is around 17 kg in each forelimb. Pennation of the muscle fibers results in a larger PCSA than for equal-sized muscles with parallel fibers. This confers the ability to resist elongation of the muscle (isometric contraction) as the limb is loaded, so elongation of the musculotendinous unit is due to stretching of the tendon that acts in series with the muscle. As the tendons stretch, they store elastic energy, which is released later in the stance phase when the limb is unloaded. This mechanism reduces muscular work and increases the economy of locomotion (Alexander, 2002).

Supraspinatus, with a mass of 793–1546 g and fiber length of 5–12 cm, has limited force generating capacity and a small moment arm at the shoulder, which makes it more suitable for stabilization than dynamic movement of the joints (Watson & Wilson, 2007). *Supraspinatus* and *infraspinatus* are active during early and midstance in walk, trot and canter (Aoki et al., 1984; Robert et al., 1998), when the primary action of *supraspinatus* appears to be stabilization of the shoulder joint. The instability seen with paralysis of the supraspinous nerve (Sweeney) supports this presumptive function.

The medial and lateral heads of the biarticular *biceps brachii* span the extensor aspect of the shoulder and the flexor aspect of the elbow. The lateral head, with a mass of 171–343 g, is composed of short (5–8 mm), pennate fibers (Watson & Wilson, 2007), a large percentage of which are slow-twitch and well suited to postural control. The medial head, which has longer fibers (15–40 mm) and fewer slow-twitch fibers, may be more important in locomotion (Hermanson & Hurley, 1990). Compared with *supraspinatus*, *biceps brachii* has a larger force generating capacity and a larger moment arm at the shoulder joint, which suggests that it may be a more effective extensor of the shoulder (Watson & Wilson, 2007).

A strong internal tendon (mass, 122–260 g; fiber length, 9–17 cm) runs through the muscle belly of *biceps brachii* uniting the tendons of origin and insertion. This tendon plays an important role in elastic energy storage, having the potential to store 277–591 J. It is estimated to withstand forces of $3.2 \times 10^4 - 5.4 \times 10^4$ N when stretched as the forelimb is retracted in late stance with the shoulder and elbow in extension (Watson & Wilson, 2007). Recoil of the stretched biceps tendon in the galloping horse has been described as a catapult mechanism that provides rapid acceleration of the distal forelimb (Wilson & Watson, 2003). In a catapult, a large force is applied to store energy, which is then released rapidly to accelerate a small mass. In the horse's forelimb, the biceps tendon is stretched by forward movement of the trunk and the changing orientation of the ground reaction force vector relative to the shoulder and elbow joints during the stance phase. Stretching continues as long as the carpus is locked in extension. When the carpus buckles, the forearm is released allowing the biceps tendon to recoil. The effect is rapid extension of the shoulder, flexion of the elbow and forward acceleration of the distal limb. Tendons can recoil elastically much faster than muscles shorten, which is beneficial in situations where rapid movement is required. In a galloping horse, the biceps tendon has been estimated to release 243 J in 0.11 s, which would require the power output of 50 kg of non-elastic muscle (Wilson & Watson, 2003). Thus the biceps catapult is an effective and efficient mechanism for protracting the forelimb in galloping horses. A further benefit of using tendon elasticity rather than muscular force is that the tendon has low energy dissipation, returning an impressive 93% of the work done stretching it and with only 7% dissipation as heat.

Part of the internal tendon of *biceps brachii* emerges from the muscle and continues distally as the *lacertus fibrosus*, a tendinous band that blends with the epimysium of *extensor carpi radialis*. *Lacertus fibrosus* has a much smaller mass than the internal tendon of *biceps brachii* and is capable of storing much less energy (10–28 J) (Watson & Wilson, 2007). These properties are consistent with its role in stabilizing the forelimb as part of the stay apparatus.

Biceps brachii has tonic activity during standing (Tokuriki et al., 1989), which supports the suggestion that the lateral part of the muscle, with its high proportion of type I muscle fibers, acts in series with *lacertus fibrosus* and *extensor carpi radialis* to stabilize the shoulder as part of the passive stay apparatus (Hermanson, 1997). During locomotion at walk, trot and canter, *biceps brachii* is active in early and midstance (Tokuriki et al., 1989). This is in contrast to *brachialis*, which acts as an elbow flexor in early swing (Tokuriki et al., 1989) and contributes to the flexor moment at the elbow at this time in walk (Clayton et al., 2000a, b) and trot (Lanovaz et al., 1999).

Triceps brachii is a biarticular muscle crossing the flexor aspect of the shoulder (long head) and extensor aspect of the elbow. It is by far the largest of the intrinsic forelimb muscles. As the name suggests, it has three heads. The biarticular long head (mass, 3200–6663 g; fiber length, 19–26 mm) and the monoarticular lateral head (mass, 514–1240 g; fiber length, 17–24 mm) comprise 81% and 15%, respectively, of the extensor muscle mass at the elbow (Ryan et al., 1992). They contain predominantly fast-twitch fibers suggesting they are important in locomotion. By contrast, the small medial head of triceps (mass, 85–271 g; fiber length, 9–17 cm) and the *anconeus* muscle each account for only 2% of elbow extensor muscle mass and both are composed almost entirely of slow-twitch fibers, suggesting their role is to support the elbow in extension during stance (Ryan et al., 1992).

The actions of triceps are to extend the elbow, to retract and extend the distal forelimb and, perhaps, to extend the limb when it is being used to raise the forehand. It is active in late swing and early stance (Tokuriki et al., 1989; Preedy, 1998; Robert et al., 1998), with activity in the long head preceding activity in the lateral head. Since *biceps brachii* and the long head of *triceps brachii* are biarticular, their interaction affects motion and stability of both shoulder and elbow joints. The nature of this interaction differs between the inverted pendulum behavior of the limb during walking and the mass-spring behavior during trotting. In the walking horse, the shoulder acts primarily as an energy damper, with a large burst of energy absorption on its extensor (cranial) aspect in midstance (Clayton et al., 2000a), which is likely due to eccentric action of *biceps brachii* controlling extension of the shoulder. At the elbow there are bursts of energy generation on the extensor aspect in early stance, which is thought to be due to concentric action of *triceps brachii*, and on the flexor aspect in late stance, which coincides with electrical activity in *biceps brachii* (Tokuriki et al., 1989). During trotting, the elbow has well-defined bursts of energy absorption on the extensor side of the joint in early stance followed by energy generation on the extensor aspect in midstance (Clayton et al., 1998). Energy absorption and generation on the extensor (cranial) aspect of the shoulder joint are similar in magnitude to those at the elbow joint but occur slightly later in the stance phase. There is an additional burst of energy generation on the extensor aspect of the shoulder in late stance (Clayton et al., 1998) corresponding with activity in *biceps brachii* (Tokuriki et al., 1989). Thus

Table 6.3 Architectural properties of the muscles of the equine antebrachium

Muscle	Mass (kg)	Volume (cm^3)	MFL (mm)	PCSA (cm^2)	MPA (°)
Flexor carpi radialis	1.80	166	89.7	18	6.7
Extensor carpi radialis	8.15	754	76.0	99	16.0
Flexor carpi ulnaris	2.62	245	18.3	134	31.6
Ulnaris lateralis	3.64	337	17.4	194	34.3
Superficial digital flexor	2.45	227	7.5	303	41.6
Deep digital flexor – humeral head	5.61	524	43.8	120	21.6
Deep digital flexor – radial head	0.45	42	10.6	39	32.3
Deep digital flexor – ulnar head	0.96	89	37.2	24	20.3
Common digital extensor	3.16	295	81.4	36	13.3

MFL, mean fiber length; PCSA, physiological cross sectional area; MPA, mean pennation angle.

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biceps brachii appears to be responsible for a net extensor moment at the shoulder through most of stance, while *triceps brachii* is generating an extensor moment at the elbow. In the swing phase, forelimb protraction is driven by the elbow flexors, which generate a flexor moment in early swing, and retraction is driven by the elbow extensors, which generate an extensor moment in late swing (Lanovaz et al., 1999).

The muscles of the forearm move and stabilize the carpal and digital joints. The architectural properties of these muscles have been described (Hermanson, 1997; Hagen et al., 2002; Brown et al., 2003; Zarucco et al., 2004) and are summarized in Table 6.3. The carpal flexors and extensors have longer muscle bellies with shorter tendons than the digital flexors and extensors. The carpal net joint moment acts on the palmar aspect through most of stance, suggesting that tension in the carpal flexors assists the passive tendinous structures in maintaining joint stability (Clayton et al. 1998, 2000a, b). *Flexor carpi ulnaris* and *ulnaris lateralis* have short, highly pennated fibers (pennation angle close to 30°), which results in a large PCSA (Brown et al., 2003). Both of these muscles insert on the accessory carpal bone, which increases their moment arm and facilitates their ability to stabilize the carpus during stance. These muscles show electromyographic activity in late swing and early stance (Jansen et al., 1992) indicating a possible role in stabilizing the carpus through the impact phase. (Note that *ulnaris lateralis* represents the *extensor carpi ulnaris* but, since its distal attachment is to the accessory carpal bone in horses, it acts as a carpal flexor rather than a carpal extensor.)

Flexor carpi radialis and *extensor carpi radialis* (Table 6.3) have long muscle fibers with small pennation angles (less than 20°), a small PCSA, and short tendons (Brown et al., 2003). These qualities suggest a role in initiating and controlling carpal flexion/extension during the swing phase. *Extensor carpi radialis* also shows evidence of a degree of compartmentalization; the proximal portion has a predominance of fast-twitch fibers that can contract powerfully, while the distal portion has more slow-twitch fibers (Hermanson, 1997). The fatigue resistant slow-twitch fibers arranged in series with the tendons of *biceps brachii* and *lacertus fibrosus* are part of the passive stay apparatus of the forelimb. Electromyographic activity in *extensor carpi radialis* is concentrated at the beginning of swing (Jansen et al., 1992) when the elbow and carpus are flexing. At this time, the net joint moment is on the cranial side of the joints (Lanovaz et al., 1999) indicating that the biarticular *extensor carpi radialis* is flexing the elbow to protract the limb and is controlling the inertially driven carpal flexion (Colborne et al., 1997a, b). Rupture of the *extensor carpi radialis* tendon allows the carpus to hyperflex during the swing phase at walk and may cause the horse to stumble or fall at trot because it cannot protract the forelimb rapidly enough. Later in the swing phase, the net joint moment moves to the caudal side of the carpus (Lanovaz et al., 1999), with *flexor carpi radialis* controlling carpal extension and retracting the distal limb in preparation for ground contact.

The digital flexor and extensor muscles (Table 6.3) are characterized by having long tendons relative to their muscle length. However, there are marked differences in muscle architecture and tendon properties of the deep and superficial digital flexor muscles that are indicative of the different roles played by these musculotendinous units in locomotion.

The deep digital flexor (DDF) has three distinct muscle bellies, humeral, ulnar and radial, each of which is innervated by a separate branch of the median nerve suggestive of neuromuscular compartmentalization (Zarucco et al., 2004). The DDF is also compartmentalized morphologically into regions with different lengths of fibers in the range 5–117 mm (Hagen et al., 2002; Brown et al., 2003; Zarucco et al., 2004). The humeral head, which comprises about 74% of total muscle volume, has the longest fibers of any muscle in the antebrachium, but also has some short and medium length fibers. Its tendon is long, but not as long as that of the ulnar head, which also has long fibers but relatively small mass and PCSA compared with the humeral head. In contrast, the fibers in the radial head are short and highly pennated (pennation angle close to 30°). The functions of the DDF are to flex the digital joints during the swing phase and to generate a propulsive force during the second half of stance. Since the DDF muscle has a relatively high percentage of fast-twitch fibers, it is susceptible to fatigue during exercise (Hermanson & Cobb, 1992; Butcher et al., 2007). The DDF tendon, which functions as a positional tendon, has a higher modulus of elasticity than the SDF tendon, which is used for elastic energy storage and release (Birch, 2007). At the walk, the deep head of DDF is active throughout stance with peaks of activity in early stance and late stance (Jansen et al., 1992). Horses with palmar foot pain may prolong the activation of DDF in early stance to move the center of pressure beneath the hoof in a dorsal direction, thereby relieving weight-bearing in the palmar part of the hoof (Wilson et al., 2001).

The superficial digital flexor (SDF) muscle has a much smaller volume than the DDF muscle. However, the fibers are very short

(2–10 mm) and highly pennate (pennation angle up to 60°) (Grandage, 1981; Dimery et al., 1986; Hermanson & Cobb, 1992; Biewener, 1998; Wilson et al., 2001; Brown et al., 2003; Zarucco et al., 2004), resulting in the largest cross-sectional area of the antebrachial muscles and endowing a large force-generating capacity (Hagen et al., 2002; Brown et al., 2003). As a consequence of the large pennation angle, the SDF is capable of minimal shortening and only about 71% of the total muscle force is transmitted to the tendon. The SDF muscle has a high percentage of slow-twitch muscle fibers (Butcher et al., 2007) that are resistant to fatigue. This fiber composition is well suited for its support role as part of the stay apparatus (Swanstrom et al., 2005), and for attenuating high-frequency forces associated with impact (Wilson et al., 2001). The fatigue-resistant, slow-twitch fibers of the SDF tendon act eccentrically or isometrically during stance with changes in length of the musculotendinous unit being due almost entirely to stretching of the elastic tendon (Butcher et al., 2007).

The third interosseous muscle (suspensory ligament) acts as an energy-storing tendon and has an even lower modulus of elasticity than the SDF tendon (Birch, 2007). It supports the metacarpophalangeal (MCP) joint during the stance phase, which is critical to the function of the equine limb. During standing, the suspensory ligament is fully capable of supporting the horse's weight passively (Dyce et al., 1996). It has been speculated that reduction in the muscular function of the equine interosseus began about 15 million years ago, when ancestral horses were increasing in size and moving to the grasslands where efficient overground locomotion was required (Camp & Smith, 1942). Today, muscle fibers comprise about 10% of the suspensory ligament. These muscle fibers are short (~0.88 mm) and highly pennate (pennation angles >45°), which increases the PCSA and contributes to the ability to generate forces but produces little work. The vast majority (95%) of the muscle fibers are type I, and presumably slow-twitch (Wilson et al., 2001; Soffler & Hermanson, 2006). Thus, the muscular content of the suspensory ligament is small but significant and the architecture of the fibers suggests that it contributes to forelimb stability and elastic energy storage during locomotion.

The common digital extensor (CDE) (Table 6.3) and lateral digital extensor muscles have long fibers, small PCSA and long tendons (Brown et al., 2003). The CDE muscle is active in terminal swing at the walk, when it extends the digit in preparation for ground contact, (Jansen et al., 1992). The CDE tendon has a stiffer matrix than the SDF tendon, which may be due to the smaller fibril diameters (Birch, 2007).

As horses bounce over the ground in the trot, canter and gallop, the forelimbs have been estimated to contribute one-third of the energy storage compared with two-thirds in the hind limbs (Biewener, 1998). During trotting, changes in potential and kinetic energy of the horse's center of mass are in phase, which allows the distal limb to make substantial contributions to elastic energy storage (Biewener, 1998). In canter and gallop, the relationship between kinetic and potential energy varies during the stride (Minetti et al., 1999), which limits the ability to store elastic energy in the distal limb. At faster speeds, vertical excursions of the center of mass are reduced and the limb sweeps through a larger angle during its stance phase causing the horse to bounce off the ground more quickly (Farley et al., 1993). The concept of the forelimb acting as a spring implies that changes in joint angles as the limb accepts weight result in shortening of the bony column and stretching of the musculotendinous units. During galloping, the proximal limb from scapula to elbow shortens by about 12 mm, whereas the limb distal to the elbow shortens by around 127 mm. One of the most obvious articular changes is extension of the MCP joint, the magnitude of which can be predicted from vertical ground reaction force (McGuigan & Wilson, 2003). In general, the limb spring is stiffer in larger animals but, within an individual, stiffness of the limb spring is nearly independent of speed.

In the equine distal limb, the suspensory ligament and SDF tendon are primarily responsible for storing and releasing elastic energy. They are subject to high tendon strains as the limb is loaded during stance, especially at the trot. In the canter, overall limb loading decreases with less elastic energy being stored in the SDF tendon, and the DDF tendon being more loaded (Butcher et al., 2007). With an increase in galloping speed, the DDF muscle and its associated tendon assume a greater role in support of the MCP joint, thus relieving some stress on the SDF tendon. The DDF muscle, however, has fast-twitch fibers that contract concentrically and are susceptible to fatigue. When the DDF muscle becomes fatigued, the SDF tendon is over-loaded and predisposed to strain injury (Butcher et al., 2007), which occurs frequently in equine athletes, especially in Thoroughbred racehorses (Peloso et al., 1994). Even though the elastic tendons are highly energy efficient and dissipate only 7% of the stored elastic energy as heat, temperatures around 45°C have been found in the SDF tendon of racehorses after galloping (Birch et al., 1997). Repeated loading of the musculotendinous unit during training and racing may lead to the accumulation of subclinical microdamage if the processes of repair and adaptation are unable to keep up with the rate of tissue damage (Hill et al., 2001).

Hoof angle affects strain distribution between the tendoligamentous structures in the distal limb. Elevation of the heels reduces peak strain in the DDF tendon and increases peak strain in the SDF tendon and suspensory ligament, whereas raising the toe has the opposite effects (Lawson et al., 2007).

Sagittal plane analysis of forelimb kinematics and kinetics

The joints of the horse's forelimb from the elbow distally are more or less constrained to move in a sagittal plane with relatively small amounts of abduction/adduction and internal/external rotation (Thompson et al., 1992; Degueurce et al., 1996). Studies of three-dimensional forelimb kinematics, which will be described at the end of this chapter, have confirmed that flexion/extension is the dominant rotation at the carpal, metacarpophalangeal, proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints (Chateau et al., 2004, 2006; Clayton et al., 2004, 2007a, b; Hobbs et al., 2006). Inverse dynamic analysis has been used to calculate net moments of force, net joint powers and net joint energies for the joints of the equine forelimb at walk and trot (Hjertén & Drevemo, 1993; Clayton et al., 1998, 2000a, b; Colborne et al., 1998; Lanovaz et al., 1999; Hodson et al., 2000; Khumsap et al., 2002, Dutto et al., 2006).

When using skin markers to represent two-dimensional motion of the limb segments, a minimum of two markers per segment is required. Typical marker configurations involve either placing a marker over the center of rotation of each joint or aligning two markers along the long axis of each segment (Fig. 6.4). Intra-limb coordination patterns can be visualized using stick figures or joint angle–time graphs (Fredricson & Drevemo, 1972; Fleiss et al., 1984; Martinez-del Campo et al., 1991; Holmström et al., 1994; Back et al., 1994; Degueurce et al., 1997; Nicodemus & Holt, 2006; Martuzzi et al., 2007; Nicodemus & Booker, 2007).

Skin displacement relative to the underlying bones is always a concern when kinematic studies are based on skin-fixed markers. In the equine forelimb, artifacts due to skin displacement may be small enough to be negligible on the antebrachial and metacarpal segments, but are large enough to alter sagittal plane kinematics significantly on the scapular, brachial, and pastern segments. Since skin displacement has a cyclic pattern, it has been possible to develop mathematical correction algorithms for many of the anatomical locations that are commonly used for marker placement (van Weeren et al., 1990a, b; Sha et al., 2004).

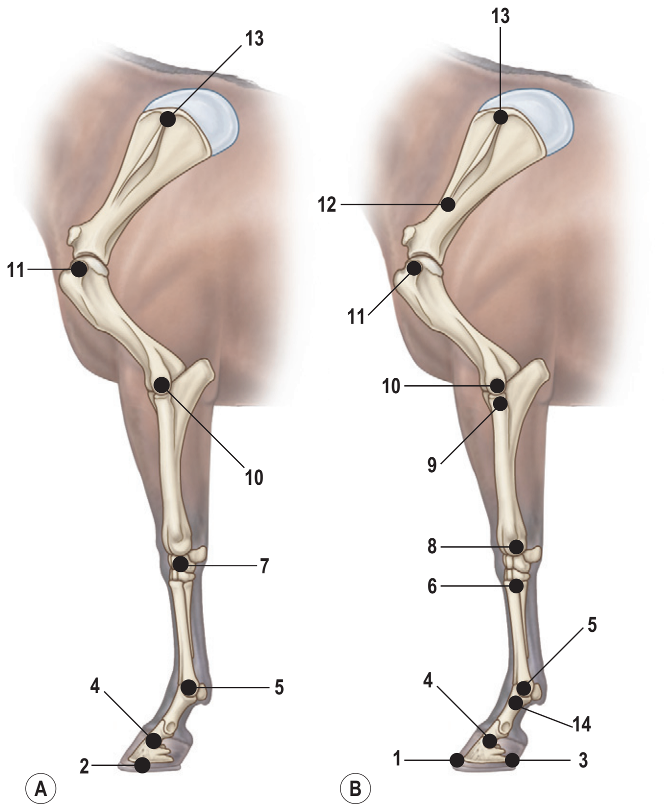

Fig 6.4 Bony landmarks underlying skin-fixed markers in two marker-placement schemes. Left: markers placed over centers of joint rotation with limb segments being represented by lines joining the markers. Right: two markers placed along the long axis of each segment are joined to represent the segment with adjacent segments intersecting at the joints. The hoof may be represented by different combinations of markers with radiographic identification of the center of rotation of the DIP joint relative to the hoof markers. 1, hoof at toe; 2, hoof at mid-lateral distal wall; 3, hoof at heel; 4, hoof at coronary band; 5, distal condyle of metacarpus; 6, proximal metacarpus; 7, ulnar carpal bone; 8, distal radius at lateral styloid process; 9, proximal radius at collateral ligament of elbow; 10, distal humerus at lateral epicondyle; 11, proximal humerus at caudal greater tubercle; 12, distal scapular spine; 13, proximal scapular spine; 14, proximal first phalanx.

The trot

The trot is the most important gait for evaluation of the quality of a horse's movement and for detection of lameness. It is a two-beat gait with the limbs coordinated by diagonal pairs. The diagonal support phases are usually separated by aerial or suspension phases in which all feet are off the ground (Alexander & Jayes, 1978). Back et al. (1995a) used standardized procedures to describe sagittal plane kinematics of the trot in a large group of Warmblood horses. The joint angle–time diagrams were analyzed simultaneously with corresponding stick figures and marker diagrams to create a complete picture of equine forelimb motion at the trot that could be related to limb function (Back et al., 1995a). Variability between horses was evaluated, and the effect of correcting for skin displacement on joint angle–time diagrams was quantified and illustrated graphically (Fig. 6.5) (van Weeren et al., 1990a; Back et al., 1995a).

Scapula

The scapula rotates around a point close to its proximal end with a sinusoidal pattern that corresponds with protraction and retraction of the limb. Maximal protraction precedes initial ground contact, and maximal retraction occurs just after lift-off. Angle–time curves before and after correction for skin displacement are similar, except that maximal retraction and the magnitude of a dip at mid-swing are underestimated without correction for skin displacement (Fig. 6.5).

Shoulder joint

The shoulder joint is extended at initial ground contact, then flexes as the limb is loaded. There is so much skin movement over the scapula and humerus that it is not possible to describe shoulder joint kinematics in late stance or during the swing phase based on skin-fixed markers unless correction procedures are applied (Fig. 6.5) (van Weeren et al., 1990a; Back et al., 1995a). The net joint moment at the shoulder (Fig. 6.6) moves from the cranial to the caudal aspect and back to the cranial (extensor) aspect in early stance, then sustains a cranial (extensor) moment until lift-off due to the action of *biceps brachii* assisted by other extensors of the shoulder (Clayton et al., 1998). The power profile suggests a component of elastic energy storage and release as the joint is loaded in early stance, followed by energy generation on the extensor aspect in terminal stance (Fig. 6.6). Early in the swing phase, there is an extensor moment at the shoulder joint as the extensor musculature acts eccentrically to control flexion, then the net joint moment moves to the flexor side, where the muscles work eccentrically to slow extension and initiate flexion (Lanovaz et al., 1999; Clayton et al., 1998; Singleton et al., 2003).

Elbow joint

The elbow joint extends through most of stance reaching maximal extension near the end of stance (Fig. 6.7). During the swing phase it undergoes a flexion cycle. The amplitudes of flexion and extension do not appear to be influenced much by skin displacement, but without correction the swing phase flexion peak occurs somewhat later (Fig. 6.4) (van Weeren et al., 1990a; Back et al., 1995a).

The net joint moment at the elbow acts predominantly on the caudal (extensor) side during most of the stance phase to resist collapse of the joint under the influence of gravity (Fig. 6.7). This is probably due to the action of *triceps brachii*, which shows electromyographic activity at this time (Korsgaard, 1982; Tokuriki et al., 1989; Robert et al., 1998). The net joint moment shifts to the cranial (flexor) side of the elbow in latestance. The power profile indicates a phase of energy generation and absorption in early stance, followed by a larger phase of energy generation in mid-stance (Fig. 6.7). There is a final period of energy absorption on the flexor aspect as elbow extension slows at the end of stance (Singleton et al., 2003). During the first half of swing, the elbow flexes with a flexor moment (Lanovaz et al., 1999) indicating active flexion driven by the internal tendon of *biceps brachii* and flexor muscles, such as *brachialis* (Tokuriki et al., 1989). There is a short period at midswing when the elbow continues to flex after the net joint moment has moved to the extensor side coinciding with the activation of *triceps brachii* (Korsgaard, 1982; Tokuriki et al., 1989) and, later, *flexor carpi ulnaris* (Korsgaard, 1982; Jansen et al., 1992). The elbow extensor muscles slow flexion (eccentric action) and then actively extend the elbow joint (concentric action) in preparation for ground contact (Lanovaz et al., 1999; Singleton et al., 2003).

Carpal joint

After initial ground contact the carpus quickly snaps into its over-extended (close-packed) position and remains in this stable position during most of stance. At faster trotting speeds, the carpus may snap into its stable position just before initial ground contact

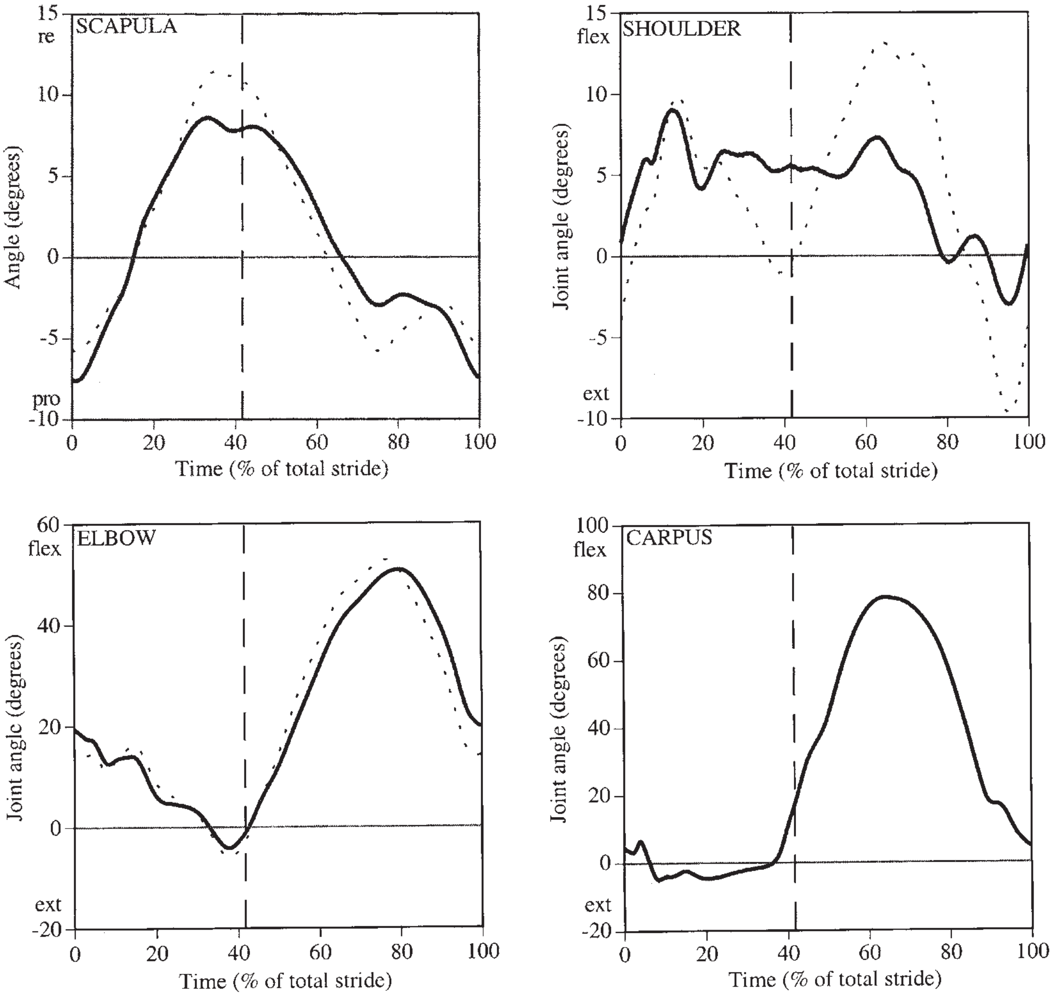

Fig 6.5 Mean joint angle–time diagrams of the forelimb of an individual horse trotting on a treadmill at a speed of 3 m/s before (continuous line) and after (dotted line) correction for skin displacement.

Reprinted from Back, W., Schamhardt, H.C., Savelberg, H.H.C.M,. et al. (1995a) How the horse moves: significance of graphical representations of equine forelimb kinematics. Equine Vet. J. 27, 31–38, with permission from the Equine Veterinary Journal.

(Back et al., 1993, 1995a; Johnston et al., 1997). A functional similarity between the equine carpus and the human knee has been identified (Colborne et al., 1997a,b). After a second extension peak at midstance, the carpus starts to flex and, before the end of stance, initiates rapid flexion that peaks in midswing (Fig. 6.8). Correction for skin displacement does not significantly alter carpal kinematics (Fig. 6.4) (van Weeren et al., 1990a; Back et al., 1995a). The amount of hyperextension during stance increases with speed and is greater when moving on an uphill gradient than when traveling on flat ground at the same speed (Burn et al., 2006).

The net carpal moment is on the palmar aspect through most of stance and peaks around midstance indicating that the deep palmar carpal ligament and other soft tissues on the palmar aspect limit hyperextension (Fig. 6.8) (Clayton et al., 1998). There are small bursts of positive and negative work but, compared with the other forelimb joints, the carpus plays only a small role in energy generation and absorption in the stance phase. However, it does play an important role in supporting the forelimb as a propulsive strut (Smythe et al., 1993).

During early swing, carpal flexion is controlled by an extensor moment (Lanovaz et al., 1999) that is most likely due to the action of passive structures, such as *lacertus fibrosus*, together with activation of *extensor carpi radialis* (Korsgaard, 1982; Jansen et al., 1992). In midswing, the moment at the carpus moves to the flexor side where it controls the whiplash effect in the distal limb that results in carpal extension (Fig. 6.8) (Lanovaz et al., 1999). The flexor moment increases during the last one-third of swing as *flexor carpi ulnaris* is activated (Korsgaard, 1982). In preparation for initial ground contact, elbow extension is accompanied by synchronous extension of the carpus and MCP joint with a proximal to distal transfer of angular momentum.

If the carpal joint of an anesthetized horse is flexed, it snaps back into its stable extended position. The mechanism responsible is known as the *clicking* phenomenon (Alexander & Trestik, 1989). It is due to the eccentric attachments of the collateral ligaments relative to their rotation axis, which makes the joint bistable: it springs either into full extension or strong flexion. Functions attributed to this clicking phenomenon include storage of elastic energy (Rooney, 1990) and damping of oscillations (Mosimann & Micheluzzi, 1969). The moments required to produce these movements *in vitro* are so small compared to those occurring *in vivo* that if the clicking phenomenon plays any role in locomotion, it must be during the swing phase when the limb is not loaded. It is speculative whether the inflection in the carpal flexion curve in early swing that coincides with the first metacarpophalangeal flexion peak is due to a clicking phenomenon and thus enables rapid movement (Palmgren, 1929) contributing to the elegance of gait (Alexander & Trestik, 1989).

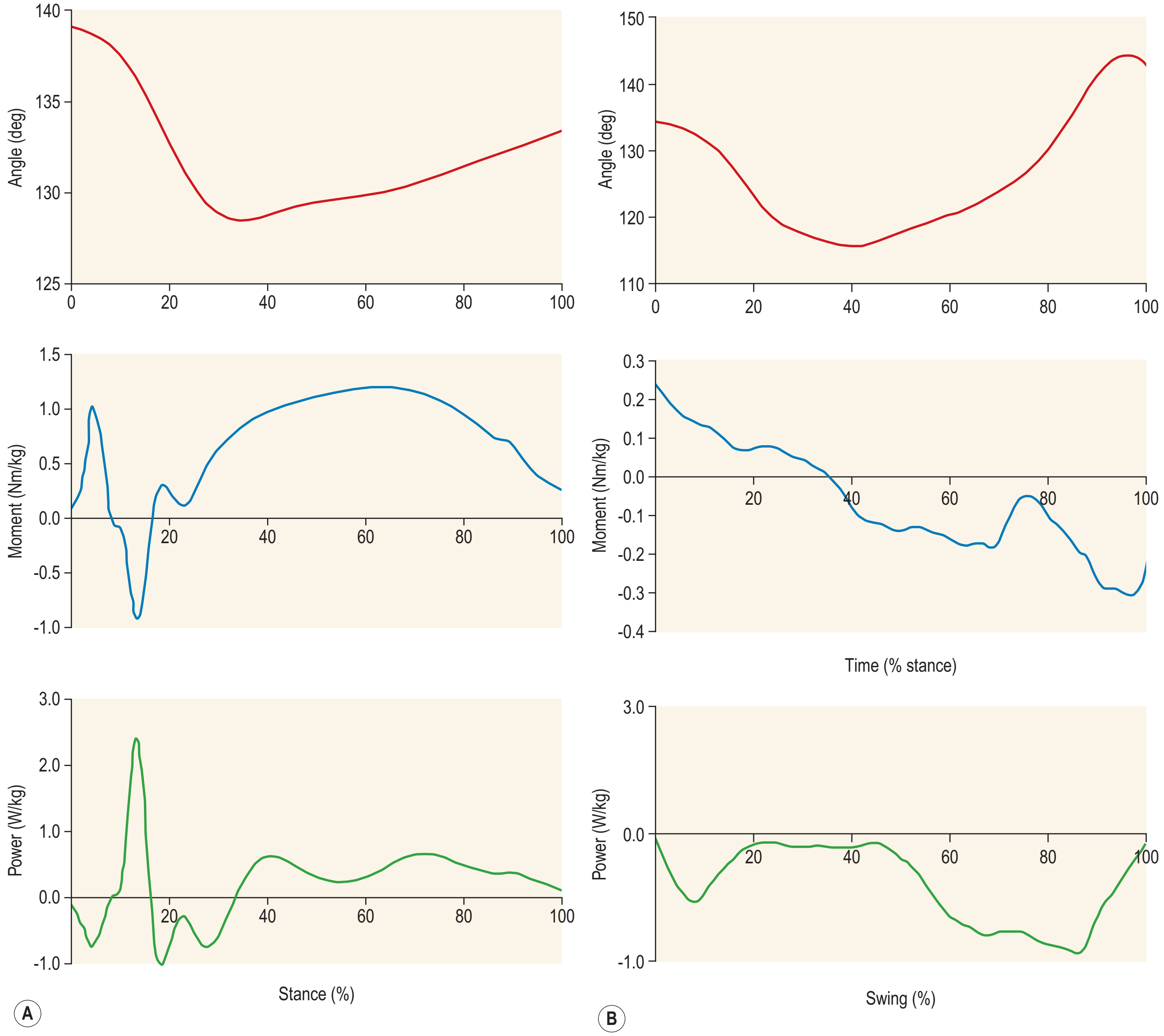

Fig 6.6 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the shoulder joint during the stance phase (left) and swing phase (right) at the trot.

Metacarpophalangeal (MCP) joint

The angle-time graph (Fig. 6.9) shows rapid fetlock extension in early stance peaking at midstance, after which the joint flexes through late stance, sometimes with an inflexion preceding hoof lift. During the swing phase, two flexion peaks are separated by a slight extension, and then, in late swing, the fetlock extends in preparation for ground contact. Correction for skin displacement does not change the MCP joint pattern when the proximal (P1) and middle (P2) phalanges are treated as a single, rigid segment (Back et al., 1995a). The net joint moment (Fig. 6.9) acts on the palmar (flexor) side of the MCP joint during the entire stance phase peaking around midstance (Clayton et al., 1998). This reflects the elastic support of the palmar soft tissues as the MCP joint extends during weight acceptance then flexes for push-off. The SDF tendon, DDF tendon and suspensory ligament experience peak strains around midstance (Riemersma et al., 1988a, b), which corresponds with the time of peak extension of the MCP joint and its maximal palmar moment. Both the SDF and DDF muscles contract actively in the first half of stance (Korsgaard, 1982) to generate a palmar moment at the distal joints (Lanovaz et al., 1999). In addition, the proximal and distal accessory ligaments provide mechanisms for passive support and the generation of a palmar moment later in stance. The net joint power profile of the MCP joint during stance shows almost equal amounts of negative and positive work (Clayton et al., 1998), which is typical of elastic energy storage and release. Energy is absorbed in the first half of stance by the SDF tendon and suspensory ligament then released later as a result of elastic recoil.

In the swing phase, the MCP joint shows two flexion peaks (Fig. 6.9) (Back et al., 1995a; Lanovaz et al., 1999), the first of which occurs soon after toe-off and is an elastic phenomenon due to loading of the SDF tendon and suspensory ligament during the preceding stance phase. The amount of flexion is controlled by a net dorsal moment provided by the digital extensor tendons (Lanovaz et al., 1999). After the elastic rebound, MCP joint flexion

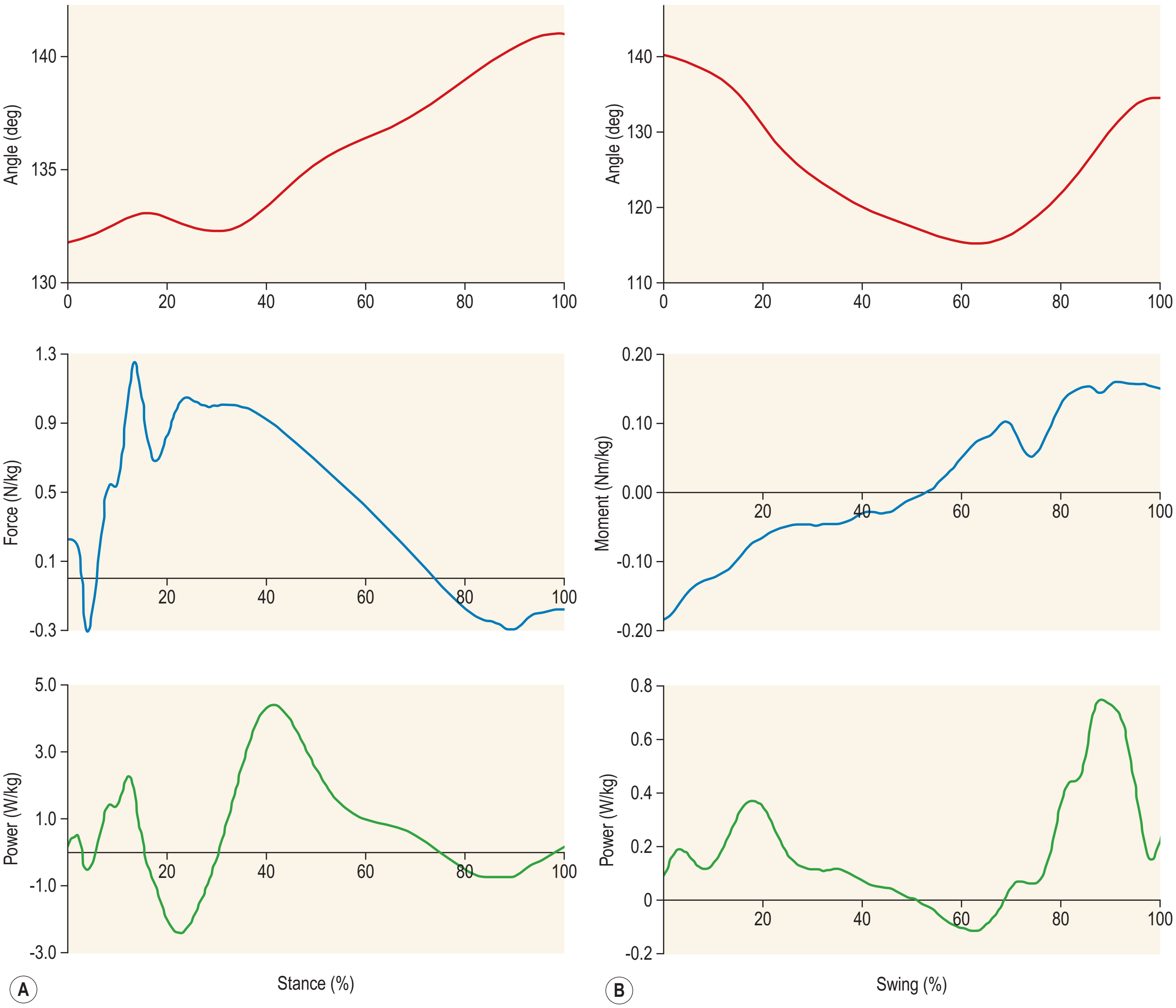

Fig 6.7 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the elbow joint during the stance phase (left) and swing phase (right) at the trot.

can be fully explained by inertial forces: the dip in the joint flexion curve is simply a relative extension of the MCP joint due to rapid flexion of the carpus. When carpal flexion slows, MCP flexion resumes. After midswing, the proximal forelimb is decelerated and a distal transfer of angular momentum results in a whiplash effect in the digit, causing the MCP joint to extend under the control of a net palmar moment. Many of the movements of the MCP joint are driven inertially in the swing phase, with input from the flexor and extensor muscles in late swing that prepares the hoof for ground contact.

Distal interphalangeal (DIP) joint

The DIP joint flexes in early stance reaching maximal flexion before midstance (Fig. 6.10), then extends as the forelimb is retracted. Maximal extension occurs just after heel-off, after which the DIP joint flexes rapidly through early swing (Back et al., 1995a). The net DIP joint moment (Fig. 6.10) acts on the palmar (flexor) side throughout the stance phase, peaking at 63% stance (Clayton et al., 1998). The palmar moment is provided by tension in the DDF tendon acting through its distal accessory ligament combined with tension in the navicular ligaments. The extensor branches of the suspensory ligament are taut to control hoof placement and prevent buckling of the interphalangeal joints in early stance (Jansen et al., 1992). Later in stance, the DIP joint extends against a palmar moment provided by the DDF tendon acting through its distal accessory ligament (Riemersma et al., 1988a, 1998b). In early swing, a small extensor moment controls joint flexion after lift-off (Lanovaz et al., 1999). Since there is little evidence of activity in the extensor muscles at this time (Korsgaard, 1982; Jansen et al., 1992), this can be interpreted as a passive effect of tendinous and ligamentous attachments. As the limb extends in the later part of the swing phase, there is a whiplash effect with angular momentum being transferred distally causing the DIP joint to extend under the control of a flexor moment provided by the DDF muscle (Korsgaard, 1982; Jansen et al., 1992) that slows joint extension prior to initial ground contact.

The power curve (Fig. 6.10) has a burst of energy absorption beginning one-third of the way through stance, peaking around 75% stance when the longitudinal propulsive force is maximal, and

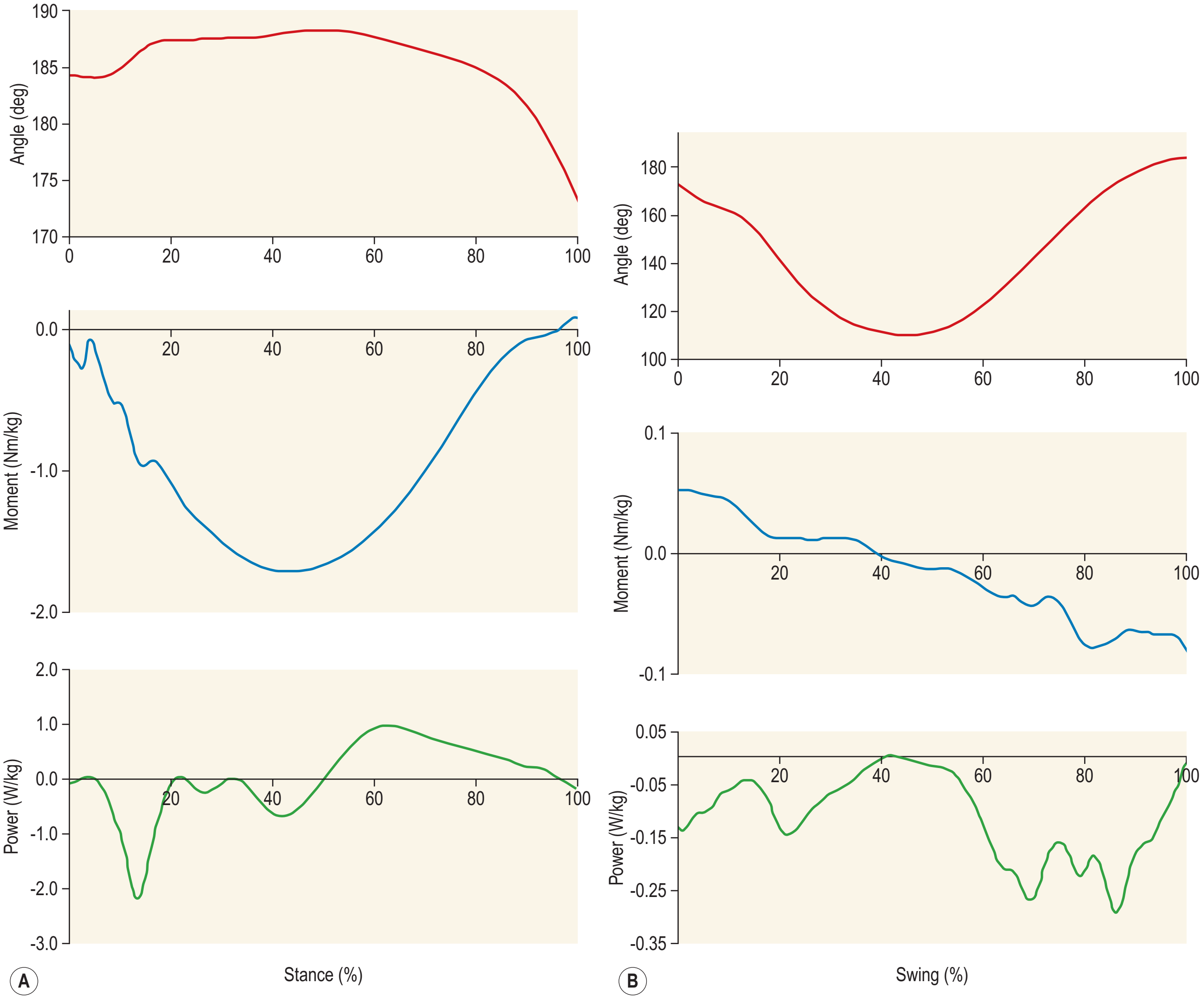

Fig 6.8 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the carpal joint during the stance phase (left) and swing phase (right) at the trot.

continuing into breakover as the DIP joint extends against a palmar moment and acts as an energy damper (Clayton et al. 1998).

Functional interpretation

In the swing phase, forelimb motion has been likened to a pendulum rotating around the proximal scapula (Krüger, 1938). All the forelimb joints have their net joint moment on the cranial/dorsal side at the start of swing (Lanovaz et al., 1999), which is the extensor side for all joints except the elbow. The elbow joint drives the forelimb movements during the swing phase at the trot; at the other joints the muscles act eccentrically to control the motion of the joints (Lanovaz et al., 1999). This is associated with generally low EMG signals during the majority of swing (Korsgaard, 1982; Tokuriki et al., 1989; Jansen et al., 1992). The cranial/dorsal moments gradually decrease in magnitude and move to the caudal/palmar side between 35% and 52% of swing. Peak values of the swing phase net joint moments decrease in a proximal to distal direction, with peak moments at the shoulder and elbow joints being several times larger than those at the distal joints. At the elbow, the net joint moment actively flexes and extends the joint during swing, which has the effect of protracting and retracting the distal limb. In midswing, the forward velocity of the proximal limb is reduced and it may even stop rotating temporarily, which produces a whiplash effect that advances the distal limb rapidly with a proximal to distal transfer of angular momentum that helps to conserve energy during swing (Hildebrand, 1987).

During the stance phase, the net joint moment is on the caudal/palmar side of all joints except the shoulder through most of the stance phase at the trot (Clayton et al., 1998). During impact, the hoof is decelerated and impact shock is absorbed by mechanisms that include shortening of the limb at the distal radius and proximal metacarpus (Hjertén & Drevemo, 1993), with a corresponding deviation in the vertical GRF (Merkens & Schamhardt, 1994). At the same time, rapid flexion of the DIP, MTP, and elbow joints assist in damping the rapid build-up of force at impact (Back et al., 1995c; Johnston et al., 1995). Forelimb mechanics in the stance phase at trot are described in terms of a spring-mass system in which limb loading by the body mass stretches elastic springs that subsequently recoil as the limb is unloaded thus increasing the efficiency of gait (Dimery et al., 1986). The shoulder, elbow, carpal and MCP joints show elastic behavior (Clayton et al., 1998) with the MCP joint being the main site of elastic energy storage and release primarily due to the actions of the SDF tendon and the suspensory ligament.

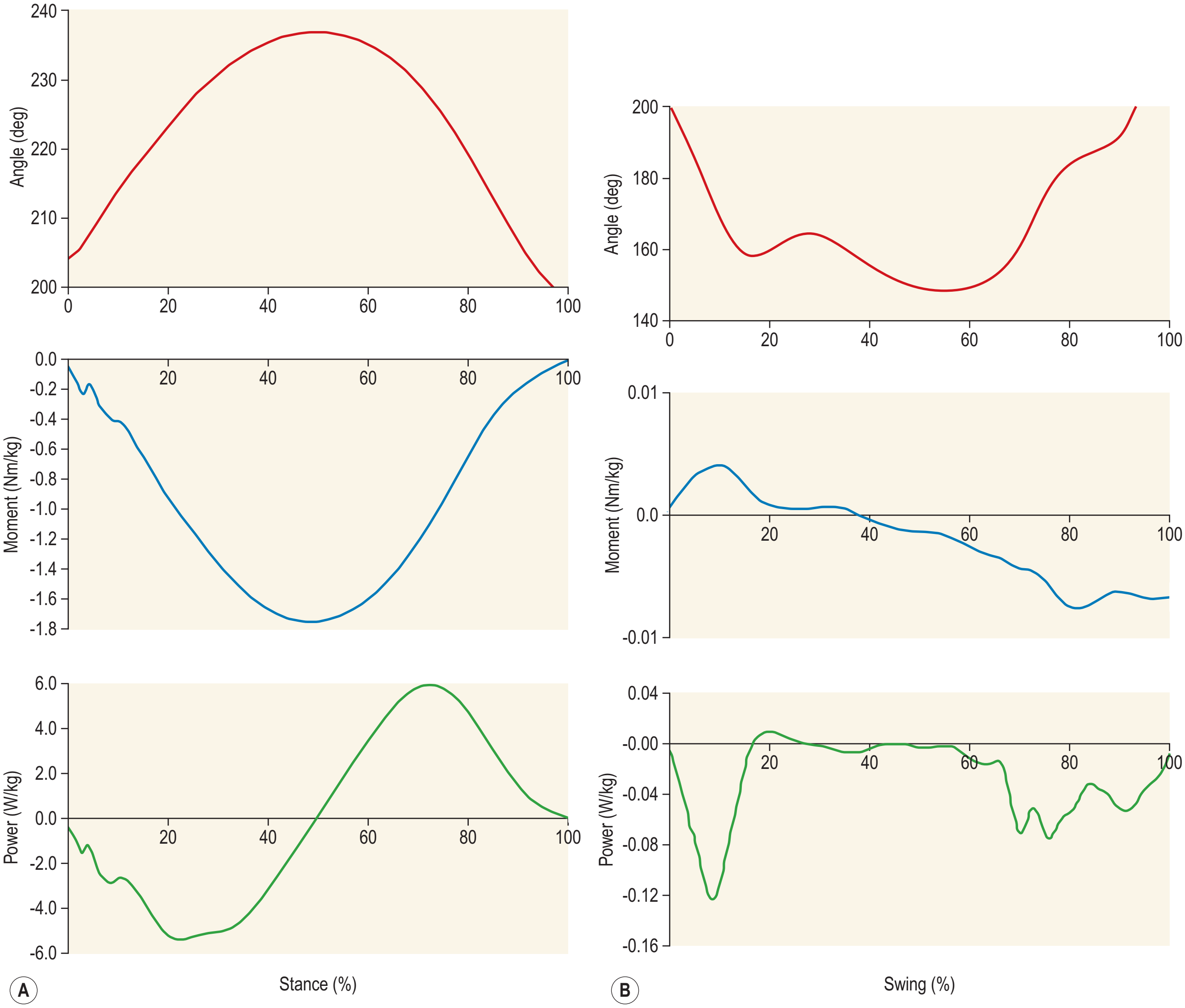

Fig 6.9 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the metacarpophalangeal joint during the stance phase (left) and swing phase (right) at the trot. The pastern segment (proximal and middle phalanges) was treated as a rigid segment.

In addition to their role in energy efficiency, the limb springs act as shock absorbers (Schauder, 1952).

The walk

Like the trot, the walk is a symmetrical gait, but inter-limb coordination is quite different in walking and trotting. The walk is a four-beat gait with a lateral sequence of limb placements and support sequences that always include at least one fore and one hind foot on the ground. The walk does not have a suspension phase and walking mechanics are described in terms of an *inverted pendulum* mechanism that implies an exchange between kinetic and potential energy as the body vaults over the supporting limb (see Chapter 19).

In the literature, forelimb stick figures and joint angle–time diagrams for the walk have been reported for individual horses (Walter, 1925; Krüger, 1937, 1938; Fleiss et al., 1984) and for groups of horses of various breeds (Back et al., 1996; Galisteo et al., 1996; Hodson et al., 2000; Nicodemus & Holt, 2006; Martuzzi et al., 2007). In a comparison of the kinematics of walk (1.6 m/s) and trot (4.0 m/s), Back et al. (1996) showed that the two gaits were similar with regard to the joint motion pattern and swing duration (Table 6.3, Fig. 6.11), but the faster speed of the trot requires the limb to perform the same movements in a shorter time. Similarities in stance distance and swing time at different speeds and in different gaits (Table 6.4) have also been noted in cats and dogs (Grillner, 1975). The limbs cover a shorter distance over the ground during the swing phase at walk and there is less forelimb protraction. Also, the elbow and carpal joints are less flexed in the swing phase at walk, resulting in a longer pendulum and a slower forward motion with less protraction. Apparently, the limbs have to be more loaded during stance and more flexed during swing to enable faster locomotion.

The forelimb MCP joint extension pattern is quite different at walk and trot (Fig. 6.11). In walking, there are two extension peaks that 'melt' together at the trot, which mirrors the vertical ground reaction force traces at walk and trot (Niki et al., 1982; Back et al., 1996; Khumsap et al., 2002). Schryver et al. (1978) explained this phenomenon as a result of the transition from a double to a single limb support. Alexander and Jayes (1978) proposed that this phenomenon was related to mechanical properties of the distal limb

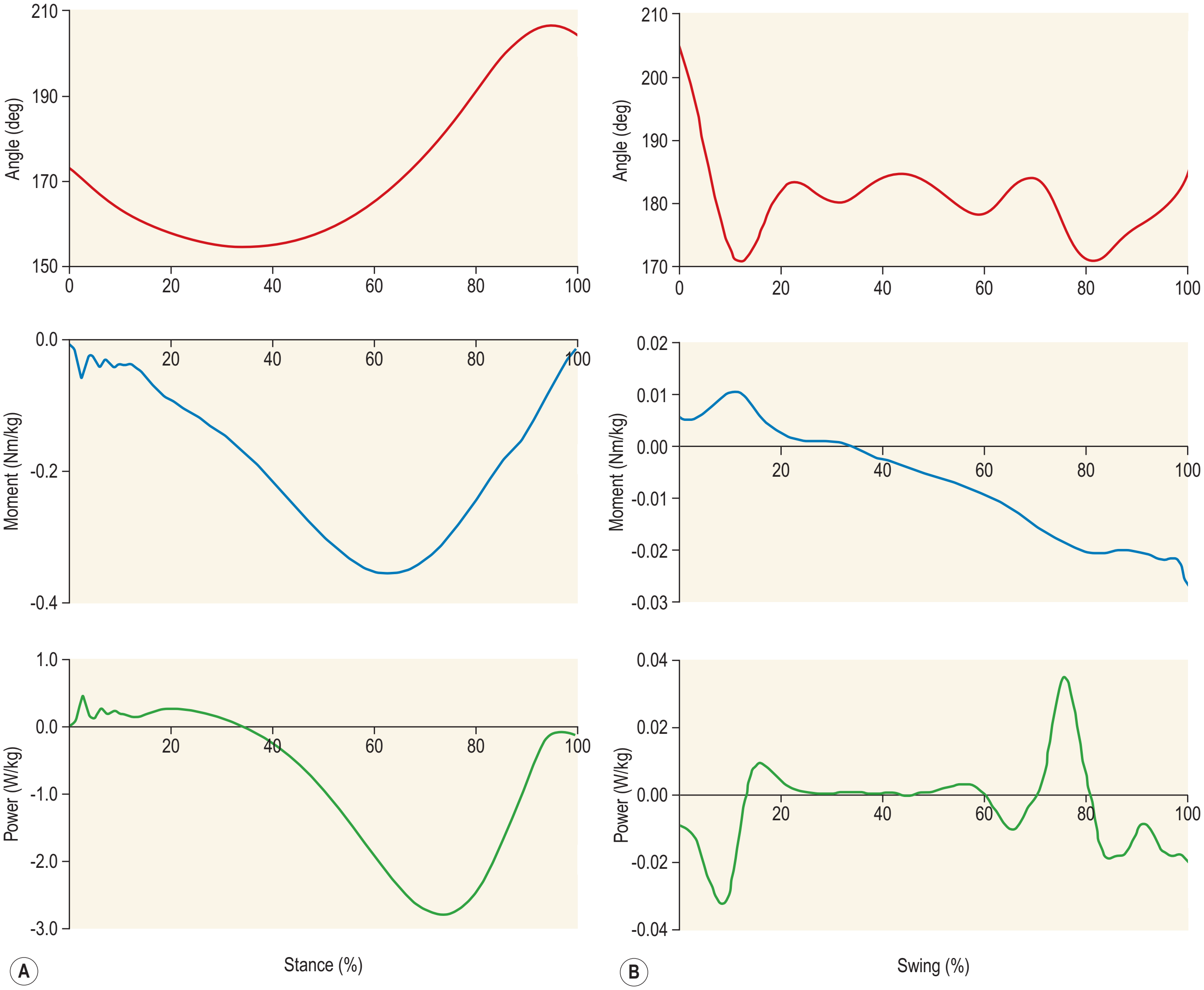

Fig 6.10 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the distal interphalangeal joint during the stance phase (left) and swing phase (right) at the trot. The pastern segment (proximal and middle phalanges) was treated as a rigid segment.

and presented a mathematical model that is capable of describing both possibilities and the gradation between them. Computer simulation experiments have shown that oscillations in the vertical GRF have roughly (not exactly, since muscle stiffness depends on muscle activation) the same frequency in walk and trot (van den Bogert, 1989). Thus, in the trot only one peak occurs since the limb is lifted before the second peak.

Peak vertical ground reaction force is smaller at walk than trot (Ueda et al., 1981; Merkens & Schamhardt, 1994; Schamhardt & Merkens, 1994), which is not surprising since a suspension phase is lacking in the walk. The vertical force has two peaks separated by a slight dip, with the second peak being higher than the first in the forelimbs (Merkens & Schamhardt, 1988; Hodson et al., 2000). As walking speed increases, the heights of both peaks increase. The longitudinal ground reaction force initially has a braking effect, followed by a propulsive effect, with the braking impulse being larger than the propulsive impulse in the forelimbs. Peak braking and propulsive forces increase with walking velocity but the corresponding impulses decrease (Khumsap et al., 2002) as a consequence of a large reduction in stance duration.

The velocity-dependent increases in peak ground reaction forces are thought to be associated with cyclic movements of the head and neck, which undergo larger excursions as velocity increases. The timing of these oscillations is such that the head is lowered as each forelimb provides a braking force and raised as each forelimb provides propulsion. The resulting torque around the cervicothoracic junction tends to rotate the trunk in the opposite direction, which increases the braking effect as the head is lowered and increases the propulsive effect as the head is raised (Khumsap et al., 2002). Therefore, the larger head and neck excursions at faster walking velocities are a mechanism to increase braking in early stance and propulsion in late stance, with the balance between braking and propulsion being maintained regardless of velocity.

During the walking stance phase, retraction of the forelimb is associated with the predominant joint moment being on the caudal/palmar aspect of all forelimb joints except the shoulder, at which the peak moment is considerably higher than at any other joint (Clayton et al., 2000b). The net moment moves to the cranial/dorsal side of all the joints during protraction in early swing, then moves to the caudal/palmar side in late swing as protraction slows and retraction begins.

The entire forelimb shows a net absorption of energy in both stance and swing phases (Clayton et al., 2000a). The elbow provides most of the positive work and is the only joint that shows net

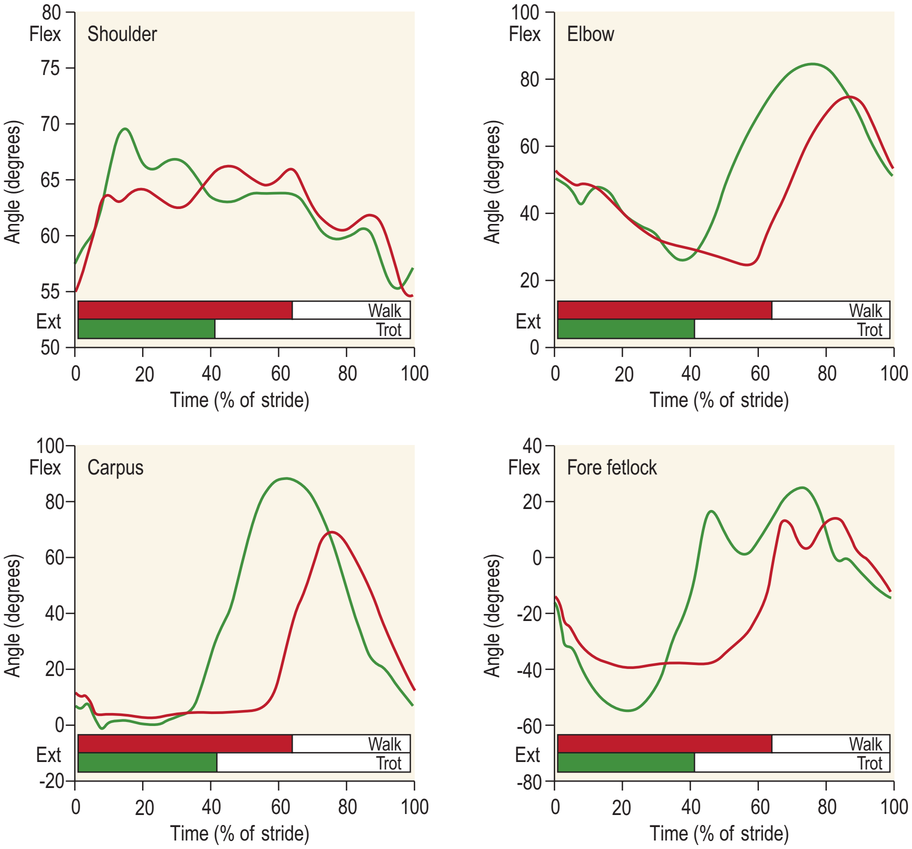

Fig 6.11 Mean joint angle–time diagrams of the forelimb joints of a group of horses walking (1.6 m/s, red line) and trotting (4.0 m/s, green line) on a treadmill. The joint angles are defined as zero when the adjacent bone segments are aligned: extension is negative; flexion is positive. The red bar represents the duration of the forelimb stance phase at walk. The green bar represents the duration of the forelimb stance phase at trot.

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generation of energy over the entire stride. Bursts of energy generation at the elbow occur on the extensor (caudal) aspect in early stance to maintain forward motion of the trunk as the braking longitudinal force increases and on the flexor (cranial) aspect during breakover to initiate swing phase protraction. Extension of the carpus aligns the limb allowing it to act as a supportive strut during stance, but does not play an important role in either energy absorption or generation. A small burst of positive work on the flexor aspect of the carpus at the start of breakover is indicative of an active role in initiating breakover at the walk. The fetlock functions elastically to store and release strain energy during stance, while the coffin joint acts as an energy damper through most of stance with a small burst of energy generation on the flexor aspect during breakover. An increase in walking velocity is not accompanied by a comparable increase in energy generation across the joints of the forelimb (Khumsap et al., 2002).

In the swing phase, peak magnitudes of the net joint powers decrease in a proximal to distal sequence (Clayton et al., 2000a). The elbow is the only joint that has a positive power profile, which is indicative of its role in driving limb protraction and retraction. Power is generated by the elbow flexors in early swing to protract the distal limb and by the elbow extensors later in swing to reverse the direction of limb movement in preparation for ground contact. The shoulder joint absorbs energy during swing. At the carpal and digital joints, net joint powers act to control joint motions that are driven by inertial forces.

The canter

The canter is an asymmetrical gait in which the footfalls of the forelimb pair and hind limb pair occur as couplets. The first limb of the couplet to contact the ground is the trailing limb, the second is the leading limb. Horses use a transverse sequence in which the trailing and leading limbs are on the same side for the fore and hind limb pairs. The sequence of footfalls is trailing hind limb, leading hind and trailing forelimbs together, then the leading forelimb. An aerial (suspension) phase usually follows lift-off of the leading forelimb.

In the literature, the canter has been described at speeds ranging from 3.0 to 11.0 m/s under various circumstances overground and on a treadmill (Clayton, 1994, 1995; Corley & Goodship, 1994; Deuel & Park, 1990; Back et al., 1997). Forelimb kinematic patterns during cantering have been illustrated using stick figures (Walter, 1925; Krüger, 1937, 1938), and have been described in terms of inter-limb timing variables (Deuel & Park, 1990; Clayton, 1993, 1994; Nicodemus & Booker, 2007). Changes in temporal and linear kinematics induced by training have been documented (Corley & Goodship, 1994).

Back et al. (1997) compared the kinematics of the leading and trailing forelimbs of Dutch Warmbloods, cantering on a treadmill at a speed of 7.0 m/s (Fig. 6.12). The leading forelimb is more protracted due to greater elbow flexion, whereas the trailing forelimb is retracted further due to greater caudal rotation of the scapula. Also, the MCP joint is more extended in the trailing forelimb suggesting that this limb is relatively more loaded than the leading forelimb (Sloet et al., 1995), which is in accordance with force plate studies showing higher vertical forces in the trailing forelimb of horses ridden overground at the canter (Niki et al., 1984; Merkens et al., 1993) (Table 6.4). In order to achieve the larger range of protraction and retraction in the trailing forelimb, the carpal joint is more flexed in the swing phase to allow the distal limb to rotate further in the same swing time. Greater carpal flexion has been reported as an effect of training in young Thoroughbreds (Corley & Goodship, 1994) and Quarter Horses (Deuel, 1994).

Table 6.4 Forelimb kinematic variables for horses walking at 1.6 m/s, trotting at 4.0 m/s (Back et al., 1996) and cantering at 7.0 m/s (Back et al., 1997)

Variable	Walk	Trot	Trailing forelimb canter	Leading forelimb canter
Stride duration (s)	1.09 ± 0.06*	0.67 ± 0.03*	0.54 ± 0.02	0.56 ± 0.04
Stance duration (s)	0.69 ± 0.04*	0.27 ± 0.01*	0.18 ± 0.01	0.19 ± 0.02
Stance duration (%)	63.2 ± 1.7*	40.3 ± 1.7*	33.6 ± 1.4	34.5 ± 2.4
Swing duration (s)	0.40 ± 0.03	0.40 ± 0.03	0.36 ± 0.02	0.36 ± 0.03
Scapula				
Angle of max protraction (°)	20.2 ± 1.6*	21.5 ± 1.5*	24.9 ± 2.1#	33.4 ± 3.2#
Angle of max retraction (°)	–22.5 ± 1.7	–22.8 ± 1.5	–31.6 ± 1.8#	–24.7 ± 1.7#
Max pro-/retraction range (°)	42.8 ± 2.5*	44.4 ± 1.7*	56.5 ± 1.6	58.1 ± 3.2
Shoulder joint				
Angle of max extension (°)	53.8 ± 5.9	54.6 ± 4.2	83.7 ± 3.9	80.2 ± 4.4
Angle of max flexion (°)	66.9 ± 4.2*	69.9 ± 5.1*	–0.5 ± 0.8	–2.0 ± 2.2
Range of motion (°)	13.1 ± 1.9	15.3 ± 1.8	25.8 ± 1.6#	23.9 ± 2.3#
Elbow joint				
Angle of max extension (°)	23.4 ± 3.1*	24.5 ± 3.1*	20.1 ± 2.1#	23.5 ± 3.8#
Angle of max flexion (°)	75.2 ± 3.6*	84.7 ± 4.3*	81.9 ± 4.6#	91.2 ± 6.7#
Range of motion (°)	51.8 ± 3.6*	60.2 ± 4.0*	61.8 ± 4.8#	67.7 ± 5.6#
Carpal joint				
Angle of max extension (°)	1.3 ± 2.3*	–2.9 ± 2.6*	–6.7 ± 3.6	–4.4 ± 2.8
Angle of max flexion (°)	69.9 ± 6.2*	87.9 ± 7.4*	83.0 ± 7.9#	91.2 ± 8.3#
Range of motion (°)	68.7 ± 5.7*	90.8 ± 7.1*	89.7 ± 7.0	95.6 ± 8.1
Metacarpophalangeal joint				
Angle of max extension (°)	–41.1 ± 6.1*	–55.9 ± 6.2*	–62.4 ± 4.7	–59.0 ± 8.1
Angle of max flexion (°)	16.5 ± 6.4*	21.3 ± 6.8*	22.8 ± 7.3#	29.1 ± 6.1#
Range of motion (°)	60.2 ± 1.4*	80.6 ± 7.1*	85.2 ± 8.0	88.1 ± 7.5

Joint angles are defined zero when the adjacent bone segments are aligned: extension is negative; flexion is positive. Scapular angle is measured relative to the vertical; protraction angles are positive, retraction angles are negative. Values are mean ± SD.

*Variables that differ significantly between walk and trot ($p < 0.05$).

#Variables that differ significantly between trailing and leading limbs at canter ($p < 0.05$).

Reproduced from Back et al. (1996, 1997).

The gallop

The gallop is an asymmetrical gait in which the footfalls of both the fore and hind limbs occur as couplets, with an aerial (suspension) phase following lift-off of the leading forelimb. The transition from a slow speed canter to the higher speed gallop involves a dissociation of the footfalls of the diagonal limb pair, such that the leading hind contacts the ground before the trailing forelimb in the gallop.

The function of the forelimbs during galloping is to support the forehand as the body mass moves forward and to generate the forces needed for braking and turning. As gallop speed increases, the trailing and leading fore and hind limb pairs act more synchronously, so the gait becomes more like a bound or bunny hop (Leach et al., 1987). Stance duration has been reported to be longer in the leading forelimb than the trailing forelimb (Leach et al., 1987), but Witte et al. (2006) did not find any differences between kinematic variables for trailing and leading forelimbs. Mean stance durations of the forelimbs have been reported to be 131 ms and 77 ms, at speeds of 9.0 m/s and 17.0 m/s, respectively. Although the duration of the suspension phase is independent of speed, overlaps between the limbs decreases with speed and approaches zero at maximal speed (Witte et al., 2006). The intervention of a suspension phase between lift-off of the trailing forelimb and contact of the leading forelimb has been described at very high galloping speeds in some horses (Seder & Vickery, 2003).

Fatigue is associated with changes in limb coordination: the percentage of stride between contacts of the leading hind and trailing

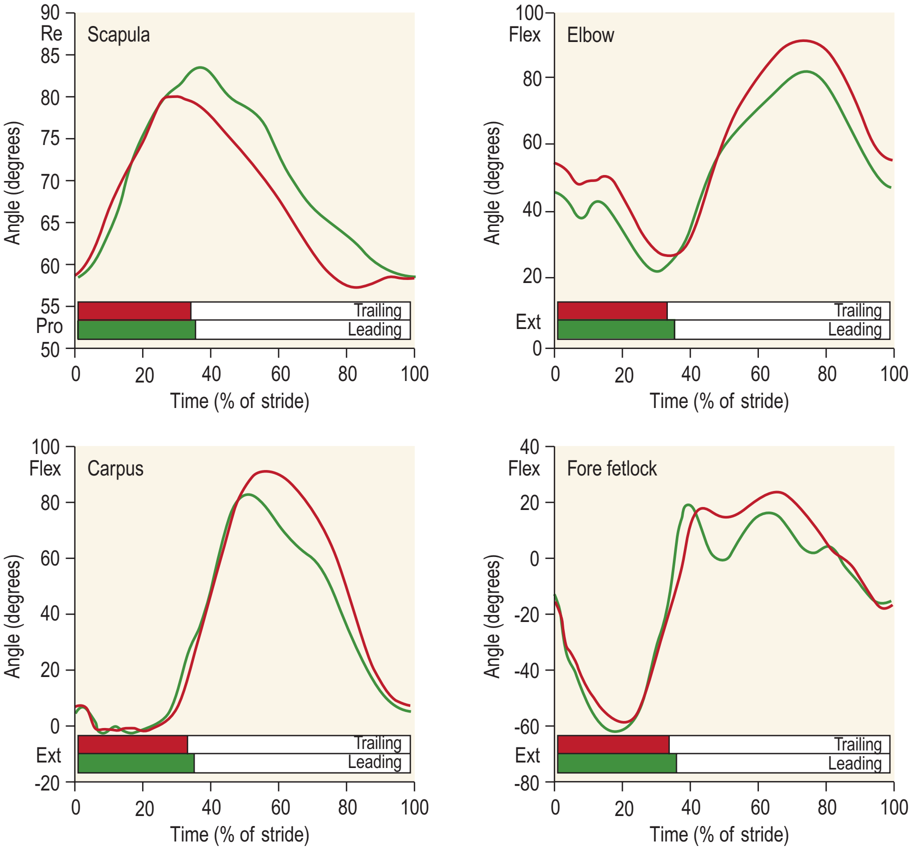

Fig 6.12 Mean joint angle–time diagrams of the leading and trailing forelimbs for a group of horses cantering on a treadmill at 7.0 m/s. Joint angles are defined as zero when the adjacent bone segments are aligned: extension is negative; flexion is positive. The red bar represents the duration of the stance phase in the trailing forelimb, the green bar represents the duration of the stance phase of the leading forelimb. The red bar represents the stance duration of the trailing forelimb, the green bar represents the stance duration of the leading forelimb.

Reprinted from Back, W., Hartman, W., Schamhardt, H.C., Bruin, G. and Barneveld, A. (1995b) Kinematic response to a 70-day training period in trotting Dutch Warmbloods. Equine Vet. J. 18 (suppl.), 127–131, with permission from the Equine Veterinary Journal.

forelimbs decreases, the percentage of stride between contacts of the two hind limbs and the two forelimbs increases, and the percentage of stride occupied by the suspension phase increases (Leach & Sprigings, 1979). It has been suggested that at the end of a race, the fatigued Thoroughbred is at serious risk of developing chip fractures of the carpal bones (Johnston et al., 1999) due to carpal hyperextension, and Burn et al. (2006) have confirmed that carpal hyperextension increases with speed. Furthermore, fatigue of the DDF muscle may overload the SDF tendon and suspensory ligament increasing the risk of injury to the MCP joint and its supporting soft tissues (Butcher et al., 2007).

In Quarter Horses galloping at 13.1 m/s, it was observed that temporal patterns of forelimb motion originated proximal to the elbow and there was a high degree of reciprocity in shoulder joint action in the trailing and leading forelimbs. In the stance phase, maximal carpal extension preceded maximal elbow extension, while in the swing phase, maximal flexions occurred sequentially at the carpus, shoulder and elbow joints (Deuel, 1994).

In the Thoroughbred, forelimb motion in the swing phase has been correlated with racetrack performance and earnings by measuring metacarpal angulation in the sagittal and frontal planes (Seder & Vickery, 2005). In the sagittal plane, peak angulation of the metacarpus to the ground during the swing phase retraction was graded on a scale of 1–5. Grade 1 was forelimbs minimally lifted with little rotation of the metacarpus, which is commonly referred to as a 'daisy cutter action'. Grade 5 was excessive metacarpal rotation with the hoof hitting the elbow, which is described as 'high knee action'. In the frontal plane, abduction ('winging') and adduction ('paddling') of the distal limb was graded on a scale of 1–5 with 1 being very little lateral motion in the forelimbs (i.e. almost vertical) and 5 being excessive lateral motion in the forelimbs. Horses with good forelimb motion (low scores) earned more purse money and had greater stakes level success than horses with bad forelimb motion (high scores). Median earnings per start was 83% higher for horses with good forelimb motion and these horses were 58% more likely to win a graded stakes race than horses with bad forelimb motion.

Three-dimensional kinematics

In two-dimensional kinematic studies, angular data are reported as flexion and extension in the sagittal plane with the estimated centers of joint rotation being used as landmarks for placement of skin markers. Measurements are limited to one degree of freedom in rotation. This type of analysis ignores abduction–adduction and axial rotation of the joints and the role of movements occurring outside the sagittal plane in the pathogenesis of injuries cannot be explored.

An alternative method is to establish a three-dimensional joint coordinate system, based on the axes of the bone segments, which are independent of the joint centers of rotation. Establishment of a joint coordinate system requires the definition of orthogonal frames that are rigid with the bones and numerically described with an orientation matrix by the use of a minimum of three, non-colinear kinematic markers per segment (for details, see Chapters 2 and 19). With this method the three angles of rotation of the joints can be described.

In the equine forelimb, *in vivo* three-dimensional kinematics have been reported on a hard surface at walk (Chateau et al., 2004; Hobbs et al., 2006) and trot (Clayton et al., 2004, 2007a, b) and also at trot on a treadmill (Chateau et al., 2006).

In Chateau et al. (2004) and Hobbs et al. (2006), joint rotations were calculated by use of a cardan sequence x, y, z, also known as the joint coordinate system (JCS) introduced by Grood and Suntay (1983). With this method, flexion-extension is calculated around the transverse axis of the proximal segment of the joint, axial rotation around the vertical axis of the distal segment, and abduction–adduction around a floating axis perpendicular to the two other axes (Fig. 6.13). This technique, which follows the recommendations of the International Society of Biomechanics (Wu & Cavanagh, 1995), clearly defines the axes around which rotations are expressed and preserves the link with clinical and physiological terminology. Clayton et al. (2004, 2007a, 2007b) used a slightly different method in which relative angular motions (helical angle changes) between the segments were calculated using a spatial attitude method (Woltring, 1994). This method, which is also well known and recognized in human biomechanics, calculates the angles around slightly different axes and this can explain small differences between the results of different studies.

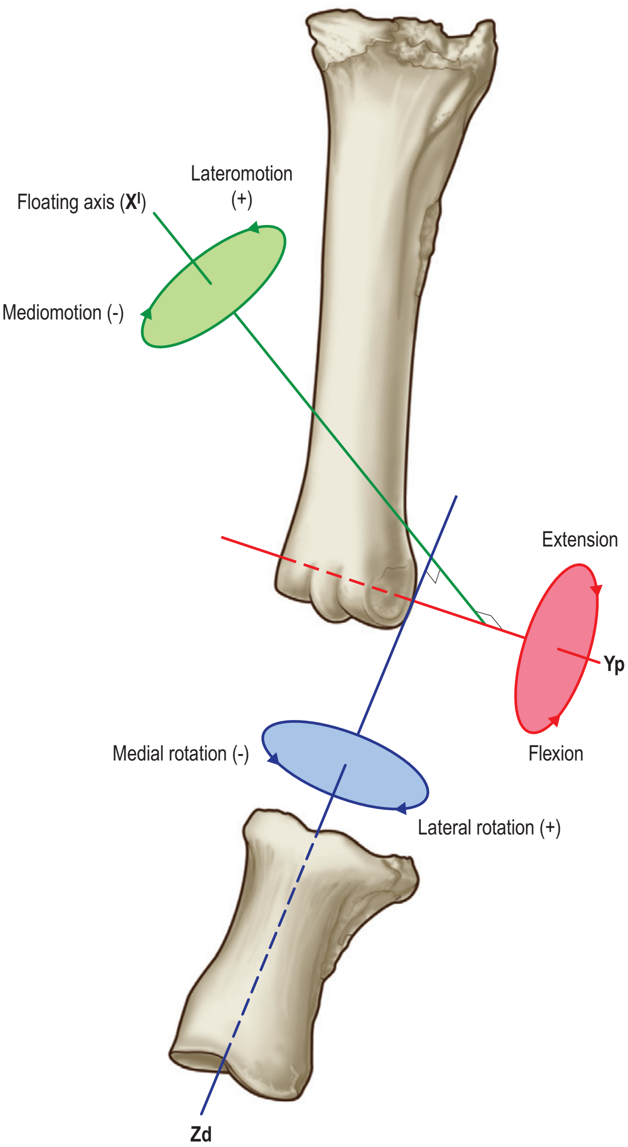

Fig 6.13 Definition of a joint coordinate system (example of the left metacarpophalangeal joint). The flexion–extension angle is calculated around the transverse axis of the proximal segment, the axial rotation angle around the longitudinal axis of the distal segment, and the abduction–adduction angle (collateromotion) around a floating axis perpendicular to the two other axes.

Reprinted from Degueurce, C., Chateau, H., Pasqui-Boutard, V., Pourcelot, P., Audigié, F., Crevier-Denoix, N., Jerbi, H., Geiger, D. and Denoix, J.-M., 2000, Concrete use of the joint coordinate system for the quantification of articular rotations in the digital joints of the horse, Veterinary Rsearch, 31, 297–311, with permission from EDP Sciences.

In the digital joints, abduction and adduction occur passively rather than being generated by abductor or adductor muscles. Denoix (1999) introduced the term *collateromotion* to describe these passive movements: lateromotion is passive abduction and mediomotion is passive adduction.

The majority of equine kinematic studies have been based on tracking markers attached to the skin, which provide a simple and non-invasive method of visualizing joint motion (Clayton, 2007b), but large errors may arise due to soft tissue movement over the underlying bone (Reinschmidt et al., 1997; van Weeren et al., 1986; Crevier-Denoix et al., 2001). In three-dimensional kinematics, those errors are crucial because they counteract the rigid-body theory (Fuller et al., 1997). Besides, skin markers are difficult to use in the distal forelimb because of the small size of P1 and P2. Indeed, those phalanges have usually been modeled as a single, rigid segment, and any motion at the PIP joint has been incorporated into the kinematics of the MCP and DIP joints. To overcome the problems inherent in using surface markers, bone-fixed markers can be used for direct measurement of skeletal motion. This technique provides the most accurate means for determining bone movements (Ramsey & Wretenberg, 1999). Several kinematic studies (Ramsey et al., 2001; Lafortune et al., 1992; Reinschmidt et al., 1997) have implanted bone pins in human subjects, none of whom reported pain or substantial discomfort during the experiments. Bone pins have also been used in horses (van Weeren et al., 1986; Lanovaz et al., 2002; Dyhre-Poulsen et al., 1994). Steinmann pins implanted in a 6 mm canal drilled through the bone cortex, do not have a significant effect on locomotion of horses (van Weeren et al., 1986). More recently, Chateau et al. (2004, 2005, 2006) and Clayton et al. (2004, 2007a, 2007b) have used markers rigidly fixed to the radius, third metacarpal bone, P1, P2 and the hoof wall to characterize three-dimensional rotations of the carpal, MCP, PIP and DIP joints.

Development of non-invasive methods for quantifying three-dimensional motion would be advantageous in a clinical setting. Hobbs et al. (2006) used plaster casts to attach marker clusters to the skin and were able to measure flexion–extension motions, including the PIP joint, with an acceptable degree of accuracy, but not internal–external rotation, which highlights the difficulties in quantifying extrasagittal movements non-invasively (Hobbs et al., 2006).

Three-dimensional forelimb kinematics for locomotion at walk and trot in a straight line

Distal interphalangeal joint

Using three-dimensional kinematics, the pattern of flexion and extension of the DIP joint at the walk and trot (Figs 6.14 and 6.15) has been shown to be very similar to two-dimensional kinematic data (Chateau et al., 2004, 2006; Clayton et al., 2007b). At both gaits, the DIP joint undergoes rapid flexion during impact. After hoof stabilization, the DIP joint continues to flex but at a slower rate. Maximal flexion of the DIP joint precedes maximal extension of the MCP joint. The DIP joint then extends in the second half of stance.

When the horse moves in a straight line, small amounts of extrasagittal motion of the DIP joint have been measured (Table 6.6), mostly during landing and breakover, when the transverse orientation of the foot is changing. At the beginning of the stance phase, the limb is globally adducted, resulting in the lateral aspect of the hoof being closer to the ground and making first contact with the ground. Changes in the mediolateral orientation of the hoof during landing unequivocally affect extrasagittal motions of the digital joints. As the hoof rocks medially, the DIP joint undergoes medial rotation associated with lateromotion that narrows the articular space laterally on the side of the hoof that hits the ground first (Chateau et al., 2004). These findings highlight a major

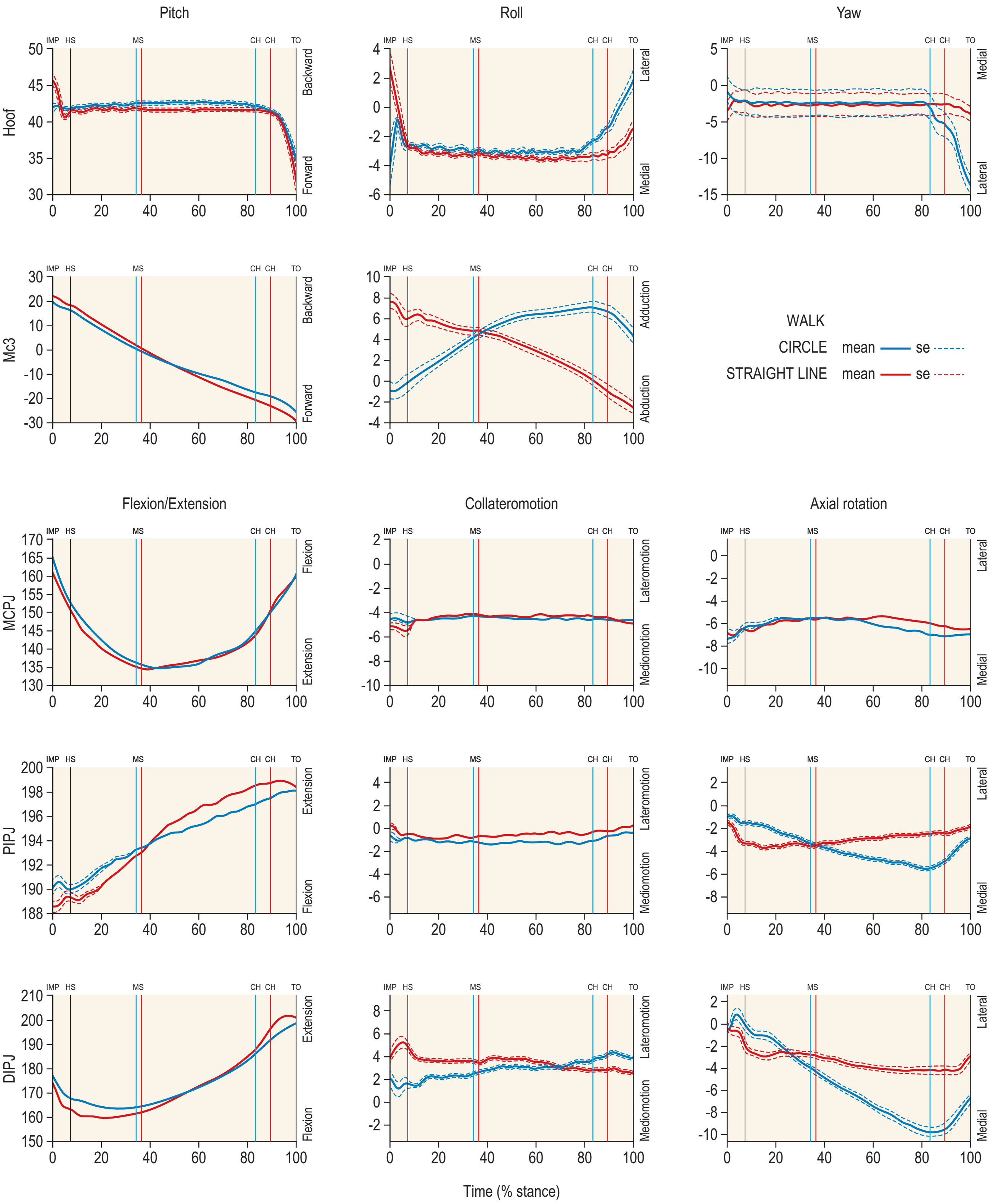

Fig 6.14 Mean attitude angle and joint angle–time diagrams of the left distal forelimb of a group of four horses walking in a straight line and turning sharply to the left. Angles (°) are plotted against time (expressed as % of the stance phase). Mc3, third metacarpal bone; MCPJ, metacarpophalangeal joint; PIPJ, proximal interphalangeal joint; DIPJ, distal interphalangeal joint; IMP, impact; HS, hoof stabilization; MS, midstance; CH, heel-off; TO, toe-off. Note that for some curves the standard error bars are superimposed on the mean values.

Reprinted from Chateau, H., Degueurce, C. and Denoix, J.-M. (2005) Three-dimensional kinematics of the equine distal forelimb : effects of a sharp turn at the walk. Equine vet. J. 37, 12–18, with permission from the Equine Veterinary Journal.

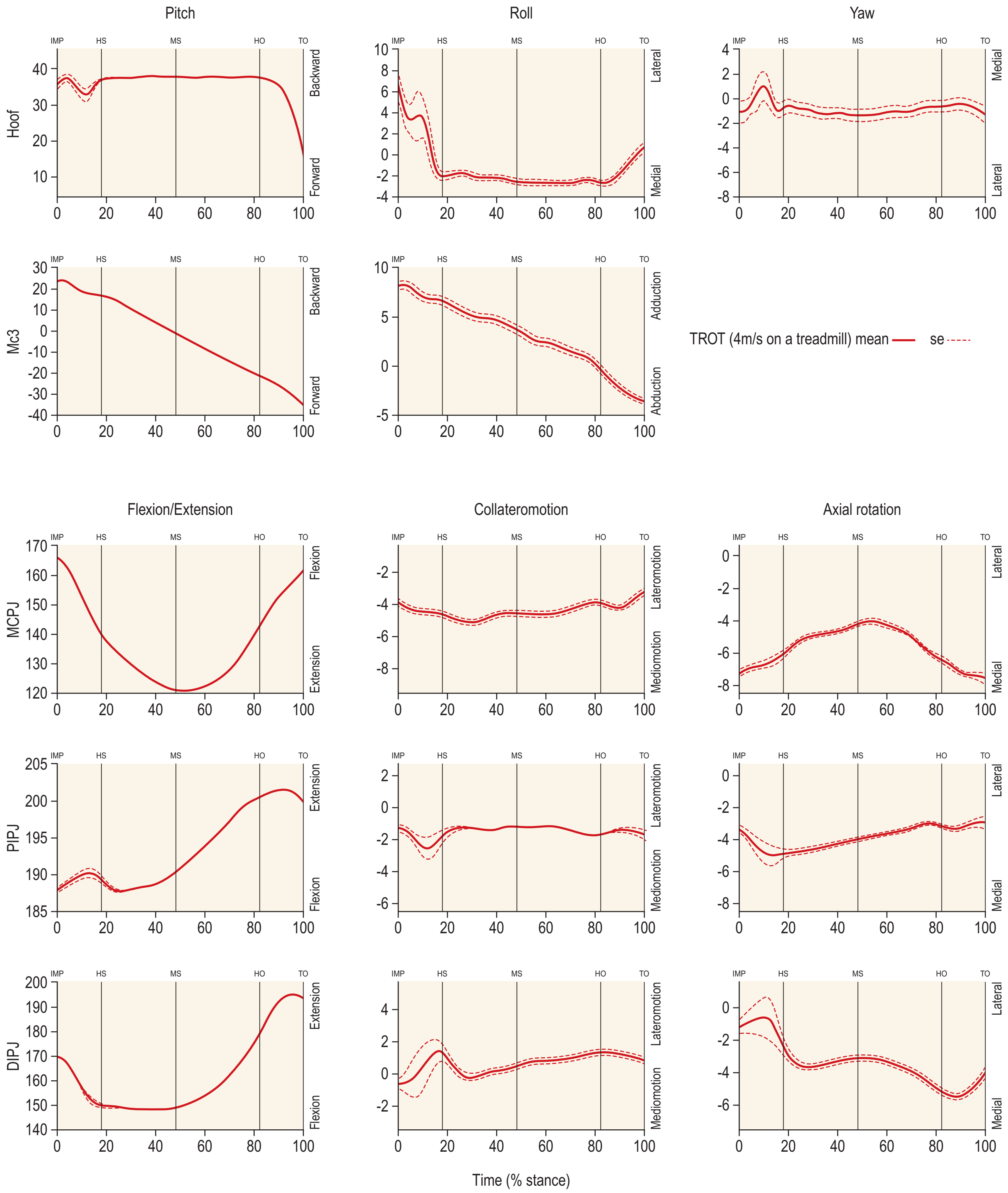

Fig 6.15 Mean attitude angle and joint angle–time diagrams of the left distal forelimb in a group of three horses trotting on a treadmill (4 m/s). Angles (°) are plotted against time (expressed as % of the stance phase). Mc3, third metacarpal bone; MCPJ, metacarpophalangeal joint; PIPJ, proximal interphalangeal joint; DIPJ, distal interphalangeal joint; IMP, impact; HS, hoof stabilization; MS, midstance; CH, heel-off; TO, toe-off). Note that for some curves the standard error bars are superimposed on the mean values.

Reprinted from Chateau H, Degueurce C, Denoix J-M. (2006) Three-dimensional of the distal forelimb in horses trotting on a treadmill and effects of elevation of heel and toe. Equine vet. J. 38, 164–169, with permission from the Equine Veterinary Journal.

Table 6.5 Mean value ± SD for range of motion in flexion and extension of the digital joints of the left forelimb of four horses walking in a straight line on a hard track at 1.3 m/s (**Chateau et al., 2004**) and three horses trotting on a treadmill at 4.0 m/s (**Chateau et al., 2006**)

	Walk	Trot
MCPJ ext	–27.6 ± 3.3	–45.7 ± 7.0
MCPJ flex	24.9 ± 3.1	41.2 ± 8.2
PIPJ flex	–0.9 ± 0.9	–1.7 ± 2.6
PIPJ ext	10.0 ± 2.5	14.3 ± 2.8
DIPJ flex	–16.4 ± 3.1	–21.7 ± 3.8
DIPJ ext	42.4 ± 4.4	45.6 ± 5.5

MCPJ, metacarpophalangeal joint; PIPJ, proximal interphalangeal joint; DIPJ, distal interphalangeal joint.

Reproduced from Chateau et al. (2004, 2006).

Table 6.6 Three-dimensional motion of the hoof, third metacarpal bone and digital joints in three horses trotting on a treadmill at 4.0 m/s (**Chateau et al., 2006**). Values are mean and (SD)

		Landing	Weight bearing	Breakover
Hoof	Pitch	1.7 (4.8)	0.1 (0.9)	–20.3 (6.7)
	Roll	–8.9 (4.4)*	–1.2 (1.0)	3.4 (1.6)*
	Yaw	0.9 (2.7)	–0.4 (1.2)	–0.7 (3.0)
Mc3	Pitch	–6.0 (1.8)	–38.1 (3.8)	–13.5 (4.3)
MCPJ	Flex-Ext	–25.6 (3.7)*	2.8 (5.5)	18.3 (6.7)
	Collat	0.8 (1.7)*	1.0 (1.5)*	0.5 (2.5)
	Axial rot	1.2 (1.6)*	–0.4 (1.0)	–1.1 (1.2)*
PIPJ	Flex-Ext	1.3 (2.6)*	11.5 (2.7)*	–0.9 (1.4)*
	Collat	–0.4 (2.0)	–0.2 (1.4)	0.2 (1.4)
	Axial rot	–1.5 (2.1)*	1.7 (1.6)*	0.2 (0.5)
DIPJ	Flex-Ext	–19.3 (5.0)*	31.3 (7.1)*	11.9 (5.8)*
	Collat	1.4 (3.3)*	0.5 (2.3)	–0.5 (1.6)
	Axial rot	–1.7 (3.0)	–2.3 (2.9)*	1.3 (1.5)*

*Values differ significantly ($p < 0.05$) between the beginning and the end of the period.

Mc3, third metacarpal bone; MCPJ, metacarpophalangeal joint; PIPJ, proximal interphalangeal joint; DIPJ, distal interphalangeal joint.

Landing is from impact to hoof stabilization; Weight bearing is from hoof stabilization to heel-off; Breakover is from heel-off to toe-off.

For segment angles, pitch angle around the transverse axis is positive during backward (palmar or plantar) rotation; roll angle around the longitudinal axis is positive during lateral inclination; and yaw angle around the vertical axis is positive during medial rotation of the segment. For joint angles, lateromotion (passive abduction) and lateral rotation are designated positive.

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function of the digital joints in compensating for asymmetrical hoof placement. Interestingly, medial rotation and lateromotion of the DIP joint were coupled, which has been observed during asymmetric loading of isolated forelimbs in other studies (Denoix, 1999; Chateau et al., 2002). When a heel wedge was applied unilaterally, the DIP joint showed collateromotion with narrowing of the joint space on the side of the wedge, together with axial rotation away from the raised side. The same association of movement has also been reported at the start of breakover with a combination of lateromotion (abduction) and medial (internal) rotation (Chateau et al., 2004; Clayton et al., 2007b).

Proximal interphalangeal joint

The PIP joint (Figs 6.14 and 6.15, Table 6.5) flexes in early stance reaching maximal flexion at about 14% of stance (Chateau et al., 2004; Clayton et al., 2007b). This movement is brief and slight in walking horses (less than 1°) and almost comparable at the trot (about 1.7°). Then, the PIP joint extends through most of stance until the start of breakover. Chateau et al. (2004, 2006) reported the mean amplitude of this extension to be 10° ± 2.5° at walk and 14.3° ± 2.8° at trot, while Clayton et al. (2007b) reported 9.4° ± 1.7° at walk and 8.5° ± 0.6° at trot. The results confirm that flexion and extension of the PIP joint cannot be neglected in biomechanical models of the distal portion of the forelimbs. In horses walking in a straight line, the PIP joint accounts for approximately 5% of the entire interphalangeal flexion (0.9° of PIP joint flexion vs. 16.4° of DIP joint flexion) and 19% of the entire interphalangeal extension (10° of PIP joint extension vs. 42.4° of DIP joint extension). The substantial involvement of the PIP joint in digital extension could explain why arthrodesis is sometimes followed by a worsening of navicular conditions (Martin et al., 1984), since loss of extension following PIP joint arthrodesis is likely to be compensated primarily by the DIP joint.

For locomotion in a straight line, extrasagittal motions of the PIP joint are minimal (Figs 6.14 and 6.15, Table 6.6). Chateau et al. (2004) did not detect a significant pattern in collateromotion for the PIP joint. Internal rotation of P2 relative to P1 occurs during landing, concurrent with the medial rocking motion of the hoof (Chateau et al., 2004; Clayton et al., 2007b). During breakover, lateral rotation of the PIP joint occurs in association with lateral rocking motion and lateral rotation of the hoof (Chateau et al., 2004).

Extrasagittal movements of the PIP joint, like those of the DIP joint, occur mainly during landing and breakover when horses walk in a straight line. The three-dimensional motions of the PIP joint, especially axial rotation, coupled with asymmetric landing of the hoof at impact, should be taken into account, even when a horse is walking in a straight line, to explain concussion of the joints and pain that may result from mediolateral imbalances.

Metacarpophalangeal joint

During the stance phase, the MCP joint (Figs 6.14 and 6.15, Table 6.5) undergoes extension and then flexion. As already observed in two-dimensional kinematic studies at the walk, extension is prolonged with a tendency toward two peaks separated by a slight dip, whereas in trot there is a single cycle of extension. No particular pattern of collateromotion was detected for the MCP joint during stance (Chateau et al., 2004) but P1 twisted laterally relative to the third metacarpal bone during extension and medially during flexion. This is in contrast to the study of Clayton et al. (2007a), in which all horses showed lateromotion during stance. The difference between studies is a consequence of the alignment of the segmental coordinate systems. If the coordinate system of P1 used by Clayton et al. (2007a) is rotated externally around its longitudinal axis by

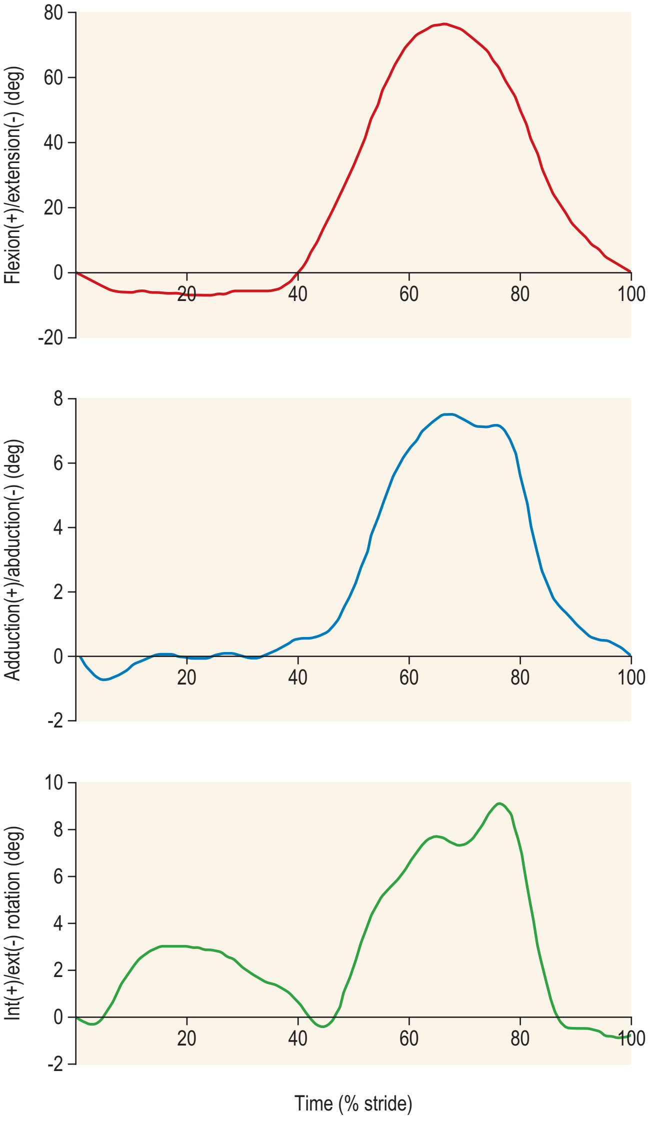

Fig 6.16 Mean joint angle–time graphs for three-dimensional carpal joint motion of three horses trotting overground at 3.1 m/s.

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10°, there is close agreement in collateromotion between the two studies.

Carpal joint

In horses trotting at 3.1 m/s, three-dimensional carpal kinematics show low variability between strides within a horse but greater variability between horses, especially in the amount of carpal flexion at the instant of lift-off which influences the amount of flexion–extension assigned to the stance and swing phases (Clayton et al., 2004). In early stance, the carpus extends and the metacarpus rotates internally relative to the radius as the joint assumes its close-packed position (Fig. 6.16). This position is maintained with only minor oscillations until just before lift-off, when the carpus begins a cycle of flexion combined with a little internal rotation that continues until midswing (Fig. 6.16). The direction of abduction–adduction varies between horses. Ranges of carpal motion during trotting are: flexion–extension 15° ± 6° in stance and 76° ± 13° in swing; abduction–adduction 5° ± 1° in stance and 13° ± 6° in swing; and axial rotation 4° ± 0° in stance and 11° ± 7° in swing (Clayton et al., 2004).

Three-dimensional forelimb kinematics when turning sharply at walk

Three-dimensional kinematics of the distal forelimb reveal small amounts of collateromotion and axial rotation when the horse moves in a straight line (Table 6.6). During turning, especially on a hard surface, frontal plane alignment between the hoof and the third metacarpus is disrupted and the digital joints must compensate for this misalignment. Pathogenesis of several digital injuries is believed to be connected with these extrasagittal movements and examination of the horse on a circle at the walk and trot is useful to further characterize a lameness because horses affected with specific digital injuries are often more lame with the involved limb on the inside of the circle (Swanson, 1988).

Motions outside the sagittal plane in the digital joints have been studied *ex vivo* during asymmetric loadings of isolated forelimbs. Intra-articular injection of a colored solution was used to evaluate variations in the contact areas between articular surfaces as a consequence of asymmetrical hoof placement (Denoix, 1999). Radiographic assessment has also been proposed (Caudron et al., 1998), but this method was limited to the measurement of combined movements between the PIP and DIP joints and carries a risk of misinterpretation due to the geometrical projection on a single plane. Changes in the transverse orientation of the foot quantified *ex vivo* using three-dimensional kinematics (Chateau et al., 2001, 2002) have shown that asymmetric placement of the foot induced a collateromotion (narrowing of the articular space) in the direction of the elevated part of the foot and an axial rotation in the opposite direction in the digital joints. However, *in vitro* studies or quasi-static radiographic studies cannot merely be extrapolated to the moving horse.

More recently, three-dimensional motion of the digital joints has been measured *in vivo* as horses turned sharply at the walk (Fig. 6.14, Table 6.7) (Chateau et al., 2005). In this study, four horses equipped with bone-fixed markers on the left forelimb were led in hand around a left turn approximately 1.5 m in diameter with the instrumented left forelimb on the inside of the turn. The three-dimensional kinematics, calculated using the principle of the JCS, were compared with data from the same horses walking in a straight line (Table 6.7, Fig. 6.14).

Landing (from first impact to hoof stabilization)

For motion in a straight line, the four horses studied by Chateau et al. (2005) showed global adduction of the distal limb at impact, which lowered the lateral aspect of the hoof and resulted in initial contact on the lateral side, followed by a medial rocking motion. When moving through a turn, the inclination of the third metacarpal bone in the transverse plane (roll angle) shows that the distal part of the limb on the inside of the turn is substantially more abducted at impact and landing is flat-footed, with little subsequent rocking motion of the hoof.

When the hoof lands during locomotion in a straight line, the DIP joint undergoes a lateromotion and a medial rotation associated with the medial rocking motion of the hoof. During flat-footed landing in a turn, however, the DIP joint underwent no significant movement of collateromotion or axial rotation. At the PIP joint, internal rotation occurs during landing when moving a straight line but not when turning.

Bearing phase (from hoof stabilization to heel-off)

In a turn, the inside forelimb is abducted at the beginning of the stance phase because the horse places this limb toward the center

Table 6.7 Three-dimensional motion of the hoof, third metacarpal bone and digital joints in four horses walking in a straight line and around a small circle (Chateau et al., 2005). Values are mean and (SD)

		Landing (IMP–HS)		Weight bearing (HS–HO)		Breakover (HO–TO)	
		Straight line	Circle	Straight line	Circle	Straight line	Circle
Hoof	Pitch	−4.1 (5.4)*	0.4 (6.0)#	0.0 (1.0)	0.4 (1.1)	−9.8 (2.9)*	−8.2 (4.1)*
	Roll	−6.2 (2.7)*	0.7 (3.8)#	−0.6 (0.9)	0.2 (0.8)	1.9 (1.3)*	4.6 (2.8)*#
	Yaw	0.9 (3.7)	−2.4 (4.2)	−0.1 (0.9)	−0.1 (2.6)	−1.3 (4.5)	−11.3 (8.6)*#
Mc3	Pitch	−3.7 (1.7)*	−3.5 (1.0)*	−41.0 (4.4)*	−33.6 (3.7)*#	−5.8 (1.4)*	−7.7 (3.0)*#
	Roll	1.2 (1.2)*	−0.6 (1.1)#	−7.5 (5.5)*	7.3 (5.2)*#	−1.5 (1.0)*	−2.7 (1.8)*#
MCPJ	Flex-Ext	−10.9 (4.6)*	−12.2 (5.1)*	−0.1 (3.4)	−7.4 (5.9)*#	9.0 (1.9)*	13.4 (3.4)*#
	Collat	0.2 (1.7)	−0.1 (0.7)	0.3 (0.8)	0.0 (0.7)	−0.3 (0.9)	0.0 (1.0)
	Axial rot	0.2 (0.9)	1.3 (0.7)*#	0.2 (1.3)	−1.1 (0.5)*#	−0.3 (0.8)	0.2 (0.6)
PIPJ	Flex-Ext	0.9 (1.8)	0.9 (4.2)	9.2 (2.4)*	6.5 (2.1)*#	−0.2 (0.6)	1.3 (0.9)*#
	Collat	−0.6 (1.5)	−0.2 (0.9)	0.4 (1.1)	−0.3 (0.8)	0.5 (0.7)*	0.8 (0.6)*
	Axial rot	−2.2 (1.1)*	−0.5 (1.3)#	1.1 (1.7)*	−4.0 (1.7)*#	0.6 (0.8)*	2.9 (0.8)*#
DIPJ	Flex-Ext	−12.1 (2.2)*	−9.3 (4.8)*#	33.1 (3.4)*	18.4 (5.9)*#	5.1 (2.5)*	12.3 (4.4)*#
	Collat	0.9 (2.4)*	−0.4 (2.2)#	−1.9 (1.6)*	2.0 (1.8)*#	−0.3 (0.8)	0.2 (1.1)
	Axial rot	−1.7 (1.6)*	1.0 (2.0)#	−2.2 (2.5)*	−10.2 (3.9)*#	1.5 (1.6)*	3.6 (1.3)*#

*Values differ significantly (*p* <0.05) between the beginning and the end of the period.

#ROM differs significantly (*p* <0.05) from the straight line.

Mc3, third metacarpal bone; MCPJ, metacarpophalangeal joint; PIPJ, proximal interphalangeal joint; DIPJ, distal interphalangeal joint; IMP, impact; HS, hoof stabilization; HO, heel-off; TO, toe-off.

Landing is from impact to hoof stabilization; Weight bearing is from hoof stabilization to heel-off; Breakover is from heel-off to toe-off.

For segment angles, pitch angle is positive during backward rotation, roll angle is positive during lateral inclination and yaw angle is positive during medial rotation of the segment. For joint angles, lateromotion (passive abduction) and lateral rotation are designated positive.

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of the circle. During the rest of stance, the inside forefoot is immobile on the ground and the horse's body mass moves over the limb in the direction of the turn. The third metacarpal bone undergoes large movements relative to the hoof in the transverse plane (Chateau et al., 2005) showing an adduction that is maximal when the heels leave the ground (Fig. 6.14).

Because the third metacarpal bone is more abducted at the beginning of stance in the limb on the inside of a turn, the DIP joint initially shows a combination of mediomotion (adduction) and lateral rotation. Adduction of the limb during the stance phase with the hoof flat on the ground, reverses the direction of these movements and the DIP joint undergoes a combination of lateromotion (2.0 ± 1.8) and medial rotation (10.2 ± 3.9) (Chateau et al., 2005). During this movement, the articular space becomes pinched laterally and P3 rotates medially relative to P2. In other words, collateromotion occurs in the direction of movement, while axial rotation occurs in the opposite direction. Interestingly this combination of articular rotations is the same as those observed *in vitro* during asymmetric loadings of the limb (Caudron et al., 1998; Denoix, 1999; Chateau et al., 2002; Viitanen et al., 2003).

The changes in direction of DIP joint angulation are easily seen on the angle-time diagrams when the curves for collateromotion and axial rotation intersect (Fig. 6.14). The effects of these angular changes should be considered during examination of a lame horse on a tight circle at the walk because the cranial and caudal parts of the stance phase do not have the same biomechanical consequences on the three-dimensional motion of the interphalangeal joints and thus on the stress imposed on the collateral ligaments.

Alterations induced by limb adduction also induce a substantial involvement of the PIP joint (Chateau et al., 2005), which undergoes medial rotation during the bearing phase in a turn. At heel-off, the PIP joint contributes 33% of the total amount of axial rotation in the digital joints during a sharp turn compared with 10% for the MCP joint and 57% for the DIP joint. The amount of axial rotation was greater than the amount of flexion at the DIP joint during sharp turns, which demonstrates the strong involvement of this joint in movements that occur outside the sagittal plane. These results corroborate clinical observations related to pathological conditions of this joint showing that degenerative diseases of the PIP joint occur most frequently in horses that make tight turns and rapid twisting movements (Stashak, 1987; Schaer et al., 2001). Injuries include pulling or tearing of the attachments of the joint capsule and collateral ligaments (McIlwraith & Goodman, 1989). Thus decreased range of motion following PIP arthrodesis may exacerbate stresses on the DIP joint and navicular apparatus and explain why long-term radiographic evaluation after PIP joint arthrodesis often reveals degenerative disease involving the DIP joint or even navicular disease (Martin et al., 1984; MacLellan et al., 2001). The biomechanical importance of the PIP joint should be kept in mind when arthrodesis is considered as a treatment option and particular attention should be paid to mediolateral hoof balance for management of the treated horses (Clayton et al., 2007b).

Breakover (from heel-off to toe-off)

The results of Chateau et al. (2005) show that, during turning, extrasagittal stress in the interphalangeal joints is maximal just before the start of breakover because adduction of the limb is maximal at heel-off. Unweighting of the palmar part of the foot allows the heels to lift-off and the hoof to rotate laterally on the ground during breakover. Average amplitude of this movement when walking around a sharp turn on a hard surface is about 11°. This movement of the hoof contributes to the sudden realignment of the interphalangeal joints that were strongly medially rotated just before the start of breakover (Fig. 6.14).

Delaying breakover is likely to exacerbate extrasagittal stresses in the interphalangeal joints, so prevention and treatment strategies for traumatic or degenerative diseases of the interphalangeal joints should take into account the biomechanical influence on breakover.

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CHAPTER 7

Hind limb function

Hilary M. Clayton, Willem Back

Introduction

This chapter reviews the structure and functions of the equine hind limbs in relation to stride kinematics (movements) and kinetics (forces), and highlights differences between the fore and hind limbs. The hind limbs carry only about 43% of body mass, so the vertical ground reaction force and vertical impulse are lower in the hind limbs than in the forelimbs. In the longitudinal direction, the propulsive component of the ground reaction force tends to be larger and the braking component smaller in the hind limbs compared with the forelimbs. The angulations of the hip, stifle and tarsal joints are well suited to play an active role in generating propulsion, which is in contrast to the supporting function of the more strut-like forelimbs.

Musculotendinous architecture

Horses are cursorial animals and within the genus *Equus* different breeds have been developed for different occupations. Breeds specialized for racing tend to have long, gracile limbs, whereas draft breeds have shorter, stouter limbs in proportion to body size (Gunn, 1983). Fat and muscle distribution also differ between breeds but, regardless of breed, successful athletes tend to have body fat percentages in the range of 7.8–8.8% (Lawrence et al., 1992; Kearns et al., 2002). In athletic horses, muscles comprise about 53% of body mass compared with 42% in non-athletes, and the propulsive muscles in the hind limb account for a larger portion of that muscle mass (Gunn, 1987). These muscles are responsible for generating external work that is required for acceleration or to raise the center of mass when moving uphill or jumping (Clayton et al., 2002; Dutto et al., 2004a, b). The muscles in the proximal hind limb are characterized by having large physiological cross sectional areas (PCSA), associated with large mass and volume and relatively long fibers that move the joints through a large range of motion. Many of these muscles have multiple bellies: the more proximal bellies have both their origin and insertion located more proximally than the distal bellies allowing the entire muscle to exert force over a wide range of joint positions without needing long muscle fibers. The muscle fibers are arranged in series with elastic tissue and they attach to the bones directly or via short tendons. These characteristics are typical of muscles that are specialized for doing work. Many of the hind limb muscles are multi-articular and have complex fascial attachments and connections that make it difficult to separate extrinsic and intrinsic functions.

Muscle volume and fiber length decrease, and pennation angles increase in a proximal to distal direction, so the muscles in the distal hind limb are smaller and less powerful with short, pennate fibers that are well-suited for generating force economically. Muscle size and fiber length are not correlated, however, so the larger muscles do not necessarily have longer fibers and smaller muscles do not always have shorter fibers (Table 7.1). Fiber length variability is low in the digital flexor muscles both within an individual horse and between different horses. The amount of force transmitted to the tendon is calculated as the product of PCSA and the cosine of the pennation angle. When pennation angle exceeds about 20° it significantly reduces the component of force transmitted to the tendon. The benefit of larger pennation angles is the increase in force-generating capacity as a result of the larger PCSA for a given volume. These muscular characteristics are typical of musculotendinous units used for elastic energy storage and recoil, which reduces the need for energetically expensive changes in muscle length, while minimizing distal limb mass. The suspensory ligament represents the end point of such modification, having minimal muscular tissue in the adult horse (Klomkleaw et al., 2002). Some muscles, notably *fibularis tertius* and superficial digital flexor, have so little muscular tissue that they function as strong tendinous bands to synchronize flexion–extension movements of stifle and tarsus in an arrangement known as the reciprocal apparatus (Wentink, 1978b).

During trotting, changes in potential and kinetic energy of the horse's center of mass are in phase, which allows the distal limb to make substantial contributions to elastic energy storage (Biewener, 1998). In canter and gallop, the relationship between kinetic and potential energy varies during the stride (Minetti et al., 1999), which limits the ability to store elastic energy in the distal limb. It has been estimated that the hind limbs are responsible for two-thirds of the elastic energy savings in horses (Biewener, 1998).

Payne et al. (2005) described the morphology and architecture of the hind limb musculature in horses of different sizes (body mass 430–600 kg) and ages (10–30 years) (Table 7.1). Data for muscle mass were scaled to body mass and measurements of fiber length were scaled to (body mass (kg))$^{1/3}$, which resulted in similar values among the seven subjects for most muscles, with the exceptions of *gluteus medius* and the hamstrings, which may have adapted in response to different types of training. After scaling for geometric similarity, fiber lengths varied more than muscle masses, particularly in the vertebral head of *semitendinosus* and in *semimembranosus*. In general, the hamstring group is capable of generating large forces and high powers. All the hind limb muscles have pennation angles greater than 20° and many have considerably larger angles. Most of the proximal muscles have little, if any, tendon and, when tendon tissue is present, it is light in weight (5.3–34.2 g) compared with tendons in the distal limb (44.8–208.7 g).

Hind limb muscle architecture has been compared in Arabians, a breed that excels in endurance races, with Quarter Horses, a breed noted for its sprinting speed (Crook et al., 2008). Overall height and mass of the horses did not differ but the Quarter Horses

Table 7.1 Architectural properties of the muscles of the equine hind limb

Muscle	Mass (g)	Volume (cm^3)	MFL (mm)	PCSA (cm^2)	Angle (°)	Force (kN)	Power (W)
Psoas minor	432	408	67 (50–205)	61	37 (35–38)	1833	65
Psoas major	1182	1116	198 (95–280)	56	29 (20–35)	1694	177
Iliacus	1395	1316	244 (170–305)	54	26 (15–40)	1617	209
Gluteus superficialis	646	609	102 (55–190)	60	36 (28–50)	1793	97
Gluteus medius	8577	8091	203 (135–300)	398	28 (15–45)	11942	1287
Gluteus profundus	1351	1275	118 (42–220)	108	30 (15–40)	3249	203
Tensor fascia lata	1448	1366	97 (60–150)	140	34 (20–43)	4210	217
Biceps femoris							
Intermediate head	870	820	235 (190–260)	27	27 (20–40)	1048	130
Vertebral head	6112	5766	258 (130–330)	37	37 (28–50)	6705	917
Caudal head	946	892	245 (170–300)	39	39 (30–45)	1092	142
Semitendinosus							
Vertebral head	26841	2532	274 (105–289)	92	28 (20–35)	2770	403
Pelvic head	727	1630	312 (180–355)	52	35 (25–45)	1567	259
Semimembranosus	3834	3617	342 (80–760)	106	35 (20–45)	3171	575
Sartorius	484	456	376 (250–460)	12	21 (20–25)	364	73
Gracilis	1760	1661	123 (80–175)	135	31 (22–35)	4037	264
Pectineus	447	422	78 (49–320)	54	29 (13–50)	1614	67
Adductor	3924	3702	176 (80–390)	211	35 (25–40)	6322	589
Quadriceps femoris							
Rectus femoris	2291	2161	98 (40–152)	220	40 (25–53)	6610	344
Vastus medialis	1878	1772	119 (90–145)	148	33 (25–41)	4448	282
Vastus intermedius	501	473	105 (60–220)	45	41 (30–55)	1355	75
Vastus lateralis	1734	1636	155 (92–220)	105	36 (30–40)	3163	260
Popliteus	280	264	38 (21–170)	70	42 (35–50)	2107	42
Gastrocnemius							
Medialis	817	771	48 (25–99)	161	36 (20–45)	4836	123
Lateralis	808	762	56 (36–70)	137	34 (30–45)	4098	121
Soleus	6	6	121 (110–151)	0	22 (22–22)	15	1
Flexor digitorum superficialis	111	105	3 (1–6)	417	52 (40–60)	12 514	17
Flexor digitorum profundus							
Flexor digitorum medialis	161	152	70 (4–100)	22	27 (12–40)	652	24
Flexor digitorum lateralis	660	622	10 (3–55)	644	44 (30–60)	19 324	99
Tibialis caudalis	224	211	57 (40–117)	37	31 (20–60)	1106	34
Tibialis cranialis	309	291	40 (17–218)	73	41 (25–60)	2199	46
Extensor digitorum longus	462	435	81 (60–110)	54	29 (25–45)	1620	69
Extensor digitorum lateralis	192	181	70 (35–110)	26	28 (20–45)	776	29

MFL, mean fascicle length; PCSA, mean physiological cross sectional area; Angle, mean (range) of pennation angles of fibers; Force, maximal isometric force generation capacity estimated as the product of PCSA and maximal isometric stress of skeletal muscle, taken as 0.3 MPa; Power, maximal power output calculated as one-tenth of the product of force and maximal contraction velocity, which was estimated based on published values of equine muscle fiber-typing. Unless indicated, different heads of the muscles were combined.

Data from Payne et al. (2005).

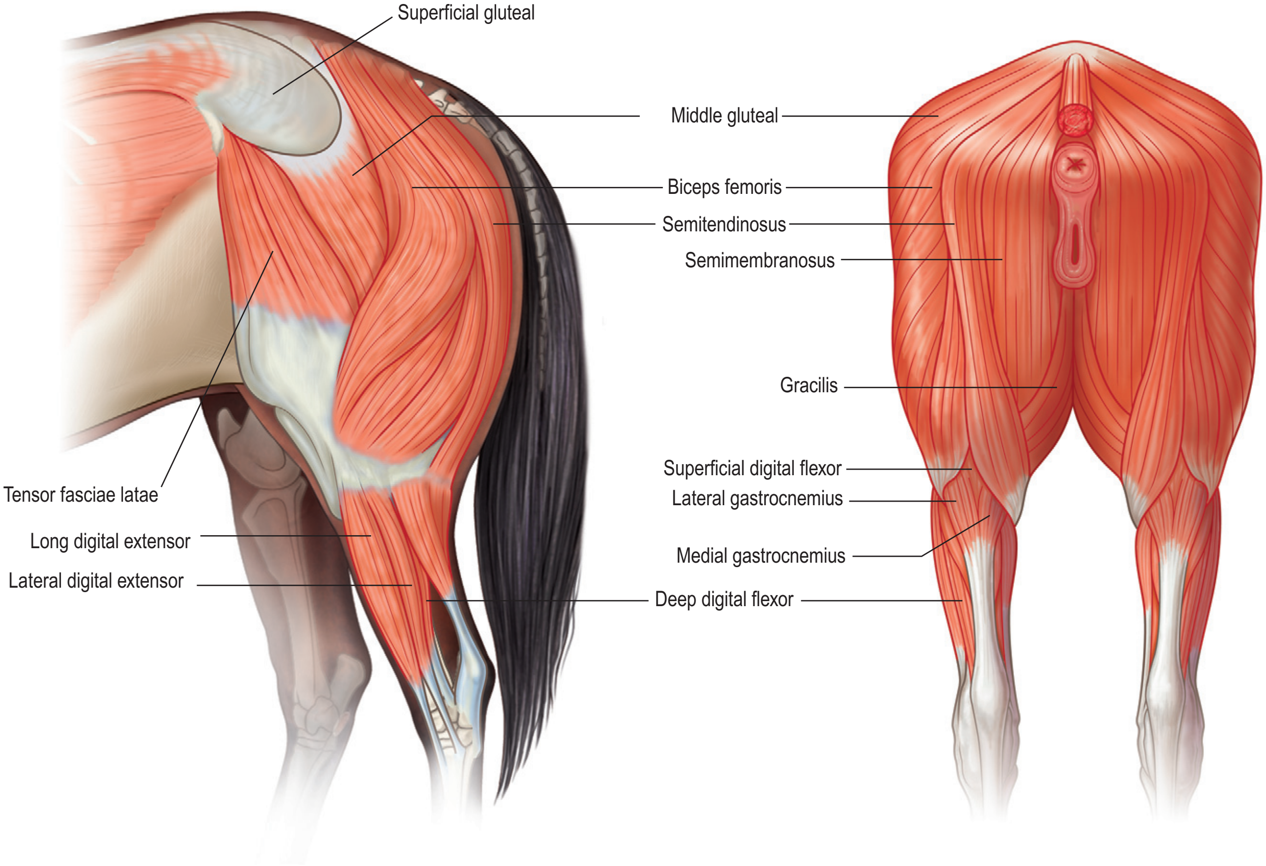

Fig 7.1 Musculature in the proximal hind limb viewed from the side (left) and from behind (right).

had greater muscle mass and volume in both proximal and distal muscles and larger PCSAs allowing the development of larger forces (Crook et al., 2008). Thoroughbreds trained for sprinting have a higher hind limb muscle to body mass ratio than those trained for hurdling (Gunn, 1987). Fiber lengths and pennation angles are similar in different breeds of horses (Crook et al., 2008). This is in contrast to human sprinters who tend to have longer fibers and smaller pennation angles in their calf muscles compared with distance runners (Abe et al., 2000), though this may be an effect of a specific type of training. PCSA and calculated maximal isometric force decrease as follows: *biceps femoris*; *semitendinosus*; *gastrocnemius*; *vastus lateralis*; *extensor digitorum longus*; *tibialis cranialis*.

Gluteus superficialis (Fig. 7.1, Table 7.1), the smallest of the gluteal muscles, is a hip flexor. It is one of the few muscles in the proximal hind limb that has a distinct tendon. This tendon is short in length (980 mm), small in mass (14.0 g) and volume (12.5 cm^3) but has a relatively large cross-sectional area (1.39 cm^2). It may provide some elastic energy storage and return. Calculated stress in the tendon is quite low (13.0 MPa).

Gluteus medius (Fig. 7.1, Table 7.1) is a monoarticular hip extensor and is the largest muscle of the hind limb in terms of mass (8577 g) and PCSA (398 cm^2). The fibers are long with pennation angles in the range 15–45° (Payne et al., 2005). These characteristics are indicative of a primary role in force and power generation. In fact, *gluteus medius* has been estimated to have by far the largest force-generating capacity of all the hind limb muscles and plays an important role in propulsion. Electromyographic studies at trot indicate that it is active during hind limb retraction in late swing and early stance (Robert et al., 1998). It contributes to a burst of power generation across the hip joint that pushes the trunk forward over the grounded hind limb (Clayton et al., 2001). The muscle fibers attach onto broad aponeurotic sheets that are somewhat compliant and may provide some elastic energy storage and return. *Gluteus medius* represents 2.0% of body mass in Quarter Horses and 1.7% in Arabians (Crook et al., 2008), which is indicative of the specialization of Quarter Horses for acceleration and speed. Internally, *gluteus medius* shows functional compartmentalization; the superficial parts of the muscle are composed primarily of type IIb fibers, which suggests a propulsive function, whereas the deeper parts have more type I fibers that are typical of a postural function (Lopez-Rivero et al., 1992; Serrano et al., 1996). Muscle fiber lengths do not appear to have a superficial to deep gradation and range from 135 mm to 300 mm throughout the muscle.

Gluteus profundus (Table 7.1) is a smaller muscle than *gluteus medius* in terms of size and PCSA, with shorter fibers but similar pennation angles.

Biceps femoris (Fig. 7.1, Table 7.1) is a multi-articular muscle that can act as a hip extensor, stifle flexor and tarsal extensor. It plays an important role in stabilization of the hip and stifle joints. The three heads (intermediate, vertebral and caudal) have a combined mass of 7928 g making it one of the largest muscles in the hind quarters. It has a large PCSA, especially the biarticular vertebral head, due to its large volume (Payne et al., 2005). This study reported pennation angles within the range of 20–55° in all three heads, whereas Crook et al. (2008) described a parallel fiber orientation (pennation angle, ≤5°) in the intermediate and caudal heads and 55° pennation angles in the vertebral head. *Biceps femoris* is the only muscle in the proximal hind limb that has a large tendon (mass, 106 g; CSA, 9.54 cm^2) though this tendon is short in length (100 mm). During trotting, it is active during hind limb retraction in late swing and early stance (Robert et al., 1998).

Semitendinosus (Fig. 7.1) has vertebral and pelvic heads. According to Payne et al. (2005), both heads have pennation angles in the range of 20–45° (Table 7.1) whereas Crook et al. (2008) identified distinct differences between the two head with the pelvic head having parallel fibers (pennation angle, ≤5°) and fibers in the vertebral head having a mean pennation angle of 23°, which supports its presumptive role in propulsion This muscle is thought to be important in generating large forces during hind limb retraction. PCSA of *semitendinosus* in Quarter Horses is double that of Arabians (Crook et al., 2008). Semitendinosus is active during retraction of both the ipsilateral and the contralateral hind limb in late swing and early stance (Robert et al., 1998).

Semimembranosus (Fig. 7.1) has vertebral and pelvic heads that cannot easily be separated and are considered together in Table 7.1. A notable feature of this muscle is its large range of fiber lengths from 80–760 mm. Some fibers run the entire length of the belly from origin to insertion; others are staggered along the muscle belly. Similar to the other hamstring muscles, semimembranosus is multiarticular and is estimated to have the capacity to develop large force and high power (Payne et al., 2005).

Adductor has two parts (*magnus* and *brevis*) that are united, and so are considered together in Table 7.1. Like *semimembranosus*, the *adductor* is a large muscle characterized by a wide range of fascicle lengths (80–390 mm) and it is estimated to produce large force and high power.

Quadriceps femoris has four parts, of which the biarticular head, *rectus femoris*, is notable for its large PCSA (220 cm^2) as a consequence of its large volume (2161 cm^3). The fiber lengths are short (<179 mm). *Quadriceps* assists in support and stabilization of the stifle joint, which is the key joint in the hind limb stay apparatus. Details of this mechanism are given later. *Rectus femoris* may also play a role in hip flexion.

Tensor fascia latae is estimated to be capable of producing moderate force and power (Fig. 7.1, Table 7.1). The tendon is relatively long (227 mm) but with a small CSA (1.35 cm^2). Electromyographic studies indicate that this muscle is active during late swing and early stance (Robert et al., 1998). It is thought to play a role in stabilizing the stifle during the stance phase (Tokuriki & Aoki, 1995).

Tibialis cranialis is a small muscle with a wide range of fiber lengths (17–218 mm) and highly pennate fibers (41°) capable of generating fairly high force but low power (Table 7.1). It is notable for having a short (92 mm), thick (CSA, 2.61 cm^2) tendon of attachment (Payne et al., 2005). Fibers in the proximal part of this muscle are longer than those in the distal part (Crook et al., 2008) and it is the only muscle in the distal hind limb that has long fibers.

Gastrocnemius (Fig. 7.1, Table 7.1) is the largest muscle of the distal limb. The medial and lateral heads combined have a volume of 1543 cm^3 and mass 1625 g (Payne et al., 2005), with the lateral head being larger than the medial head but having shorter fiber lengths (Crook et al., 2008). The muscle belly contains extensive tendinous bands organized in series and in parallel and united by short (48–56 mm), pennate muscle fibers (see Table 7.3) (Payne et al., 2005). This architecture is consistent with a capacity for economical force generation via tendinous stretch and recoil within the muscle belly. As a consequence of the fiber pennation, the lateral head has the largest PCSA of all the hind limb muscles (644 cm^2). The estimated force-generating capacity of *gastrocnemius* is quite high (8930 N) and is combined with a relatively large power-generating ability (244 W). The two heads have a thick (3.32 cm^2) common (calcanean) tendon. Stress in the calcanean tendon has been estimated as 47 MPa (Ker et al., 1988), 30 MPa (Biewener et al., 1998) and 27 MPa (Payne et al., 2005). The *gastrocnemius* and cranial-tibial muscles may also play a role in centering the line of action of the resultant load on the tibia thus reducing the strain due to bending (Wentink, 1978a).

Fibularis (peroneus) tertius forms the cranial arm of the reciprocal apparatus and is entirely tendinous (mass, 64.3 g; volume, 57.4 cm^3; CSA, 1.59 cm^2). Rupture of *fibularis tertius* as a consequence of hyperextension of the tarsus, does not have much effect on the horse's stance or walking ability (Strubelt, 1928; Schamhardt et al., 1985), although Wentink (1978b) recorded slight hyperextension at the end of stance and less flexion of the tarsal joint during swing. At trot, the loss of elastic rebound of *fibularis tertius* is responsible for delayed protraction of the distal limb in early swing.

Flexor digitorum superficialis (SDF) (Fig. 7.1, Table 7.1) in the hind limb is almost entirely tendinous, forming the caudal arm of the reciprocal apparatus that synchronizes stifle and tarsal motion in the sagittal plane. The muscle belly has a small volume of only 105 cm^3 with uniformly short (1–6 mm) and highly pennate (40–60°) fibers, resulting in a surprisingly large PCSA (417 cm^2) (Table 7.1). Estimates suggest that SDF has a capacity to generate high force (12500 N) but low power (17 W). The SDF tendon is long (748 mm) with a large mass (2.25 cm^2) (Payne et al., 2005). As a consequence of having short muscle fibers and a long tendon, the hind limb SDF is particularly well suited to elastic energy storage and release and is more effective in this regard than the forelimb SDF (Brown et al., 2003).

Flexor digitorum profundus (DDF) has three parts. *Flexor digitorum medialis* and *tibialis caudalis* are characterized by small volumes and short to medium length fibers (Fig. 7.1, Table 7.1), whereas *flexor digitorum lateralis* has a larger volume and short fibers (3–55 mm) embedded within large amounts of aponeurotic tendinous tissue that give the muscle belly a striated appearance on gross morphological examination (Payne et al., 2005). This muscle is estimated to have the capacity to develop high force (21100 N) but relatively low power (157 W) (see Table 7.3). Although the short muscle fibers and large PCSA are not compatible with active shortening of the musculotendinous unit, this architecture is well suited to work isometrically during elastic energy storage and release.

Flexor digitorum lateralis is particularly effective in this regard, and more so than the humeral, radial or ulnar head of DDF in the forelimb (Brown et al., 2003; Payne et al., 2005). The DDF tendon has the largest cross-sectional area of the distal limb tendons (3.64 cm^2). Stress in the *flexor digitorum lateralis* tendon has been estimated to be as high as 105 MPa (Ker et al., 1988) or as low as 40–50 MPa (Biewener et al., 1998). Tendons fail at stresses of approximately 120 MPa (Zajac, 1989), indicating that *flexor digitorum lateralis* may be operating close to, and may even exceed, its limit during isometric muscular contractions that generate high forces. In spite of this prediction, digital flexor tendon injuries do not occur frequently in the equine hind limbs.

Extensor digitorum longus is a small muscle that generates a moderate force but little power (Fig. 7.1, Table 7.1). Its long (472 mm) tendon has a small cross-sectional area (1.13 cm^2) and experiences low stress. Estimates of peak stress range from 14.4 MPa (Payne et al., 2005) to 36 MPa (Ker et al., 1988).

The stay apparatus

In the standing horse, the body weight acts through the hip joint and is counteracted by the ground reaction force acting through the hoof. The net effect is to exert a compressive force on the hind limb. The joints are maintained in extension by the action of the extensor musculature. In general, the magnitude of extensor muscle force required to maintain the standing posture increases with body mass and with joint angulation. Thus, smaller animals tend to adopt a crouched posture with more flexion of the joints, whereas larger animals stand with more upright limb angulations to reduce loading of the extensor musculature (Biewener, 1989). Horses spend a considerable proportion of their time standing, which is facilitated by the presence of the passive stay apparatus that uses tendoligamentous structures to reduce the muscular activity required to maintain the standing posture (Dyce et al., 1996).

The reciprocal apparatus is responsible for passively stabilizing the hind limb during standing. Extension of the stifle joint, which is the key to hind limb stabilization, is achieved by hooking the patella over the medial femoral trochlea (Sack, 1989). When the trochlea protrudes between the middle and medial parts of the patellar ligament, it holds the stifle in extension by mimicking the action of *quadriceps femoris*. Tension in the largely tendinous SDF prevents tarsal flexion and the more distal joints are stabilized passively by a system of ligaments and tendons. The equine patella is enveloped by the parapatellar fibrocartilage, which gives attachment to all parts of *quadriceps* as well as to *tensor fascia latae*, *biceps femoris*, *gracilis* and *sartorius*. During quiet standing with the patellar locking mechanism engaged, the only muscular force needed to stabilize the stifle is provided by tonic, low-level activity in *vastus medialis*, which inserts on the medial aspect of the parapatellar fibrocartilage. Tension in this muscle is estimated to be only 2% of the force that would be needed without the patellar locking mechanism (Schuurman et al., 2003).

Upward fixation of the patella is an inability to disengage the patellar locking mechanism. It may be mild causing a slight hesitation in hind limb protraction or it can be severe enough to fix the entire hind limb in extension, effectively precluding locomotion. Contributing factors include shrinking of the patellar fat pad in underweight animals, abnormal coordination of muscles, such as *vastus lateralis*, that actively disengage the patella (Wentink, 1978a) or spastic activity in *vastus medialis* that precludes disengagement (Schuurman et al., 2003).

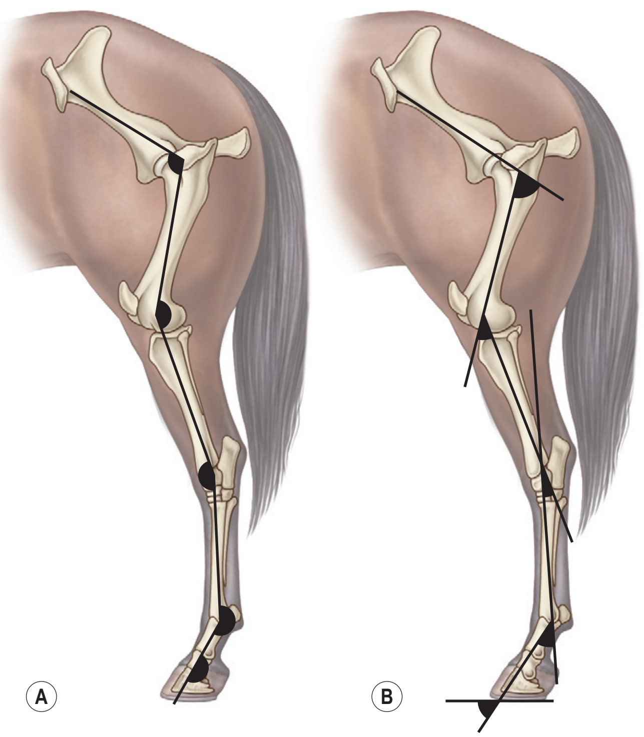

Fig 7.2 Two methods of measuring joint angles of the hind limbs with the measured angles being represented by black arcs. Left: measurement of the angle between the proximal and distal segments comprising the joint on the anatomical flexor aspect. Right: measurement of the angle by which the distal segment differs from alignment with the proximal segment, deviation toward the flexor aspect is negative (–), deviation toward the extensor aspect is positive (+).

Sagittal plane analysis of hind limb kinematics and kinetics

Although kinematic gait analysis of the equine hind limb has been performed since the early part of this century (Walter, 1925; Krüger, 1938), the development of the computer gave new impetus to this field of research, both in the area of clinical applications (Fleiss et al., 1984; Kobluk et al., 1989; Martinez-del Campo et al., 1991; Back et al., 1995a, 1995b) and in computer simulation studies (van den Bogert & Schamhardt, 1993). The reciprocal apparatus, which couples stifle and tarsal joint motion, has been studied extensively (Strubelt, 1928; Molenaar, 1983; Wentink, 1978b; van Weeren et al., 1990). Back et al. (1995b) standardized the graphical presentation of kinematic data of the equine hind limb using joint angle–time diagrams in a large group of horses.

The hip joint is the pivot point for rotation of the hind limb, and the ball and socket construction allows some motion outside of the sagittal plane. The more distal joints are constrained to move primarily in a sagittal plane with only small amounts of abduction–adduction and internal–external rotation (Lanovaz et al., 2002). Thus kinematic analysis in the two-dimensional sagittal plane captures most of the kinematic information describing hind limb movement patterns. Hind limb joint angles may be measured in several ways (Fig. 7.2): between the proximal and distal segments on the anatomical flexor aspect; as the angle by which the distal segment deviates from alignment with the proximal segment; or as some variation of these methods. The angle may be expressed in absolute terms or it may be normalized to the standing angle, the angle at ground contact or the average angle during the stride (Mullineaux et al., 2004). Three-dimensional kinematics of the tarsal joint have been measured using bone-fixed markers (Lanovaz et al., 2002) and will be described at the end of this chapter.

When skin markers are used to represent sagittal plane motion of the hind limb segments, a minimum of two markers per segment are required. Typical marker configurations involve either placing a marker over the center of rotation of each joint or aligning two markers along the long axis of each segment (Fig. 7.3). Intra-limb coordination patterns can be visualized using stick figures or by joint angle–time graphs (Fredricson & Drevemo, 1972; Martinez-del Campo et al., 1991; Holmström et al., 1994; Back et al., 1994; Hodson et al., 2001, Dutto et al., 2006).

Errors introduced into kinematic data due to skin movement relative to the underlying skeletal landmarks (van Weeren et al., 1992) may be small enough to be neglected on the crural and metatarsal segments, but are large enough to cause obvious changes in sagittal plane kinematics on the pelvic, thigh and pastern segments (Fig. 7.4). Errors as large as 15° in stifle angle and 30% in moment arm of *gastrocnemius* have been attributed to the effects of skin displacement in a walking pony (van den Bogert et al., 1990). Correction algorithms have been developed for many of the anatomical locations that are commonly used for marker placement for two-dimensional analysis of hind limb kinematics (van Weeren et al., 1992).

Kinematic information can be combined with ground reaction forces and morphometric data for the equine hind limb segments (Buchner et al., 1997; Nauwelaerts et al., 2011) (Fig. 7.5, Table 7.2) to calculate net joint moments and net joint powers using inverse dynamic analysis (see Chapter 19 for details). This method offers a more complete description of the functional responsibilities of the joints. In the equine hind limb, inverse dynamic analysis has been used to improve understanding of joint function during walking (Colborne et al., 1997a, 1997b; Clayton et al., 2001; Dutto et al., 2006) and trotting (Clayton et al., 2002; Dutto et al., 2006).

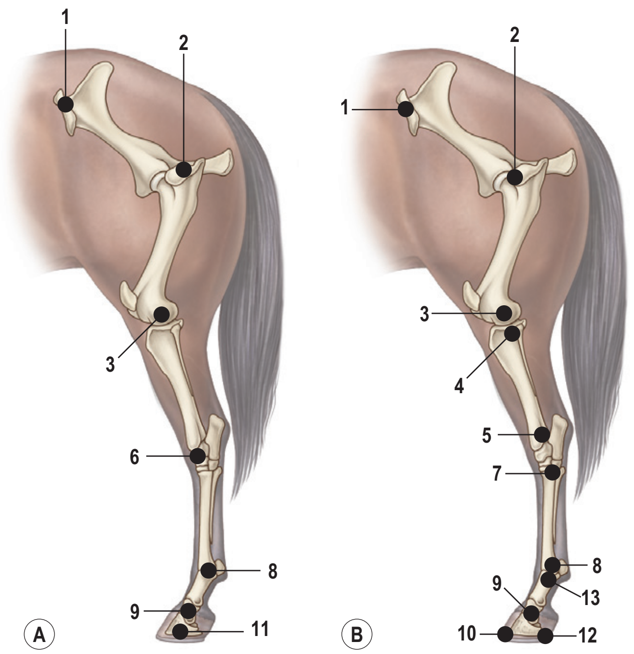

Fig 7.3 Locations of skin-fixed markers overlying bony landmarks in two marker-placement schemes. Left: markers are placed over the centers of joint rotation and the limb segments are represented by lines joining the markers. Right: two markers aligned along the long axis of each segment are joined to represent the segment and adjacent segments intersect at the joints. The hoof may be represented by different combinations of markers with or without radiographic identification of the center of rotation of the DIP joint. Anatomical locations of the markers on the hind limb: 1, tuber coxae; 2, proximal femur at cranial greater trochanter; 3, distal femur at lateral epicondyle; 4, proximal tibia at fibular head; 5, distal tibia at lateral malleolus; 6, talus; 7, proximal metatarsus; 8, distal metatarsus; 9, hoof at coronary band; 10, toe of hoof; 11, mid-lateral hoof; 12, heel of hoof; 13, proximal pastern.

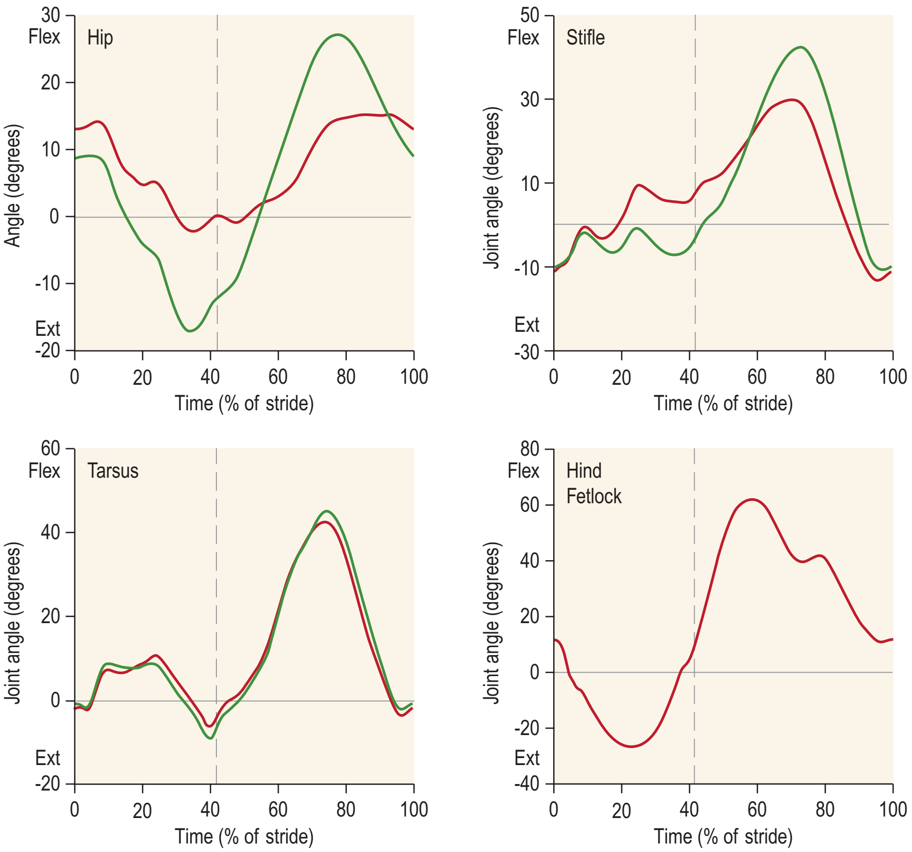

Fig 7.4 Mean angle–time diagrams for the joints of the hind limb in a group of horses trotting on a treadmill at 3 m/s before (red line) and after (green line) correction for skin displacement. The horizontal zero line indicates the joint angle of the horse standing square. The vertical dashed line marks the transition from stance to swing phase. At the fetlock there is no difference after correction for skin displacement.

Reprinted from Back, W., Schamhardt, H.C., Savelberg, H.H.C.M., et al., 1995b. How the horse moves: significance of graphical representations of equine hind limb kinematics. Equine Vet. J. 27, 39–45, with permission from the Equine Veterinary Journal.

The trot

The trot is a symmetrical, two-beat gait with the limbs moving by diagonal pairs. The diagonal stance phases are usually separated by aerial or suspension phases, so the trot is classified as a running or leaping gait in which the body mass is modeled as a spring mass system. Since the trot is the most important gait for lameness detection, it has been the focus of many kinematic studies in various breeds of horses (Clayton, 1994a; Holmström et al., 1994; Back et al., 1995b; Galisteo et al., 1997; Galisteo et al., 1998; Cano et al., 1999; Cano et al., 2001; Nicodemus & Holt, 2006; Nicodemus & Booker, 2007). The following paragraphs describe sagittal plane kinematics and kinetics of the joints of the hind limb during trotting and indicate the effects of skin displacement on the amplitude and pattern of joint angular displacement (Fig. 7.4).

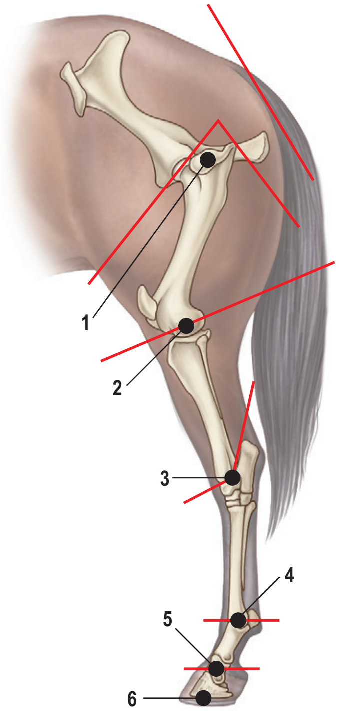

Fig 7.5 Locations of skin markers used to locate the centers of mass of the hind limb segments in Table 7.2. The segments are separated along the incision lines shown in red.

Reprinted from Buchner, H.H.F., Savelberg, H.H.C.M., Scharmhardt, H.C., Barneveld, A., 1997. Inertial properties of Dutch Warmblood horses. J. Biomech. 30 (6), 653–658, with permission from Elsevier..

In Warmblood horses trotting at 4.0 m/s, stride duration is 0.67 s, and hind stance duration occupies about 40% of stride duration (Table 7.3) (Back et al., 1995b). Stride and stance durations are negatively correlated with velocity (Robert et al., 2002). Although hind limb swing duration is the same at walk and trot, the limbs rotate through a larger range of motion at trot, requiring greater force and impulse generation, and with more flexion of the stifle and tarsal joints during the swing phase, which shortens the limb pendulum and hastens protraction. As trotting speed increases, range of motion increases in the hip and tarsal joints (Hoyt et al., 2002).

As in the forelimb, gait efficiency in the hind limb is increased by using the tendons as energy-conserving elastic springs (Dimery et al., 1986). Energy is stored by stretching the tendons as the limb is loaded and it is released during the unloading phase when it contributes to propulsion and joint flexions during the swing phase. In early swing, the release of elastic energy supports tarsal and stifle flexion (Wentink, 1978b), which occur synchronously, since these joints are coupled by the reciprocal apparatus. In general, electromyographic activity in the hind limb musculature is low during the swing phase at trot (Wentink, 1978a; Jansen et al., 1992; Tokuriki & Aoki, 1995), which supports the idea that movements in the swing phase are heavily reliant on passive energy from elastic recoil of the tendons. In the absence of ground reaction forces, resistance to limb movements in the swing phase is due mainly to segmental inertia. Flexion of all the hind limb joints as the limb is protracted reduces the effective limb length and moment of inertia about the hip joint.

Hip joint

The hip joint shows a more or less sinusoidal flexion and extension pattern. In early stance, hip angle is constant during the impact phase, after which the joint extends to reach maximal extension in terminal stance. The swing phase flexion cycle peaks just after mid-swing, which represents the position of maximal hind limb protraction. The hip then extends and retracts the limb prior to hoof contact with the ground (Fig. 7.6). In the absence of correction for

Table 7.2 Hind limb segmental masses, densities, reference lines for division of segments (see Fig. 7.2), and position of segment centers of mass in sagittal plane

Segment	Mass (kg)	Density (g/cm³)	Proximal and distal markers	Distance as % segment length	
				x-axis	y-axis
Thigh	18.6 ± 2.3	1.05 ± 0.007	1–2	59 ± 8	−12 ± 4
Crus	8.3 ± 0.8	1.11 ± 0.019	2–3	38 ± 2	−8 ± 2
Metatarus	2.84 ± 0.22	1.28 ± 0.03	3–4	32 ± 4	−7 ± 2
Hind pastern	0.89 ± 0.04	1.23 ± 0.03	4–5	43 ± 5	−13 ± 4
Hind hoof	0.99 ± 0.17	1.18 ± 0.01	5–6	31 ± 5	−22 ± 4

Position of center of mass is determined first along the segmental x-axis (longitudinal, positive distally from the proximal reference marker toward the distal reference marker), then shifted along the y-axis (perpendicular to x-axis, positive cranially). Distances are measured as a percentage of the segment length between the two reference markers. Data are mean ± SD for 12 hind limbs of six Warmblood horses.

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Table 7.3 Hind limb kinematic variables for horses walking at 1.6 m/s, trotting at 4.0 m/s (Back et al., 1996b), and cantering at 7.0 m/s (Back et al., 1997)

	Walk	Trot	Trailing hind limb canter	Leading hind limb canter
Stride duration (s)	1.09 ± 0.06*	0.67 ± 0.03*	0.553 ± 0.02	0.547 ± 0.02
Stance duration (s)	0.69 ± 0.04*	0.27 ± 0.01*	0.177 ± 0.01#	0.185 ± 0.01#
Stance duration (%)	63.4 ± 1.4*	40.5 ± 1.9*	32.1 ± 1.3#	33.9 ± 1.3#
Swing duration (s)	0.40 ± 0.03	0.40 ± 0.03	0.376 ± 0.02	0.362 ± 0.02
Pro-/retraction				
Angle of max protraction (°)	23.1 ± 1.8*	21.6 ± 1.3*	22.7 ± 1.4#	35.8 ± 1.7#
Angle of max retraction (°)	−23.6 ± 1.6*	−26.6 ± 1.5*	−37.6 ± 1.2#	−29.7 ± 1.0#
Max pro/retraction range (°)	46.7 ± 2.9*	48.1 ± 1.6*	60.3 ± 1.7#	65.5 ± 1.6#
Hip joint				
Angle of max extension (°)	68.9 ± 3.8*	67.8 ± 3.9*	66.7 ± 4.4	73.8 ± 3.2
Angle of max flexion (°)	93.7 ± 3.2*	91.1 ± 3.6*	91.0 ± 3.6	96.3 ± 3.2
Range of motion (°)	24.8 ± 1.9*	23.3 ± 1.8*	24.3 ± 1.9	22.5 ± 1.8
Stifle				
Angle of max extension (°)	7.0 ± 4.9*	11.0 ± 4.0*	13.5 ± 4.6#	2.3 ± 5.1#
Angle of max flexion (°)	46.1 ± 5.9*	58.3 ± 5.1*	55.5 ± 3.0	57.9 ± 4.3
Range of motion (°)	39.1 ± 3.7*	47.3 ± 3.8*	42.0 ± 3.9#	55.5 ± 4.7#
Tarsus				
Angle of max extension (°)	10.4 ± 3.5	10.3 ± 2.9	7.0 ± 2.6	8.1 ± 3.0
Angle of max flexion (°)	46.0 ± 0.1*	65.7 ± 5.1*	56.0 ± 8.0#	64.5 ± 8.6#
Range of motion (°)	35.6 ± 4.5*	55.4 ± 5.3*	49.0 ± 8.3#	56.5 ± 7.6#
Metatarsophalangeal				
Angle of max extension (°)	−37.0 ± 4.2*	−53.0 ± 4.0*	−60.6 ± 3.4#	−53.9 ± 3.8#
Angle of max flexion (°)	34.8 ± 9.1*	32.0 ± 7.5*	35.6 ± 8.9#	43.8 ± 7.3#
Range of motion (°)	71.8 ± 9.0*	85.0 ± 7.7*	96.1 ± 9.1	97.7 ± 7.0

*Indicates variables that differ significantly between walk and trot ($p < 0.05$).

#Indicates variables that differ significantly between trailing and leading limbs at canter ($p < 0.05$).

Angles are expressed relative to 180° alignment of the proximal and distal segments; flexion angles are positive, extension angles are negative. Protraction and retraction angles are measured relative to the vertical: protraction positive, retraction negative. Values are mean ± SD.

Reproduced from Back et al. (1996b, 1997).

skin displacement, the pattern of hip joint motion hardly changes but the range of motion is reduced by about half resulting in an underestimation of the range of flexion–extension by as much as 30° (Fig. 7.4) (Back et al., 1995b).

The hip joint–time curve and the cranio-caudal oscillations of a marker on the distal metatarsus have a similar pattern of movement (Back et al., 1995b) indicating that the entire hind limb can be considered to move like a pendulum with a rotation point in the acetabulum. Maximal protraction occurs almost 10% later in the stride for the hind limb compared with the forelimb. Pelvic rotation contributes little to hind limb motion in the sagittal plane as the pelvis maintains a fairly constant angle relative to the horizon. However, pelvic rotation in the horizontal plane is larger with a range of motion of around 11° during trotting (Gomez Alvarez et al., 2008).

There is an extensor moment at the hip joint through most of stance with two bursts of energy generation in the extensor musculature that push the trunk forward over the grounded hind hoof (Fig. 7.6). The net joint moment moves to the flexor aspect during breakover and remains there through the first one third of swing. Positive work is done as hind limb protraction is initiated by concentric action of the hip flexors followed by passive recoil of elastic structures, such as the tendon of *tensor fascia latae* (Tokuriki & Aoki, 1995) and *fibularis tertius* (Wentink, 1978b). Energy generation in the hip flexors in early swing increases linearly with trotting velocity (Clayton et al., 2002). The net joint moment is low during

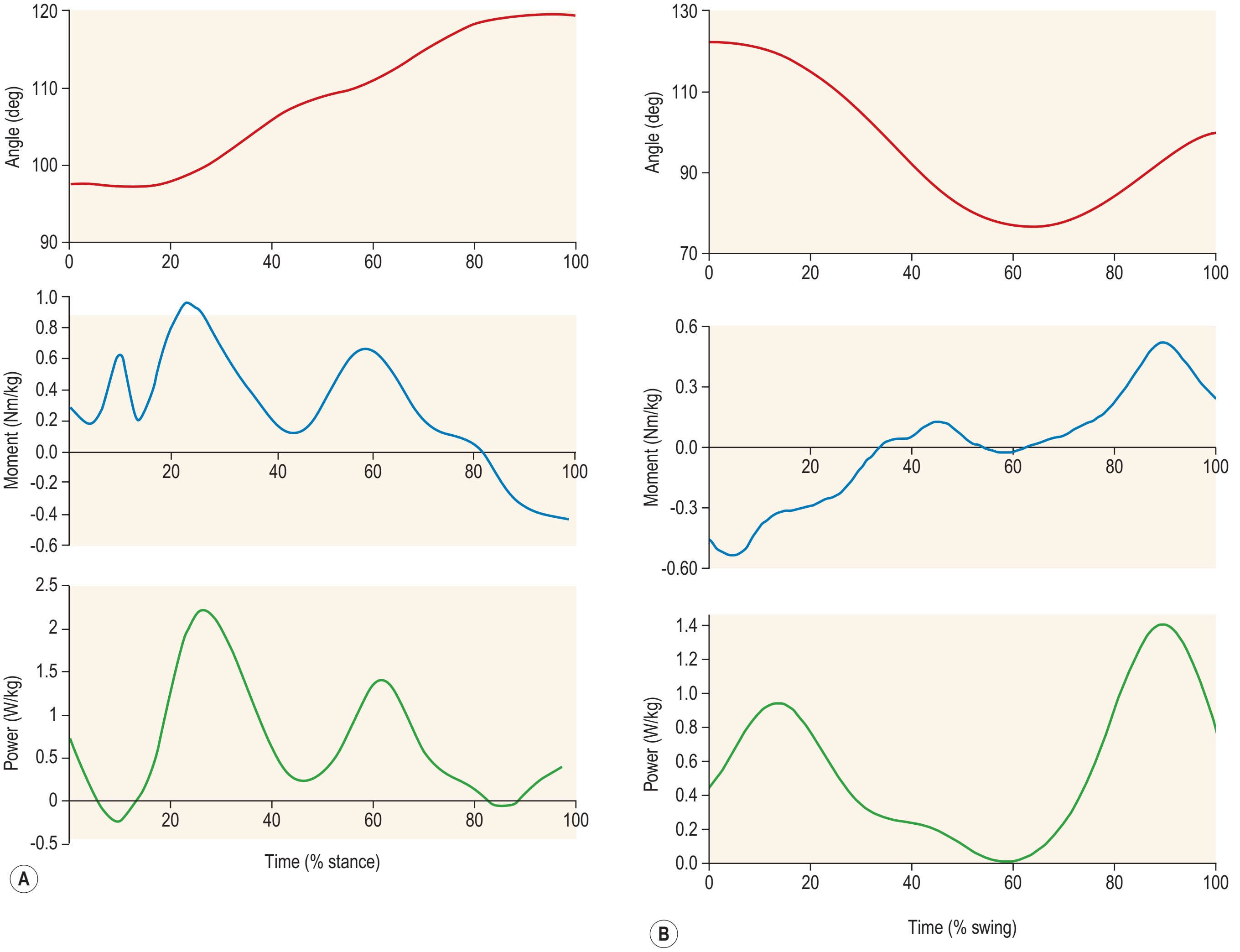

Fig 7.6 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the hip joint during the stance phase (left) and swing phase (right) at the trot.

midswing, then in late swing the extensor moment increases as the hip extensor muscles do positive work to initiate hind-limb retraction in preparation for ground contact (Khumsap, 2002). *Gluteus medius*, *biceps femoris* and *semitendinosus* are active at this time (Robert et al., 1998). The magnitude of this late swing phase burst increases with velocity squared (Clayton et al., 2002), which may reflect the need to overcome the forward kinetic energy (½ mv^2) of the limb.

Stifle joint

After initial ground contact the stifle joint flexes rapidly during loading then shows only minor angular changes through the remainder of the stance phase (Fig. 7.7). Without correction for skin displacement there are errors in the amount of stifle flexion in late stance and in the time of maximal stance phase flexion (Fig. 7.4). In the swing phase, peak flexion of the stifle in midswing tends to be underestimated by skin markers without correction for skin displacement (Back et al., 1995b).

The net joint moment is on the flexor (caudal) side of the stifle through most of the stance with energy generation on the flexor side in early stance and midstance due to the action of the hamstring muscles that provide support and propulsion (Khumsap, 2002; Dutto et al., 2006). In early swing, an extensor moment corresponds with a period of energy absorption as the stifle extensors control the amount of flexion. In late swing, a flexor moment is present as energy is absorbed by the stifle flexors, which are acting eccentrically to control large bursts of joint extension (Fig. 7.7) (Khumsap, 2002). The early swing phase burst of energy absorption increases linearly with velocity, whereas the later burst increases with velocity cubed (Clayton et al., 2002).

Tarsal joint

The tarsal joint flexes rapidly in early stance, after which the flexion–extension pattern in midstance varies between horses; some have a second flexion phase, some show a fairly constant angle through midstance, and in others the joint extends after the initial phase of flexion. Maximal tarsal extension occurs around the end of stance and is followed by a swing phase flexion cycle peaking in midswing via an inflection in early swing that occurs just after passing its angle at square stance (Fig. 7.8) (Kobluk et al., 1989; Holmström et al., 1994; Back et al., 1995b; Khumsap et al., 2003). Correction for skin displacement (Fig. 7.4) produces only minor differences in the tarsal flexion–extension curves (van Weeren et al., 1990; Back et al., 1995b). Even after correction for skin displacement, the tarsus

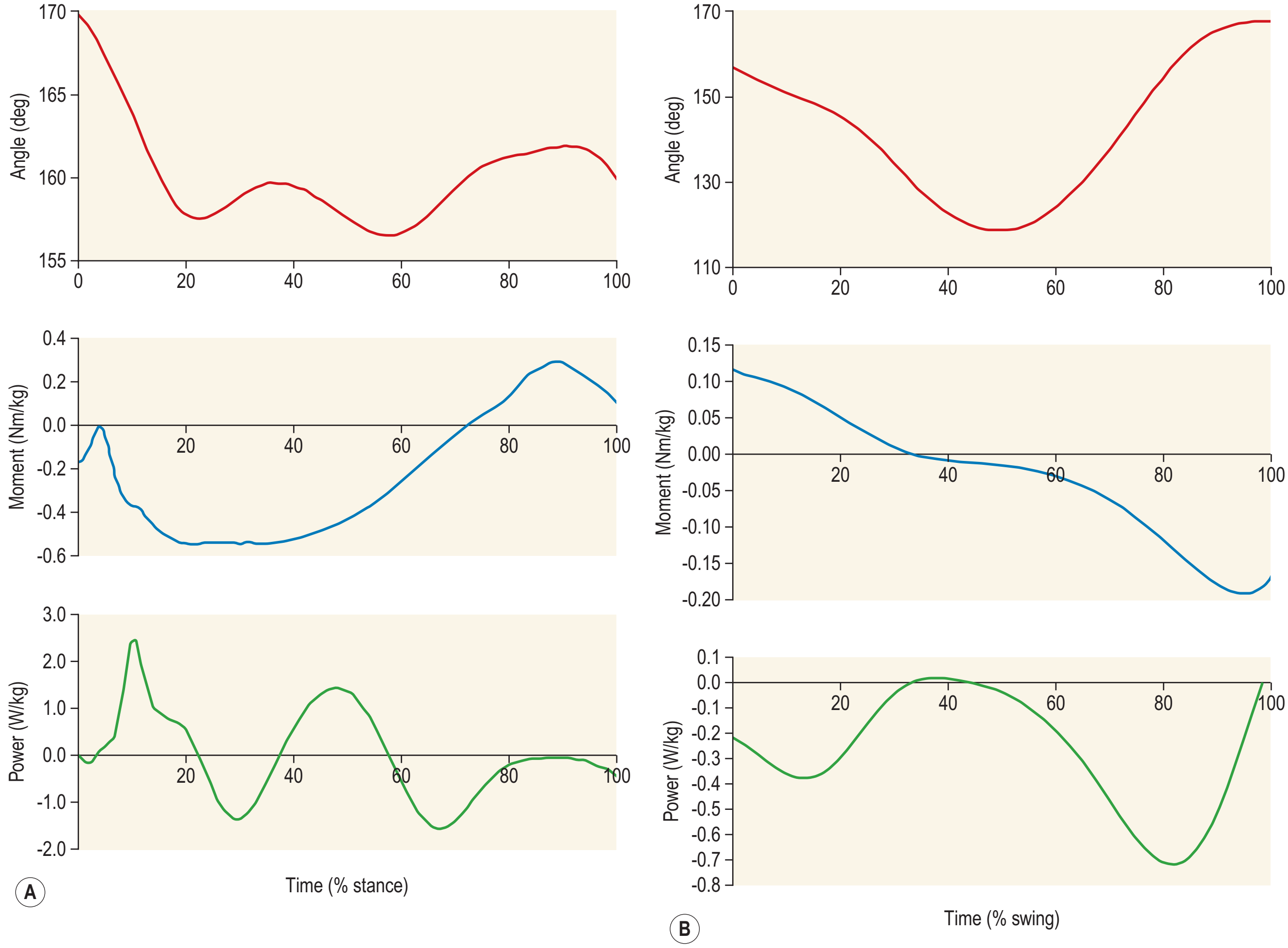

Fig 7.7 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the stifle joint during the stance phase (left) and swing phase (right) at the trot.

appears to extend more than the stifle in late stance due to stretching of *fibularis tertius*, especially at faster speeds. In attempting to explain these discrepancies, Molenaar (1983) assigned functional significance to the axial and abaxial insertions of *fibularis tertius*.

The net joint moment is on the extensor aspect of the tarsus throughout stance, with the value peaking in midstance. The power profile varies somewhat according to the kinematic pattern in midstance but consistent features include a burst of energy absorption in the first half of stance and a burst of energy generation later in stance that may represent elastic recoil (Fig. 7.8) (Dutto et al., 2006). The net joint moment is on the flexor aspect in the first half of swing. It corresponds with a phase of elastic energy release in *fibularis tertius*, which was stretched in late stance. There may also be active energy generation in the tarsal flexors and/or digital extensors, such as the long digital extensor, which shows electromyographic activity at this time (Jansen et al., 1992). The net joint moment moves to the extensor (caudal) side of the tarsus in the second half of swing, when energy generation in the tarsal extensors actively extends the joint and lowers the hoof in preparation for ground contact. This is in contrast to the forelimb in which carpal extension in late swing is due to inertia and is controlled by the carpal extensor muscles. The early swing phase burst of energy generation increases linearly with trotting velocity, whereas the burst of energy generation in late swing increases with velocity cubed (Clayton et al., 2002).

The passive spring action and coupling mechanism in the tarsus can be reproduced in a horse under general anesthesia in lateral recumbency. The joint moves rapidly into maximal flexion or extension as it passes through a critical mid-point angle (Alexander & Trestik, 1989). This snapping action is a consequence of the eccentric attachments of the tarsal collateral ligaments relative to the center of rotation of the tarsocrural joint (Updike, 1984; Badoux, 1987). Inflections in the joint angle–time curves of the tarsal joint *in vitro* indicate the positions at which a labile equilibrium is passed and the joint rapidly flexes or extends. Evidence of this phenomenon is also seen *in vivo*; three-dimensional analysis of tarsal kinematics shows that craniocaudal translation becomes decoupled from tarsal flexion–extension as the joint passes through −50° of flexion and becomes coupled again later in swing as the joint passes back through that same angle (Lanovaz et al., 2002).

Metatarsophalangeal (MTP) joint

After initial ground contact, the MTP joint extends and reaches maximal extension at midstance. The joint then flexes through the remainder of stance to reach a flexion peak in early swing through the passive action of the SDF tendon (Molenaar, 1983). After a slight extension in midswing there is a second flexion peak that occurs close to the time of maximal flexion of the stifle and tarsal

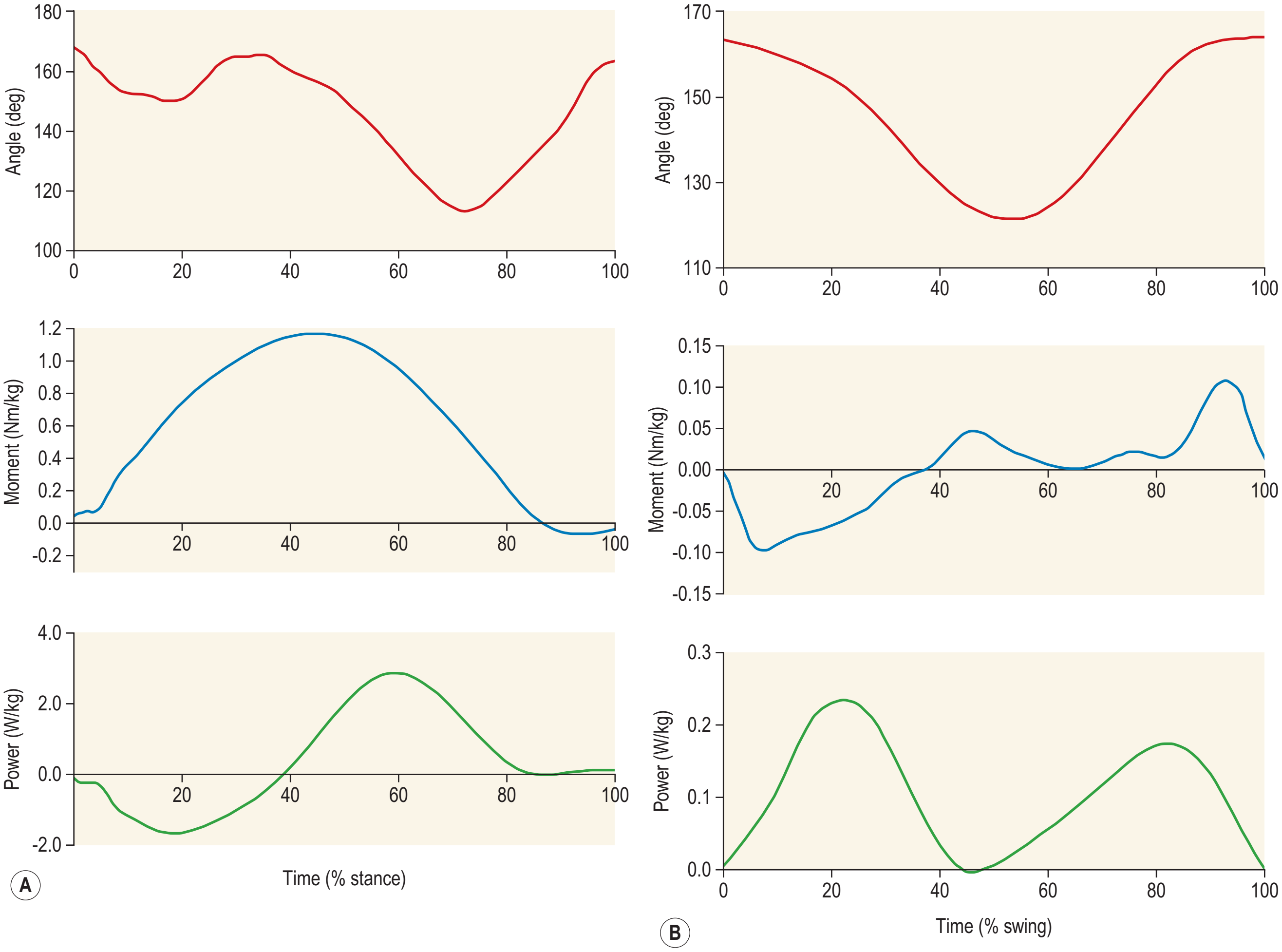

Fig 7.8 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the tarsal joint during the stance phase (left) and swing phase (right) at the trot.

joints. At the end of swing, when the stifle and tarsal joints are extending, the MTP joint extends under the control of the digital flexor muscles (Fig. 7.9). No differences are found between the curves before and after correction for skin displacement when the pastern is treated as a rigid segment (Fig. 7.4) (Back et al., 1995b).

The net joint moment is on the flexor (plantar) aspect of the MTP joint throughout the stance phase, where it acts to support and control the amount of extension. The power profile is typical of elastic energy storage and release with a phase of energy absorption followed immediately by an almost equal phase of energy generation (Fig. 7.9) (Khumsap, 2002; Dutto et al., 2006). At the beginning of the swing phase, MTP flexion is actively supported by activity of the DDF muscle (Jansen et al., 1992), but the net joint moment is on the extensor aspect at this time indicating that the extensors are controlling MTP flexion. The net moment moves to the flexor aspect in the second half of swing to control MTP extension by the long digital extensor tendon in preparation for ground contact (Khumsap, 2002; Dutto et al., 2006).

Distal interphalangeal (DIP) joint

The DIP joint flexes during the rapid loading phase at the beginning of stance reaching peak flexion before midstance. Maximal extension is during breakover in the terminal part of stance. In the swing phase, the DIP joint flexes rapidly via a small flexion peak to reach peak flexion at midswing. It then extends to initial ground contact (Fig. 7.10) (Back et al., 1995b).

The net joint moment is on the flexor (plantar) aspect throughout stance. Some horses show a little negative work in early stance, the presence of which may be related to hoof angulation, then in late stance there is a burst of energy absorption on the flexor aspect of the DIP joint (Fig. 7.10). The net joint moment is on the extensor aspect of the DIP joint in early swing where it acts to control joint flexion during protraction (Khumsap, 2002).

Hoof interaction with the ground

Although the fore and hind distal limbs are anatomically similar, they have different angles, velocities and accelerations during the impact phase (Back et al., 1995d). The hind hooves have a more exaggerated heel first contact and so take longer to become flat on the ground (Merkens & Schamhardt, 1993; Schamhardt & Merkens, 1994; Back et al., 1995d). Furthermore, the angle of the metatarsus at impact is smaller than that of the metacarpus (Clayton, 1994a; Back et al., 1995d).

Within approximately 3% of stride duration, hoof angle, vertical velocity and vertical acceleration of the hoof are zero, but it is not

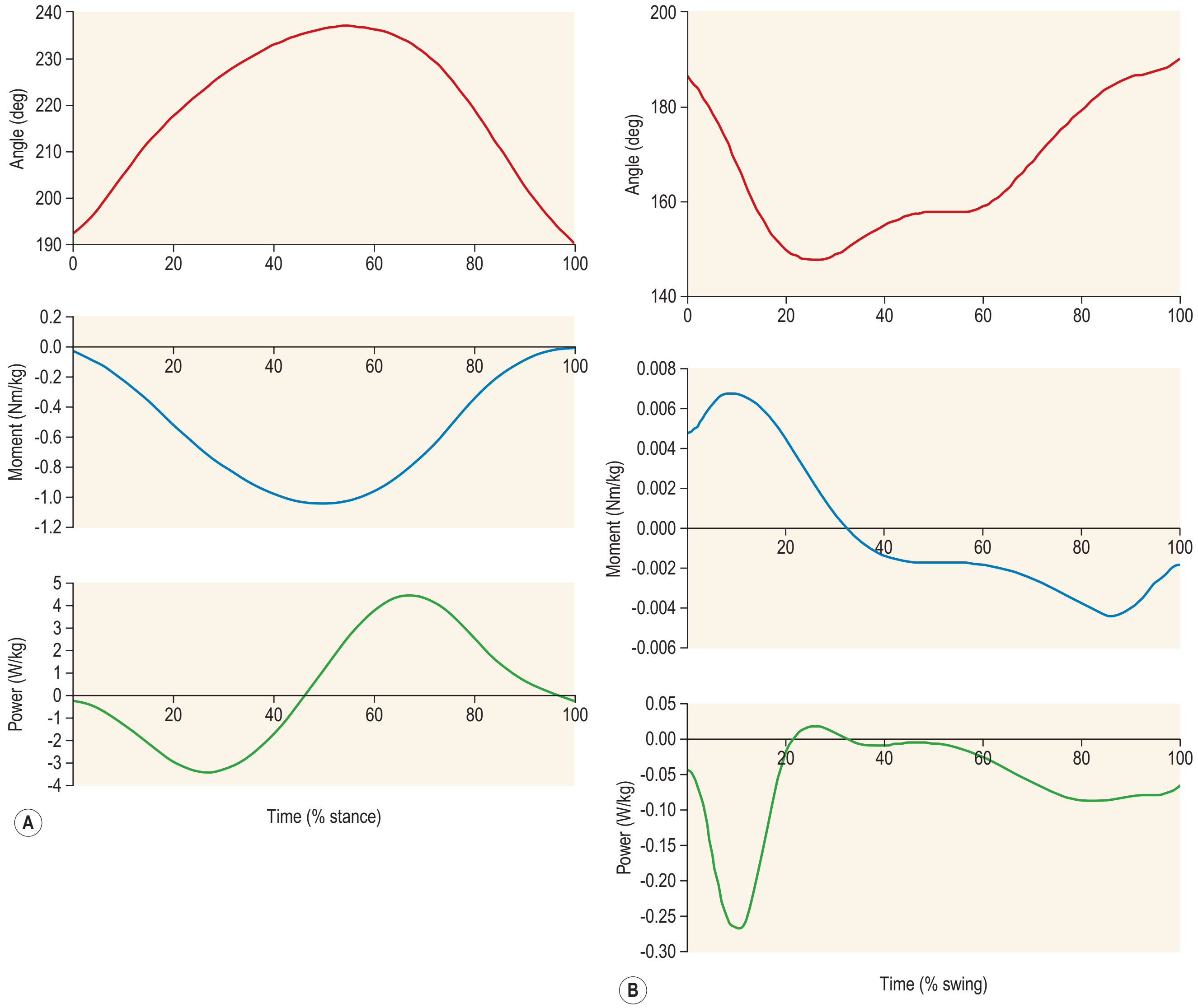

Fig 7.9 Joint angle (above, extension positive), net joint moment (center, extensor moment positive) and net joint power (below, power generation positive) for the metatarsophalangeal joint during the stance phase (left) and swing phase (right) at the trot.

until approximately 6% of stride duration that the horizontal velocity and acceleration decline to zero.

The fore hoof contacts the ground with a higher vertical velocity and bounces more at impact, whereas the hind hoof has a higher horizontal velocity and shows more sliding (Back et al., 1995d; Johnston et al., 1995, 1996). Impact is associated with high frequency oscillations that are still visible in the MTP joint acceleration–time diagram until 14% of stride duration (Fig. 7.11) (Schamhardt & Merkens, 1994; Back et al., 1995d). Impact oscillations are dampened by the hoof and other structures as they are transmitted proximally. The net effect of changes in hind limb joint angles during early stance is to shorten the distance from hip to hoof (Hjertén et al., 1994), which also contributes to the shock-absorbing capacity of the hind limb.

Kinematic differences between the distal fore and hind limb might explain the lower incidence of chronic lameness in the hind limbs compared with the forelimbs (Stashak, 1987). Repetitive impulsive loading in combination with rapid oscillations in the joint, even within physiological limits, plays a mechanical role in the development of osteoarthrosis (Radin et al., 1991).

The walk

The walk and trot are both symmetrical gaits, but they differ in inter-limb coordination. The walk is a four-beat gait with a lateral sequence of limb placements in which there is always at least one fore and one hind foot on the ground. Since there is no suspension or aerial phase, the walk is classified as a stepping gait, which affects the patterns of limb loading and force distribution.

In the literature stick figures and joint angle–time diagrams for the hind limbs during walking have been reported for individual horses (Walter, 1925; Krüger, 1937, 1938; Fleiss et al., 1984) and groups of horses of various breeds (Back et al., 1996, Galisteo et al., 1996; Hodson et al., 2001; Nicodemus & Holt, 2006; Martuzzi et al., 2007). Walk and trot kinematics are similar with regard to the intra-limb coordination pattern (Fig. 7.12), stance distance and swing duration but since the trot is a faster gait than walk, the limb shows the same movements in a shorter time (Back et al., 1996). The hind limb is less loaded during stance and has smaller vertical ground reaction forces at walk compared to trot (Ueda et al., 1981; Merkens & Schamhardt, 1994; Schamhardt &

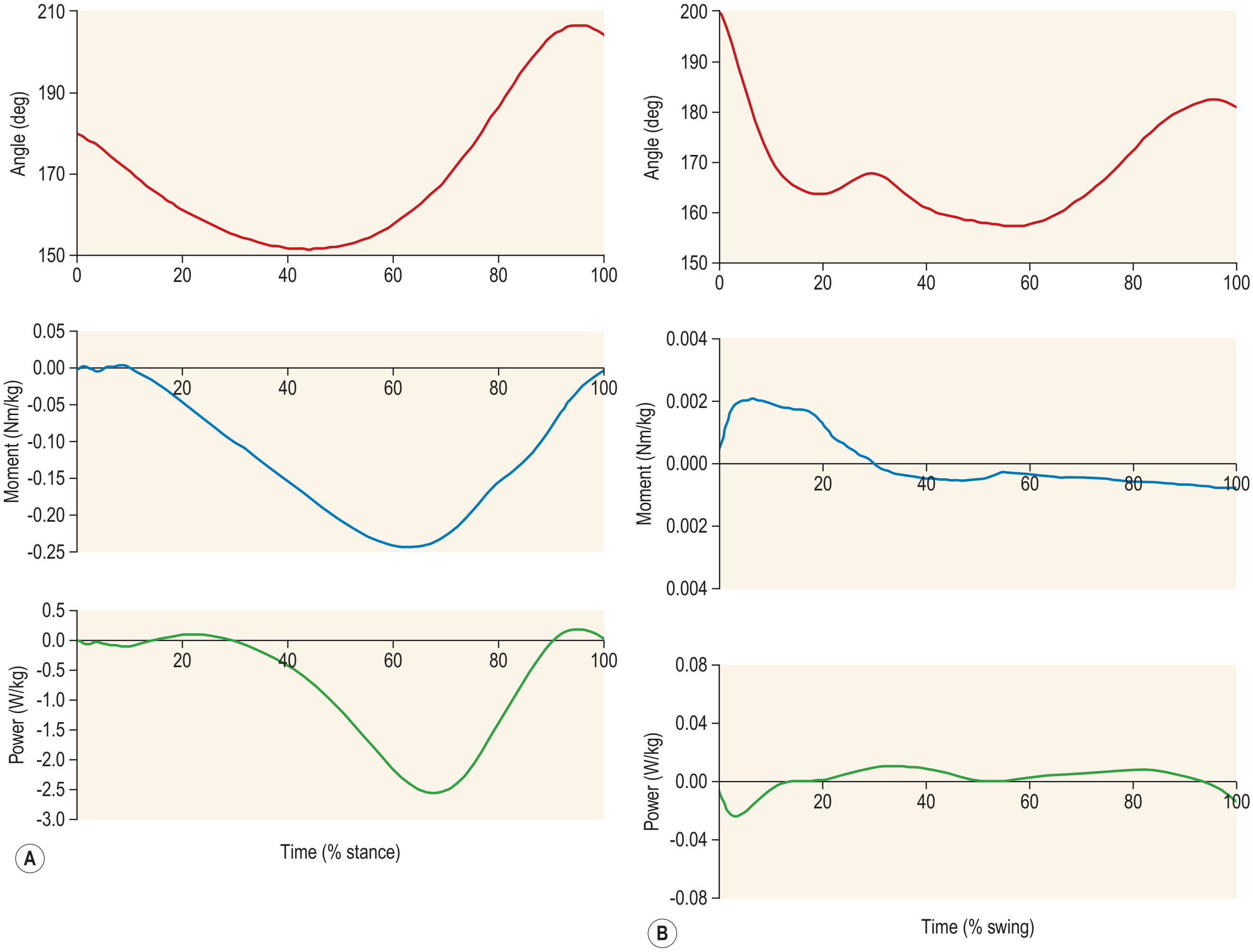

Fig 7.10 Joint angle (above, extension positive), net joint moment (center, extension moment positive) and net joint power (below, power generation positive) for the distal interphalangeal joint during the stance phase (left) and swing phase (right) at the trot.

Merkens, 1994), which is associated with less MTP extension and less tarsal flexion during stance. Push-off is less powerful in walk than trot.

At a walking speed of 1.6 m/s, hind stance duration occupies 63.4% of stride duration (Table 7.3) (Back et al., 1996). Stance duration is negatively correlated with walking velocity (McLaughlin et al., 1996; Khumsap et al., 2001a). Although swing duration is the same for walk and trot, the limbs swing through a smaller range of motion at walk, requiring less force and impulse generation. The stifle and tarsal joints are less flexed during the swing phase at walk, which results in a longer pendulum and a slower forward swing.

During walking, the vertical ground reaction force of the hind limb shows two peaks separated by a dip. As walking velocity increases, the first vertical force peak increases, while the dip decreases and becomes more distinct. This indicates that, as the horse walks faster, the limb is loaded more in early stance and then unloaded to a greater extent in midstance, which is partly due to rebound of the more heavily loaded limb spring. At very low velocities, the vertical dip almost disappears (Khumsap et al., 2001a). The hind limb longitudinal ground reaction force has a braking phase followed by a propulsive phase that peaks just before the start of breakover. At walk, only one limb provides braking and only one limb provides propulsion at any time (Merkens et al., 1986). The timing of the peaks in the longitudinal force do not appear to be related to kinematic events and the magnitudes of the peaks do not change with velocity (Khumsap et al., 2001a). The left and right hind stance phases overlap by 12% of stride duration and, during this time, the vertical and braking longitudinal forces increase in the hind limb that is accepting weight. The first vertical force peak coincides with lift-off of the contralateral hind limb. The dip in vertical force occurs during tripedal support (one hind, two fore), then the second peak is during the support by a lateral pair of limbs. The midstance position, marked by the hind hoof being vertically beneath the hip joint, occurs at 28% stride, which is close to the time that the longitudinal force changes from braking to propulsive at 30% stride (Hodson et al., 2001).

Flexion and extension of the hip joint are responsible for protraction and retraction of the entire hind limb during walking. Maximal protraction occurs shortly before the end of swing, and maximal retraction is during breakover. The thigh, crural and metatarsal segments rotate caudally with fairly constant angular velocities through the middle part of stance. As the limb is loaded in early stance, the stifle, tarsal and DIP joints flex and the MTP joint hyperextends. After an initial flexion, the tarsus extends through the remainder of stance, while the stifle flexes a little after midstance. The MTP joint extension pattern during the stance phase at walk has two extension peaks coinciding with those in the vertical ground reaction force. These peaks are more pronounced at a faster walk and ‘melt’ into one extension peak at the trot, similar to vertical ground reaction force recordings at walk and trot (Back et al., 1996; Niki et al., 1982).

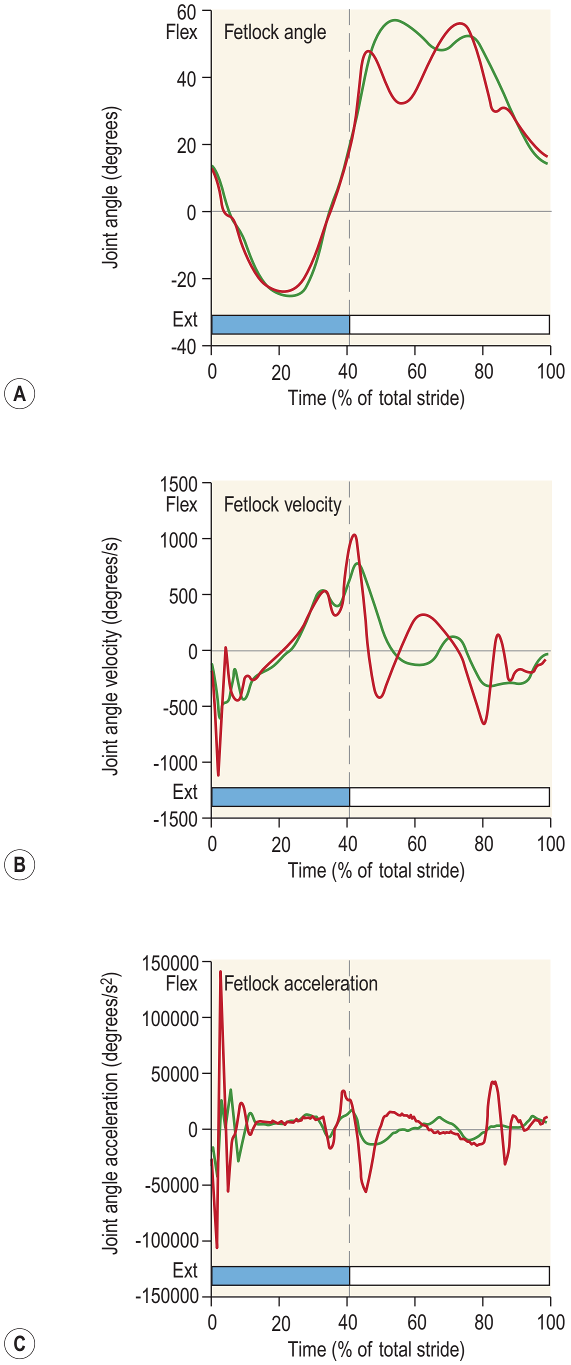

Fig 7.11 Metatarsophalangeal joint angle–time (above), angular velocity–time (middle) and angular acceleration-time (below) graphs of the fore- and hind-limb metatarsophalangeal joints for a group of horses trotting on a treadmill. At bottom of graph, blue bar indicates stance phase, white bar indicates swing phase.

Reprinted from Back, W., 1995. Repetitive loading and oscillations in the distal fore and hind limb as predisposing factors for equine lameness, American Journal of Veterinary Research, http://avmajournals.avma.org/loi/ajvr.

After the heels leave the ground at 55% stride, the thigh and metatarsal segments reverse their direction of rotation and begin to swing cranially during breakover, while the crus continues to rotate caudally with almost constant angular velocity. Maximal hind limb retraction occurs just before lift-off at 63% stride and coincides with the reversal in the direction of rotation of the thigh segment. At the start of the swing phase, the hip, stifle and tarsal joints flex to raise and protract the distal limb. The crural, pastern and hoof segments start to swing cranially soon after the hind hoof lifts off (around 70% stride), which coincides with the first swing phase flexion peak at the MTP joint. Peak flexions of the stifle, tarsal and DIP joints occur around 80% stride, followed by peak hip flexion at 85% stride. The thigh and cannon segments reverse their direction of rotation and begin to swing caudally at 90% stride followed by the crural segment at 95% stride. Maximal hind-limb protraction occurs at 97% stride.

The net joint moment is on the caudal/plantar side of all hind limb joints at the start of stance when the limb is being actively retracted. It moves to the cranial/dorsal side around 24% stride at the hip and stifle and in terminal stance at the more distal joints. It remains on the cranial/dorsal side of all joints during the first half of swing when the proximal joints provide active limb protraction, then moves to the caudal/plantar aspect to initiate retraction prior to ground contact. The hip joint is the main source of energy generation during walking. It is assisted by the tarsal joint, in both stance and swing phases, and by the MTP joint during stance. The DIP joint acts as an energy damper during stance, whereas the stifle joint absorbs almost equal amounts of energy in stance and swing phases. The DIP and MTP joints absorb energy as the limb is protracted and retracted during the swing phase suggesting that their movements are driven by inertial forces and are controlled by muscles acting eccentrically (Clayton et al., 2001).

An increase in walking velocity is associated with increases in magnitudes of the net joint moments and peak powers at the hip, stifle, tarsal and MTP joints in early stance. Energy generation at the hip makes the largest contribution to the increase in velocity assisted by the tarsus, which contributes to the forward and upward acceleration of the limb into the swing phase (Khumsap et al., 2001b). Peak powers and energy bursts are considerably lower at walk than at trot (Clayton et al., 2001), which is similar to the situation in humans (Chapman & Caldwell, 1983).

The canter

The canter is an asymmetrical gait in which the footfalls of both the fore and hind limbs occur as couplets. The first limb of the couplet to contact the ground is defined as the trailing limb, the second is the leading limb. The sequence of footfalls is trailing hind limb, leading hind and trailing forelimbs together, then the leading forelimb. An aerial phase usually follows lift-off of the leading forelimb. The transition from a slow speed canter to the higher speed gallop involves dissociation of the footfalls of the diagonal limb pair (leading hind and trailing fore).

In the literature, canter has been described at speeds ranging from 3–11 m/s. The recordings were made under various circumstances from a collected canter of a mounted horse overground to an extended canter of an unmounted horse on a treadmill (Clayton, 1994b; Corley & Goodship, 1994; Deuel & Park, 1990). Canter kinematics have been illustrated using stick diagrams (Walter, 1925; Krüger, 1937, 1938) and diagrams illustrating the coordination of inter-limb timing variables (Deuel & Park, 1990; Clayton, 1993, 1994b). Changes in temporal and linear kinematics induced by training have also been described (Corley & Goodship, 1994).

Back et al. (1997) compared the kinematics of the leading and trailing hind limbs of Warmblood horses, cantering on a treadmill at a speed of 7 m/s (Fig. 7.13), and found greater protraction in the leading hind limb, due to more hip flexion, and greater retraction in the trailing hind limb (Table 7.3). As the leading hind limb has a somewhat larger total range of maximal protraction and retraction, the tarsal joint has to be more flexed to allow the distal limb to reach further in the same swing time. As a consequence of the asymmetry in inter-limb timing between trailing and leading limbs

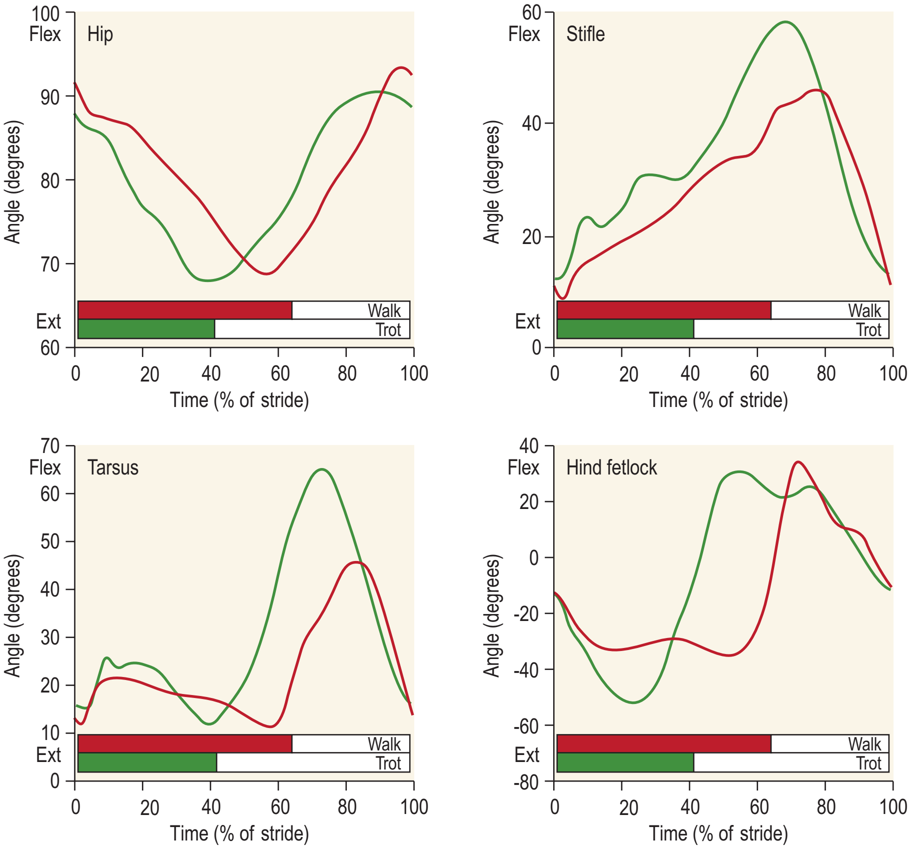

Fig 7.12 Mean joint angle–time diagrams of the hind limb joints of a group of horses walking at 1.6 m/s (red line) and trotting at 4 m/s (green line) on a treadmill. The joint angles are defined as zero when the adjacent bone segments are aligned. Bars at bottom of graph indicate stance and swing phases at walk (red bars) and at trot (green bars).

Reprinted from Keg, P.R., Scharmhardt, H.C., van Weeran, P.R., et al., 1996. The effect of the high palmar nerve block and the ulnar nerve block on lameness provoked by a collagenese-induced tendonitis of the lateral branch of the suspensory ligament, Veterinary Quarterly, 18, sup 2, with permission from Taylor & Francis Ltd, http://www.informaworld.com.

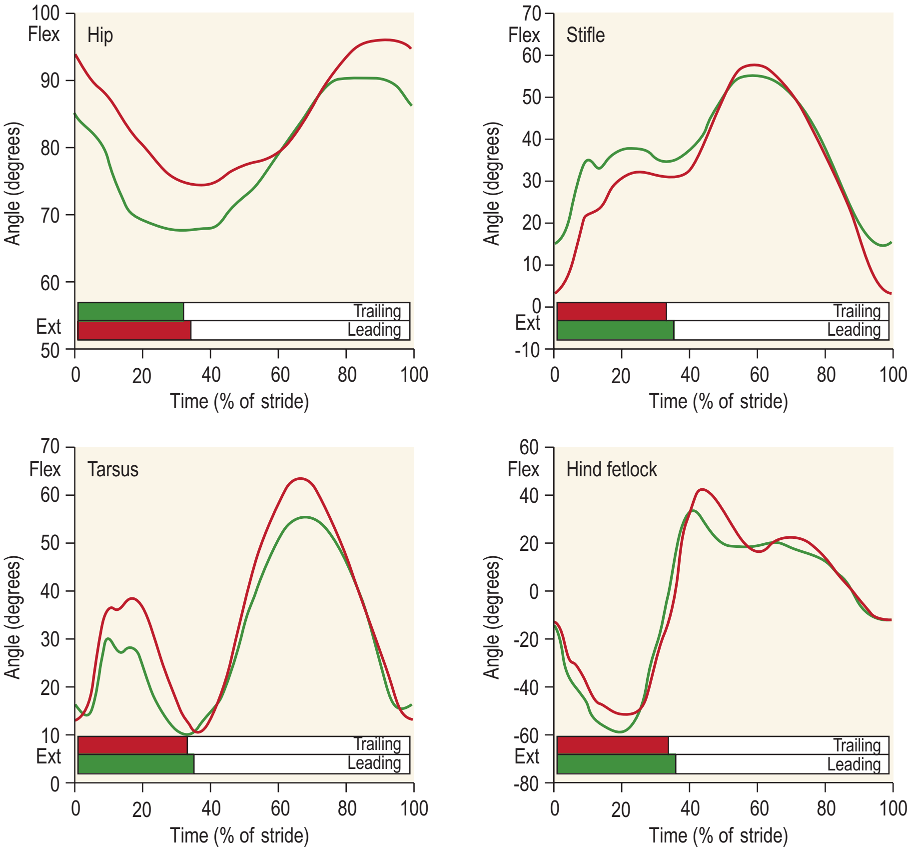

Fig 7.13 Mean joint angle–time diagrams of the trailing (red line) and leading (green line) hind limbs of a group of horses cantering on a treadmill at 7 m/s. Joint angles are defined zero when the adjacent bone segments are aligned. The bars at the bottom of the graphs show the stance phase of trailing limb in red and stance phase of leading limb in green.

Back, W., Hartman, W., Schamhardt, H.C., Bruin, G., Barneveld, A., 1995c. Kinematic response to a 70-day training period in trotting Dutch Warmbloods. Equine Vet. J. 18 (Suppl.), 127–131, with permission from the Equine Veterinary Journal.

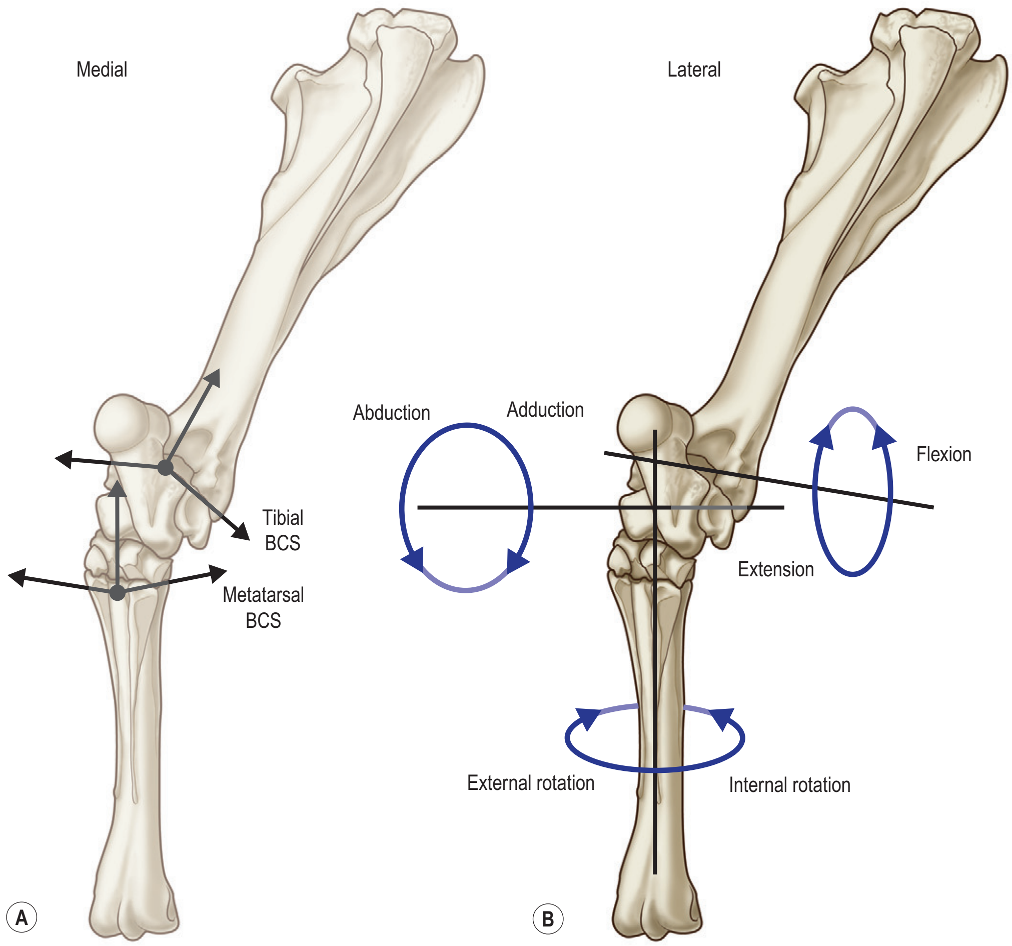

Fig 7.14 Caudolateral view of the right tarsus showing the local coordinate systems of the crural and metatarsal segments (left) and the three rotations measured in three-dimensional analysis of the tarsus (right).

Reprinted from Lanovaz, J.L., Khumsap, S., Clayton, H.M., Stick, J.A., Brown, J., 2002. Three-dimensional kinematics of the tarsal joint at trot, Equine Vet. J., 34 (Suppl.), 308–313, with permission from the Equine Veterinary Journal.

at canter, the hind footfalls occur as couplets. The trailing limb is the supporting limb and carries more load.

Three-dimensional kinematics of the tarsal joint at trot

Three-dimensional tarsal kinematics have been measured using marker triads fixed rigidly to the tibia and third metatarsus (Fig. 7.14) to describe three-dimensional motion in terms of three rotations (flexion–extension, abduction–adduction, internal–external rotation) and three translations (mediolateral, craniocaudal and proximodistal) (Lanovaz et al., 2002). At a velocity of 2.8 m/s, stance duration occupied 38% of the stride. Flexion–extension patterns and magnitudes were very similar to those recorded during sagittal plane analysis, even though the flexion–extension axis is defined differently in two-dimensional and three-dimensional analyses (Fig. 7.14). This is not surprising, however, since even large misalignments of the flexion–extension axis have little effect on the measured values when this is the dominant motion (Ramakrishnan & Kadaba, 1991). The tarsus flexes during stance, reaches peak extension around the time of lift-off, then undergoes a larger flexion cycle during swing. Abduction–adduction appears to be coupled with flexion–extension; there is a small cycle of abduction in stance and a larger cycle in swing with approximately 1° of abduction for every 3° flexion. In stance, there is a small cycle of internal rotation followed by a small cycle of external rotation in swing (Fig. 7.15). Translational movements in the stance phase consist of cranial then caudal translation, lateral then medial translation and distal followed by proximal translation. The same patterns occur in the swing phase but the magnitudes are larger in accordance with the greater angular excursions.

The tarsocrural joint is assumed to be the source of most of the motion of the tarsus. The trochlea of the talus and the tibial cochlea act like threads on a bolt with the tibia following an almost circular path along the talar ridges (Badoux, 1987). Experimental measurements are in general agreement with these predictions (Lanovaz et al., 2002). If the tarsocrural joint behaves as a pure screw joint and is the only source of motion within the tarsus, all movements should be highly coupled to the flexion–extension angle and any non-coupled movement would indicate motion at other sites within the joint complex. Abduction–adduction and the three translations are strongly coupled with flexion–extension but internal–external rotation is uncoupled during weight-bearing. In the swing phase, around 55% of stride duration, the cranial–caudal displacement becomes uncoupled from flexion–extension indicating that the third metatarsus is displaced slightly cranially relative to the talus and tibia.

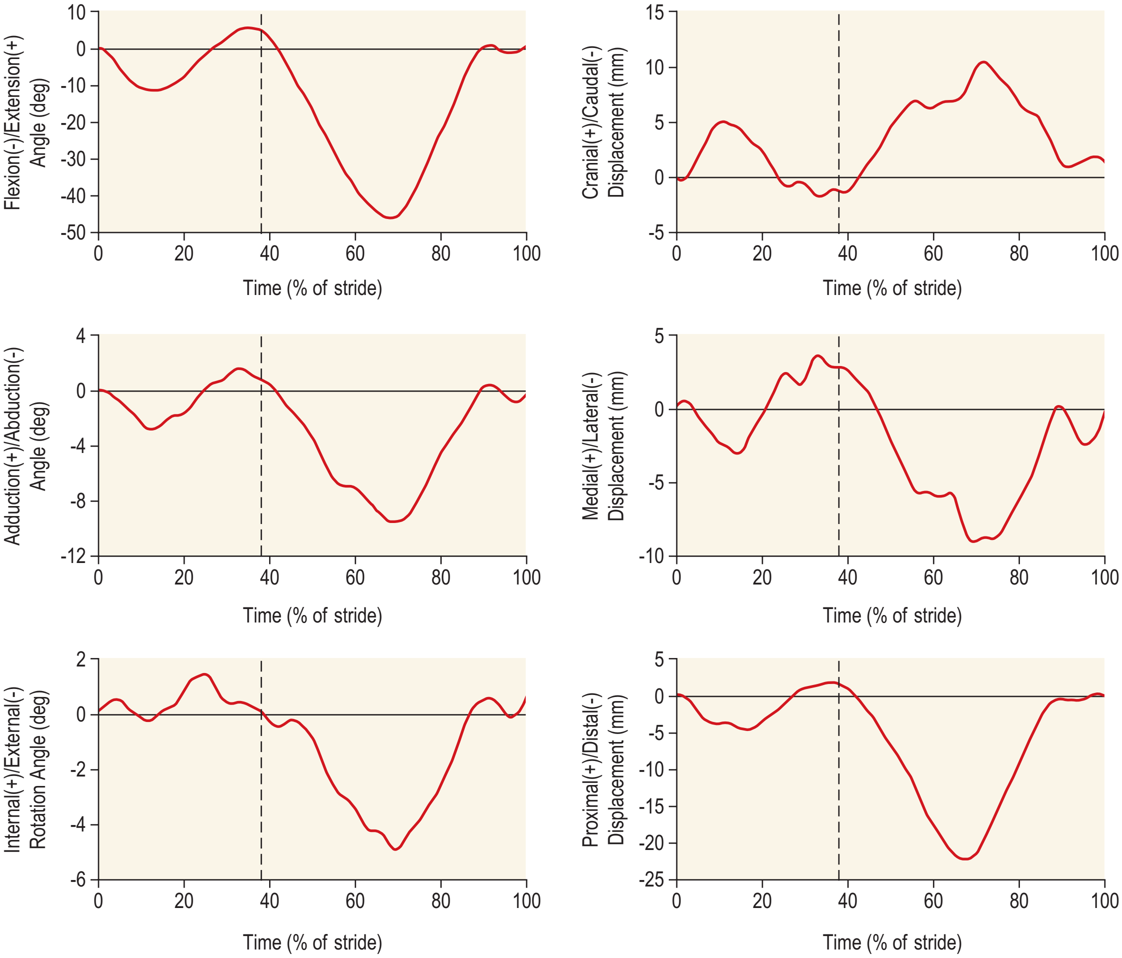

Fig 7.15 Three rotations and three translations measured at the tarsal joint during trotting overground at 2.8 m/s. Left panel shows rotations: flexion–extension (above), abduction–adduction (middle) and external–internal rotation (below). Right panel shows translations: craniocaudal (above), mediolateral (middle) and proximodistal (below). Vertical dashed lines show transition from stance to swing phase.

Reprinted from Lanovaz, J.L., Khumsap, S., Clayton, H.M., Stick, J.A., Brown, J., 2002. Three-dimensional kinematics of the tarsal joint at trot. Equine Vet. J. 34 (Suppl.), 308–313, with permission from the Equine Veterinary Journal.

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CHAPTER 8

The role of the hoof and shoeing

Willem Back, Frederik Pille

Introduction

To deliver maximal performance it is essential that a horse has good balance. A part of the required balance comes from factors connected to the hoof (Balch et al., 1991a; Curtis, 1999, Aoki, 1999; Arabian et al., 2001; Eliashar, 2007). 'No foot, no horse' is a well-known saying that emphasizes the important role of the hoof (Davies, 2002).

After domestication of the horse 5000–6000 years ago, man assumed much of the responsibility for the balance between hoof growth and hoof wear. The Greek horse people (hippiaters) were in favor of breeding horses with good hoof quality that did not need shoes. The Romans invented the hipposandal that was attached to the hoof with straps and was used to protect the feet of the horse en route to the battlefield, where they were removed. The first iron horseshoes with nails were made by the Celts 2000 years ago and were similar to the ones we use today (Fig. 8.1).

During locomotion every stride involves forces at the hoof–ground interface that load the locomotor apparatus. Repeated application of forces that have a high magnitude and/or an abnormal direction of action, overload the limb and may lead to the development of pathological processes (Johnston & Back, 2006). When we have an insight how these forces work, we can modulate them by corrective hoof trimming and optimal shoeing as rational measures to treat and prevent lameness, e.g. at purchase (Anderson, 1992). That is the basic theme of this chapter.

Functional anatomy of the foot

General anatomy

The equine foot has evolved from the third digit, which has been greatly elongated and strengthened. The hoof wall has developed from the nail of the third digit. The hoof of the first digit is still present, though rudimentary, in the form of the chestnut on the medial side of the radius (forelimb) or metatarsus (hind limb), while that of the fifth digit, especially in Coldbloods, persists as the ergot on the palmar/plantar side of the metacarpo-/metatarsophalangeal joint (Dyce & Wensing 1980; Pollitt 1995).

The hoof capsule consists of several parts: the coronet, the wall, the sole, the frog and the heels (Fig. 8.2). The horn of each part of the hoof is produced by a corresponding area of dermis (corium). The estimated horn regeneration time based on a growth rate of 8–10 mm/month is 12 months for the toe, 6–8 months for the quarters, and 4–5 months for the heels. The coronet separates and connects the skin above from the hoof wall below. Deep to the coronet lies the dermis that produces the horn tubules of the hoof wall via the horn papillae, which project distally into the horn of the hoof wall. The horn tubules are responsible for the striated appearance of the hoof wall. The nonpigmented innermost part of the tubular hoof wall is less stiff than the outer part and serves as a mechanical buffer zone assisting the feet of horses in transmitting load through the tissues without inflicting damage (Wagner et al., 2001, 2002).

Projecting from the inner surface of the hoof wall are the primary epidermal lamellae (600/hoof) and secondary epidermal lamellae (100–200/primary lamella). The insensitive horn of these epidermal lamellae interdigitates with the sensitive dermal lamellae to form the functional connection between the hoof wall and P3. The horn that forms the epidermal lamellae is unstructured (non-tubular). As the hoof wall grows, it moves distally by a mechanism that allows the primary epidermal lamellae to slide past the stationary secondary epidermal lamellae. Primary epidermal laminae morphology (spacing, orientation and curvature) is responsive to mechanical stress at the laminar junction (Thomason et al., 2005, 2008). On the solar surface, the white line demarcates the junction between sensitive and insensitive tissues and is in fact a distal projection of dermal and epidermal laminae (cf. terminal papillae). When shoes are nailed in place, the nails should enter peripheral to the white line.

The bony skeleton of the hoof consists of the distal phalanx (P3) or coffin bone, the navicular bone and part of the middle phalanx (P2) or short pastern bone. All three of these bones take part in the formation of the distal interphalangeal or coffin joint (Fig. 8.3). During flexion of the coffin joint, the navicular bone generally follows the coffin bone although small but consistent motions exist between the navicular bone and the coffin bone (Bowker et al., 2001; Van Dixhoorn et al., 2002).

The medial and lateral hoof cartilages (ungual cartilages) are square-shaped structures located on either side of P3 and are connected to P1 and P2 by connective tissue. They are large and flexible. Between them lie the digital cushion and a venous plexus. Compression of these structures during locomotion assists the return of venous blood to the heart (Hoffman et al., 2001; Pietra et al., 2004). The navicular bone is connected to P3 by the distal navicular or 'impar' ligament, to P2 by connective tissue and the synovial membranes of the coffin joint, navicular bursa and tendon sheath, and to P1 by the proximal navicular ligaments. The navicular bone is covered on one side by hyaline cartilage and on the opposite side by fibrocartilage (Viitanen et al., 2003b). Its hyaline cartilage side is in contact with the palmar/plantar aspect of P2 and P3. The deep digital flexor tendon (DDFT) curves around the palmar/plantar

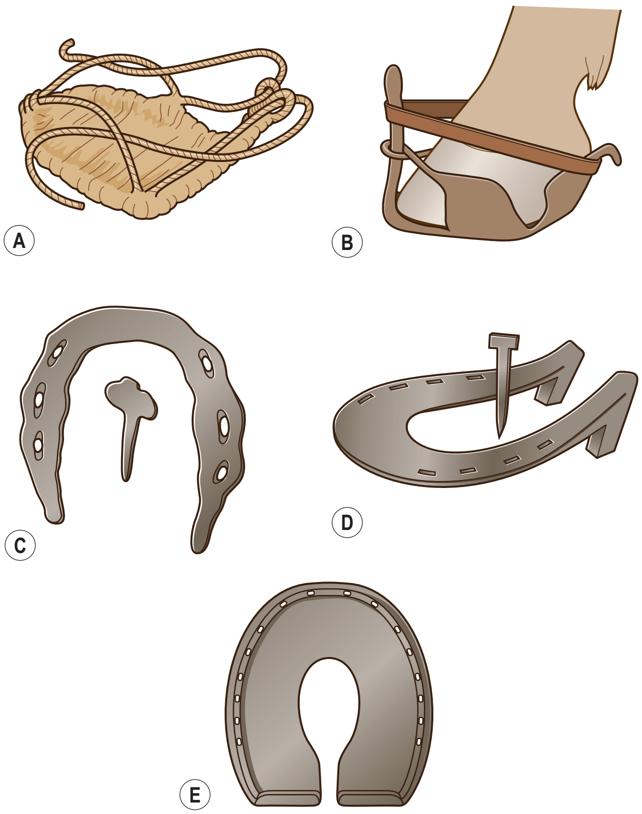

Fig 8.1 The development of the horseshoe. (A) Ancient grass sandal. (B) Roman iron hipposandal fastened without nails. (C) Celtic horseshoe with oval nailholes. (D) Medieval shoe with square nail holes. (E) Renaissance shoe with fullering.

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aspect of the navicular bone before attaching to the flexor surface of P3. The navicular bursa is interposed between the DDFT and the fibrocartilage of the navicular bone.

Vascular supply

The blood supply enters the hoof via the palmar/plantar digital arteries, which run through the terminal arch within P3 (Fig. 8.4). A network of arteries perforates the dorsal surface of P3 and ramifies in the lamellar dermis. Some branches from this plexus are directed proximally to supply the coronet, where they anastomose with branches of the circumflex artery of the coronet. The dorsal branches leave the palmar/plantar digital arteries just before they enter the terminal arch of P3. The palmar/plantar branches run to the heel region where they form the venous plexus and anastomose with the circumflex artery of the sole.

Nerve supply

The hoof is innervated by the palmar/plantar digital nerves, which are located caudal to the vein and artery in the pastern region (Fig. 8.5). The nerves can be blocked by injection of a local anesthetic at the proximal pastern level where the nerves are crossed by the ligament of the ergot (low palmar block) or more distally as the nerve passes deep to the hoof cartilage (palmar digital block). Palmar digital nerve blocks anesthetize the caudal third of the hoof and its contents; low palmar nerve blocks just distal to the fetlock joint anesthetize the entire hoof.

Proprioception

Bowker et al. (1993, 1995) described the concentration of nociceptors in the palmar/plantar part of the frog and in the proximal navicular area. It is hypothesized that these so-called lamellar bodies supply the central nervous system and the brain with proprioceptive information describing the location of the body in space (Van Wulfen & Bowker, 2002). This information is needed to control the central pattern generator (CPG) and thus intra- and inter-limb coordination (Fig. 8.6).

Studies of the effects of local anesthesia in sound horses have yielded conflicting results. Keg et al. (1996) demonstrated no effect of a low palmar nerve block on gait symmetry as evaluated kinetically, whereas Kübber et al. (1994) did detect some kinematic effects. It is not known whether the differences between these studies were due to the sensitivity of the analytic equipment or to the (un-) soundness of the horses.

Hoof mechanics in the standing horse

Hoof–pastern axis

Ideally, hoof trimming optimizes the interaction between the hoof and the ground during locomotion. Since the hoof is a three-dimensional structure, it should be balanced in both the craniocaudal and mediolateral planes. Forces at the toe, medial and lateral heels collectively are optimally distributed when the hoof and pastern angles are aligned (Balch et al., 1997; Davies, 2002).

Hoof balance

Craniocaudal balance

Craniocaudal balance evaluates the hoof in a lateral view (Fig. 8.7). It is assessed with the horse standing square on a level surface. Alignment of the dorsal hoof wall with the pastern axis is achieved by adjusting the absolute and relative lengths of the heels, the quarters and the toe. A hoof that is balanced in this manner usually contacts the ground flat-footed or slightly heel first. When the hoof has a more acute angle than the pastern, the hoof–pastern axis is said to be broken backwards. Conversely, when the angle of the hoof is more upright than that of the pastern, the hoof–pastern axis is said to be broken forward. Radiographic studies have shown that P1 is always a little more upright (vertical) than P2 and P3 with the three phalanges being most closely aligned when the hoof is trimmed with the dorsal hoof wall parallel to the pastern axis (Bushe et al., 1987). Under these circumstances the angle between the solar surface of P3 and the ground is approximately 5°, whereas the dorsal face of P3 is parallel to the dorsal hoof wall at a distance of about 19 ± 0.5 mm in Warmbloods (Back, 2001).

There is a difference between the shape of the fore and hind hooves: the fore hoof is wider and usually has a smaller (more acute) hoof angle, while the hind hoof is narrower and has a larger hoof angle. In farriery books (Hermans, 1984; Hertsch et al., 1996; Ruthe et al., 1997), angles ranging from 45–50° for the forelimbs and 50–55° for the hind limbs have been reported, but more recently the average angles have been reported to be over 50° in the forelimb and over 55° in the hind limbs (Clayton, 1988; Kobluk et al., 1990; Balch et al., 1991a; Butler, 1995; Hickman & Humphrey, 1997; Oosterlinck et al., 2010c). In racehorses, a significant decrease in hoof angle was observed in association with starting fast exercise work (Peel et al., 2006). According to the same study,

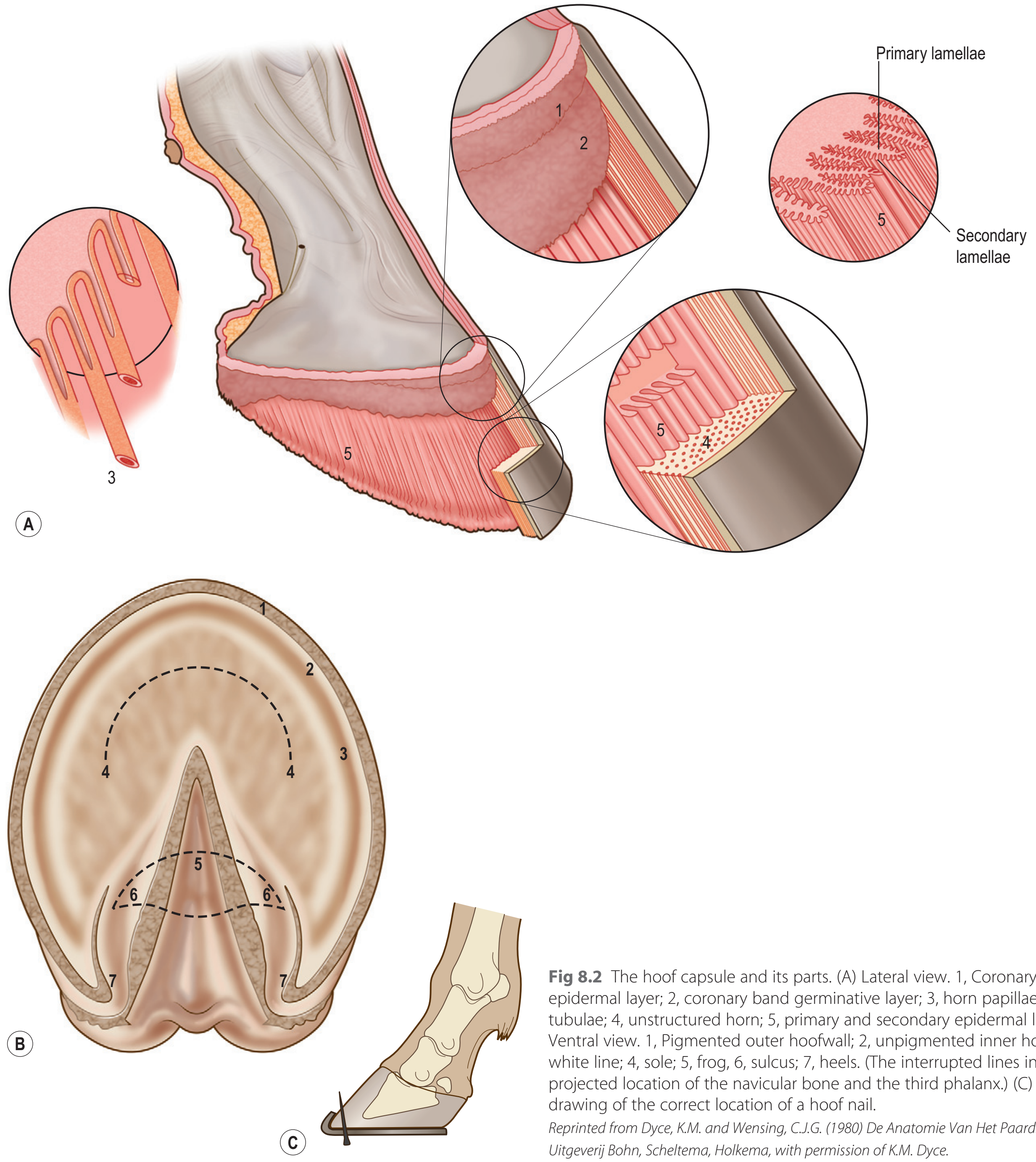

Fig 8.2 The hoof capsule and its parts. (A) Lateral view. 1, Coronary band epidermal layer; 2, coronary band germinative layer; 3, horn papillae and tubulae; 4, unstructured horn; 5, primary and secondary epidermal lamellae. (B) Ventral view. 1, Pigmented outer hoofwall; 2, unpigmented inner hoofwall; 3, white line; 4, sole; 5, frog, 6, sulcus; 7, heels. (The interrupted lines indicate the projected location of the navicular bone and the third phalanx.) (C) Schematic drawing of the correct location of a hoof nail.

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wet pasture conditions may also be associated with a reduced hoof angle.

There exist also differences in hoof shape between contralateral limbs. A study on radiographic measurements of the front feet of normal Warmblood horses found that in 70% of the horses the left hoof capsule and coffin bone were significantly larger than the right (Kummer et al., 2006; White et al., 2008). According to Wilson et al. (2009), contralateral differences in hoof spread are related to generalized asymmetry in forelimb left–right morphometry. Contralateral differences in hoof shape may suggest unequal loading of limbs, which in turn may contribute to injuries and reduced performance. Kroekenstoel et al. (2006) determined that foals with uneven feet show asymmetrical loading of the interphalangeal joints (Lejeune et al., 2006), whereas foals are born with a broken back-foot axis that becomes more upright with increased bone growth and tendon strength.

The second component of craniocaudal balance is the location of the bearing surface of the hoof relative to the weight-bearing axis through the cannon bone. The bulbs of the heel should lie vertically below the central axis of the cannon bone in the sagittal plane. In some horses, although the hoof–pastern axis is aligned, the whole hoof capsule is located too far forward so that the bulbs of the heels are ahead of the central axis of the cannon bone. The resulting caudal concentration of the weight bends the hoof tubules at the heels, which reduces their ability to withstand compression, and leads to underrun heels (Stashak, 1987; Balch et al., 1997). Normally, the dorsal toe wall and caudal heel wall should run parallel to each other and the toe wall length relative to heel wall length

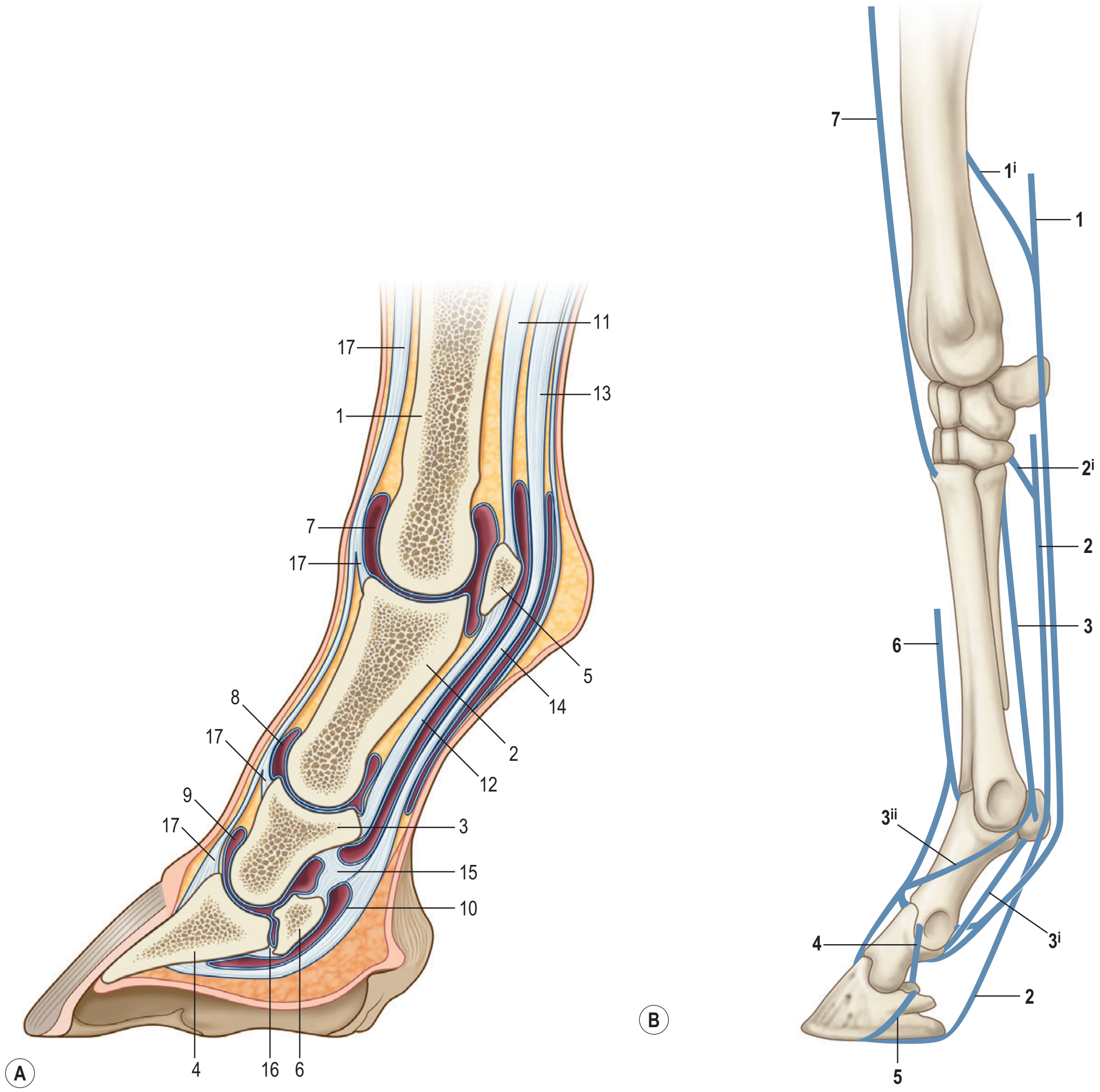

Fig 8.3 (A) Sagittal section of the equine distal fore limb. 1, Metacarpal bone (McIII); 2, first phalanx (P1); 3, second phalanx (P2); 4, third phalanx (P3); 5, proximal sesamoid bone; 6, navicular bone; 7, fetlock joint; 8, pastern joint; 9, coffin joint; 10, navicular bursa; 11, suspensory ligament; 12, straight sesamoidean ligament; 13, deep digital flexor tendon; 14, superficial digital flexor tendon; 15, synovial membrane of coffin joint, navicular bursa and tendon sheath with connective tissue; 16, distal navicular 'impar' ligament; 17, attachments of common digital extensor tendon to first, second and third phalanges. (B) Schematic drawing of tendons and ligaments of the equine lower limb. 1, Superficial digital flexor tendon; 1^{I}, proximal accessory ligament; 2, deep digital flexor tendon; 2^{I}, distal accessory ligament; 3, suspensory ligament; 3^{I}, straight sesamoideum ligament; 3^{II}, rami extensori; 4, proximal navicular ligament; 5, distal navicular 'impar' ligament; 6, common digital extensor tendon; 7, extensor carpi radialis tendon.

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should be 2:1.0 in the fore hooves and 2:1.5 in the hind hooves (Hermans, 1984). Underrun heels have been defined as having a difference between the angles of the toe and heels that is more than 5° (Balch et al., 1997).

Mediolateral balance

Mediolateral balance evaluates the hoof in a frontal plane and attempts to optimize hoof balance by either a static or a dynamic evaluation (Seeherman, 1991; Balch et al., 1997). Static balance seeks to achieve symmetry in the square standing horse so that a line that bisects the limb longitudinally is intersected at 90° by a transverse line drawn across the heels (geometric limb axis). Caudron et al. (1997a,b, 1998) used radiographs to evaluate and correct this balance. In the dynamic method, the hoof is trimmed so that the medial and lateral sides contact the ground simultaneously, which adds a new dimension to the equation and makes the solution even more elusive. In a horse with ideal conformation, static and dynamic balancing will show a rather similar result, but when conformational defects are present the two methods produce different results.

When a horse is standing quietly, the force due to gravity is compensated by the ground reaction force (GRF) acting near the geometric center of pressure (CP) of the foot, which lies around the apex of the frog (Barrey, 1990; Balch et al., 1997; Ovnicek, 1997). The hoof rotates around the instantaneous center of rotation of the coffin joint, which is located in the distal part of P2. Equilibrium

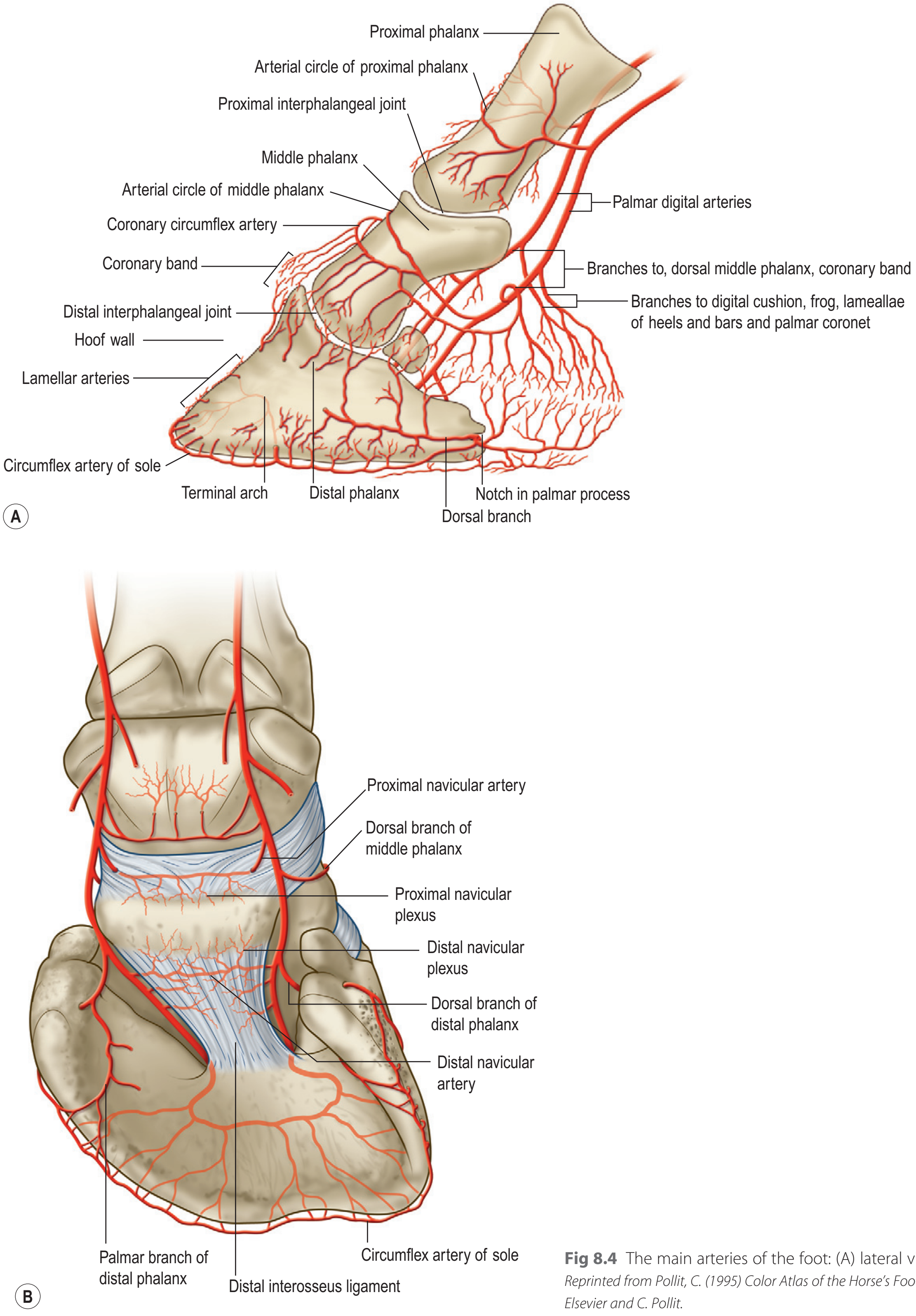

Fig 8.4 The main arteries of the foot: (A) lateral view, (B) caudal view.

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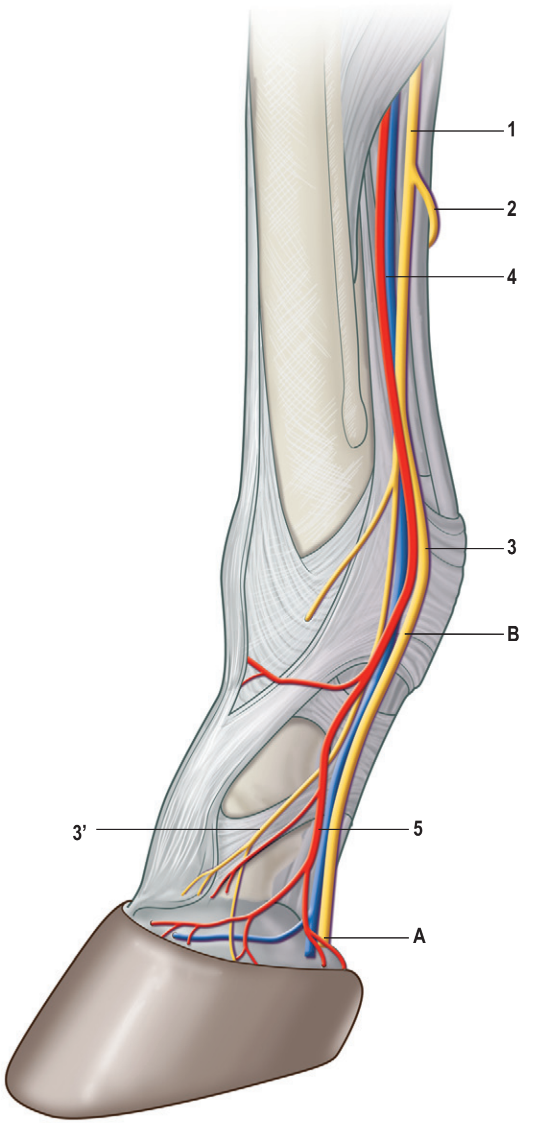

Fig 8.5 Sensory innervation of the foot, medial view. 1, Medial palmar nerve; 2, ramus communicans; 3, digital medial palmar nerve; 3′, ramus dorsalis; 4, medial palmar artery and vein; 5, medial digital palmar artery and vein; (A) site of digital nerve block; (B) site of low palmar (abaxial) nerve block.

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exists when the moment (torque) of the GRF about the coffin joint (F_{GRF}* d_{GRF}) is equal to the moment of the DDFT (F_{DDFT}* d_{DDFT}). Ideally, the central reference point (CRP) should be located midway between the toe and the heels (Wright & Douglas, 1993), although in wild horses the distance from the toe to the CRP is only about one-third of the toe-to-heel distance (Ovnicek, 1997; Fig. 8.8).

Four point trimming

Ovnicek (1997) studied the hooves of 65 wild horses. From his observations he developed the natural trimming technique for unshod horses. The principles of this technique are that the heels are trimmed back to the widest point of the frog, along the sole plane. The toe is beveled to a 15–20° angle in a manner akin to what would be done in preparation for a rocker-toe shoe. The quarters are hollowed slightly by rasping so they are not weight-bearing on a firm surface. This leaves a raised area projecting downwards at the heel buttress. There is a gradual arc between the impression mark at the lateral side of the toe and the heel impression mark on each side of the foot. The hoof wall has four loading points: one at each side of the toe and one at each heel. Little to no sole, frog and bars are ever removed. Within a few months this method of trimming should result in a stronger hoof structure with a cupped sole, spreading heels, and a well-developed frog. Dejardin et al. (2001) demonstrated that four point trimming results in strain concentration above the hoof contact points with the strain magnitude being dependent on contact area.

Hood et al. (2001a) found that on a deformable surface, load distribution is principally solar and located transversely across the central region of the foot. Therefore, it is hypothesized that the typical hoof conformation observed in feral horses is the result of increased erosion of the central solar and quarter regions of the bearing wall, allowing the heels and the lateral and medial toe to remain relatively long. The rapid disappearance of this initially noneroded areas when horses are maintained on a flat nondeformable surface further supports that they are caused by lack of contact when the horse is on a more natural deformable terrain. Hood et al. (2001a) concluded that so called four-point loading is the product of ground surface abrasion and, as such, is the mirror image of the loading pattern seen in horses kept on a natural terrain. Hence, the hoof ground interaction after an artificial four-point trim may only partially mimic the natural hoof ground interaction observed in feral horses.

Hoof mechanics during locomotion

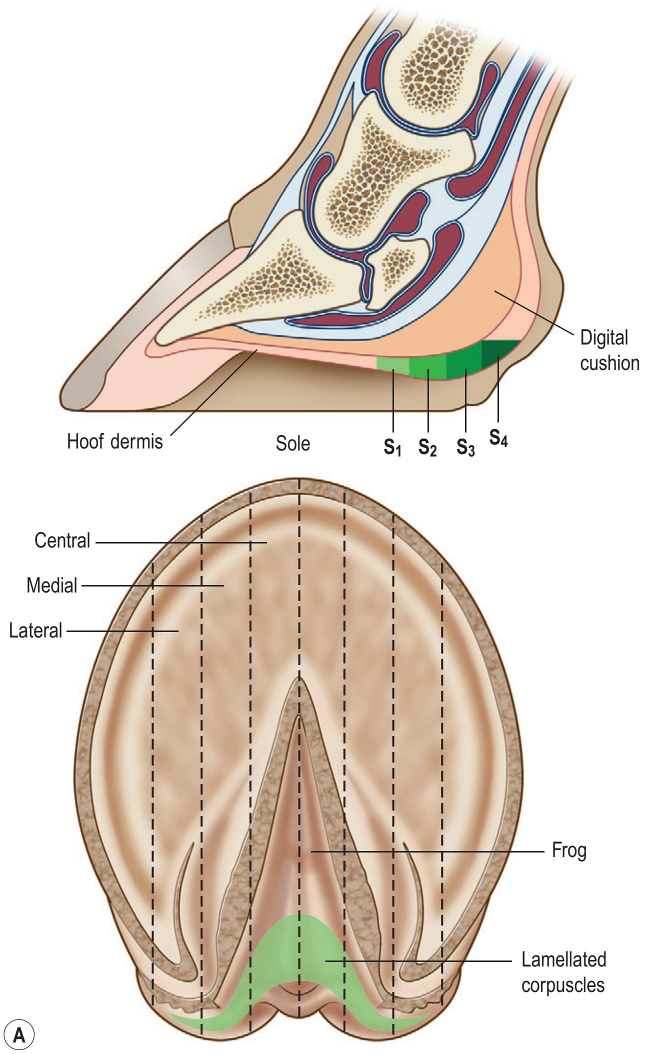
Several techniques have been used to document the kinematics and kinetics of the hoof. One of the requirements of the recording equipment is that it should have a high enough sampling frequency to distinguish events such as initial ground contact, heel-off and toe-off with sufficient accuracy (Linford, 1994). This can be especially difficult on outdoor tracks where reflective markers disappear in the sand (Merkens & Schamhardt, 1994; Scheffer & Back, 2001).

Initial ground contact

When the horse is observed in the lateral view, initial ground contact is heel first, flat-footed or toe first. The hind limbs show a greater tendency to heel first contacts than the forelimbs, and heel first contacts occur more frequently during high-speed locomotion (Back et al., 1995). However, in some movements, such as piaffe, toe first contacts are normal. The frequency of toe first contacts increases when the hoof is trimmed with an acute angle (long toes and/or low heels). Conversely, when horses are trimmed with a steep hoof angle (short toe and/or long heels), heel first contacts are more numerous (Clayton, 1990a). Therefore, the manner of initial ground contact depends on speed, gait and farriery. Nevertheless, Van Heel et al. (2004) found that most horses tend to land on the lateral side of the foot, especially in the hind limbs, which is only minimally influenced by trimming.

Impact

Immediately after initial ground contact, the hoof is rapidly decelerated by the vertical landing forces and horizontal braking forces that reduce its speed to zero during the impact phase that follows initial ground contact (Back et al. 1995; Burn 2006; Parsons & Wilson, 2006). The forces and decelerations associated with impact have been measured using a force plate (Merkens & Schamhardt, 1994; Merkens et al., 1994; Wilson & Pardoe, 2001; Weishaupt et al., 2002; Oosterlinck et al., 2010b), force shoe (Barrey, 1990; Frederick & Henderson, 1970; Ratzlaff et al., 1985, 1993; Kai et al., 2000; Rollot et al., 2004; Roland et al., 2005; Chateau et al., 2009a; Robin



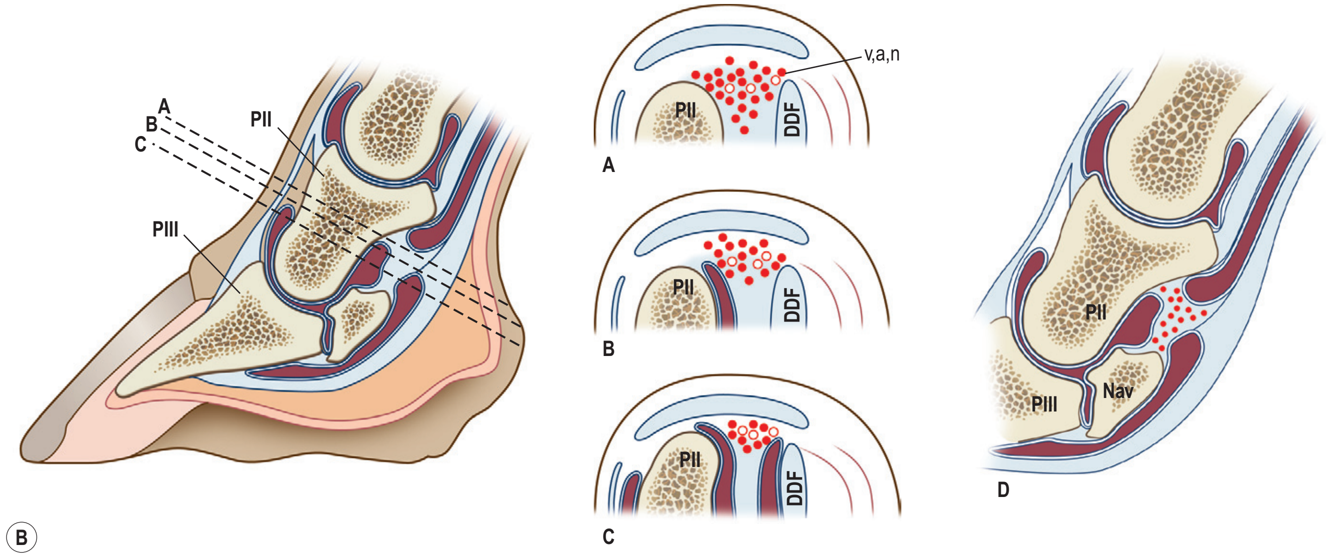


Fig 8.6 (A) Sensory receptors in the foot. In the sagittal view the four zones of the sole (S1–S4) represent locations of the lamellated corpuscles with the relative density being indicated by the intensity of the green shading in zones S1–S4. S4 shows the highest density of lamellated corpuscles. In the ventral view the lamellated corpuscles were obtained from the areas shaded in green. (B) Sensory receptors in the navicular region. Inset shows the three levels from which drawings **a**–**c** were obtained. Note that the lamellated corpuscles (dots) are located primarily abaxially and proximal to the collateral sesamoidean ligament (CSL) often in association with the palmar digital nerve (n), as well as with the artery (a) and vein (v). **d** is a parasagittal drawing from the abaxial region of CSL. Sensory receptors are shown as red dots. PII: pastern bone; PIII: coffin bone; DDF: deep digital flexor tendon; Nav: navicular bone.

(A) Reprinted from Bowker, 1993, Sensory receptors in the equine foot, American Journal of Veterinary Research, with permission from American Journal of Veterinary Research http://avmajournals.avma.org/loi/ajvr. (B) Reprinted from Bowker, R.M., Linder, K.E., Sonea, I.M. and Guida, L.A. (1995) Sensory nerve fibers and receptors in the equine distal forelimbs and their potential role in locomotion. Equine Vet. J. 18, 141–146, with permission of the Equine Veterinary Journal.

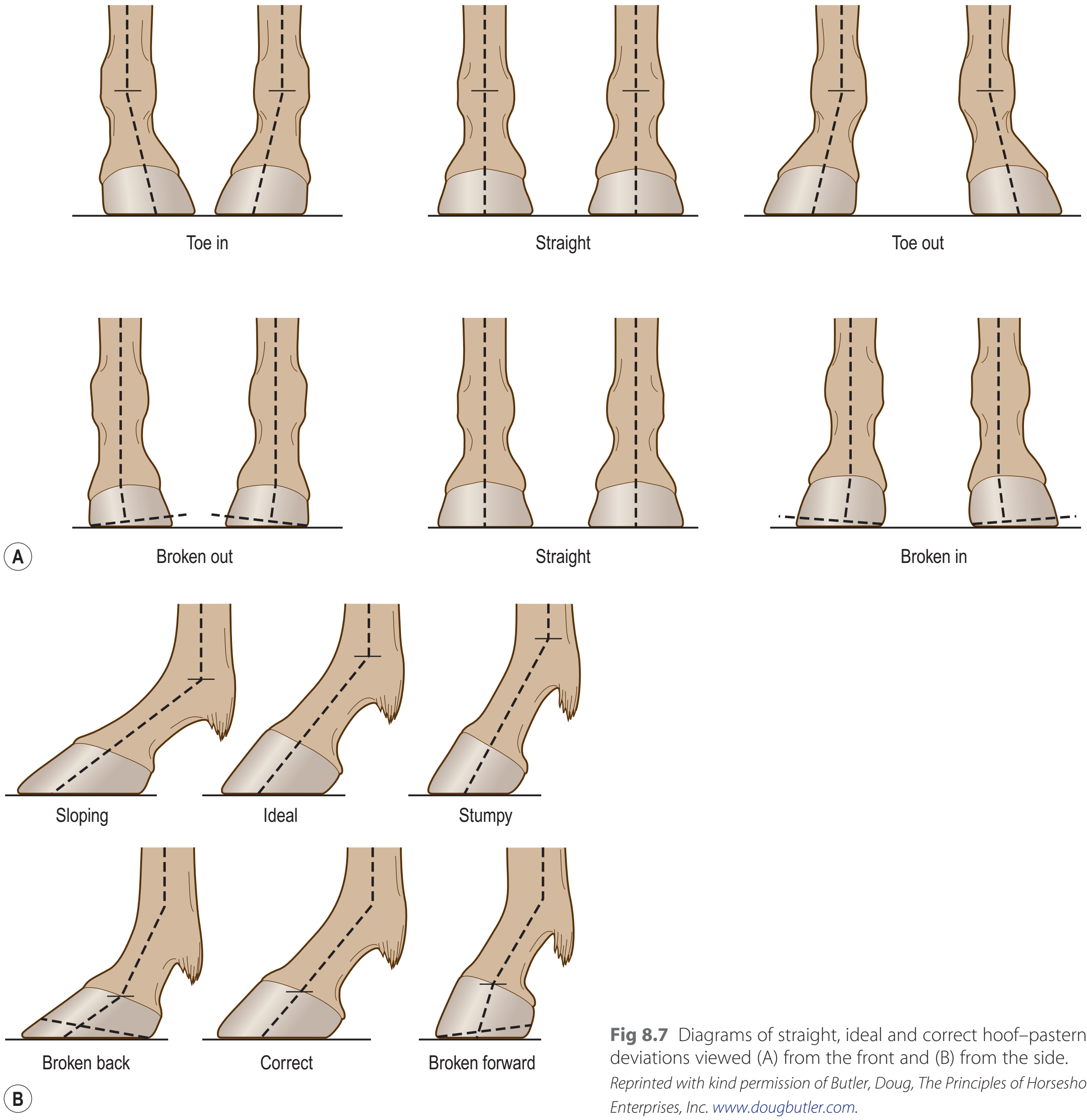


Fig 8.7 Diagrams of straight, ideal and correct hoof–pastern axes and common deviations viewed (A) from the front and (B) from the side.

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et al., 2009) and accelerometers (Benoit et al., 1993; Burn et al., 1997; Back et al., 2006). The hoof and interphalangeal joints attenuate the shock wave associated with impact (Dyhre-Poulsen et al., 1994; Lanovaz et al., 1998; Willemen et al., 1998). Approximately 67% of the damping of impact vibrations takes place at the interface between the hoof wall and the distal phalanx. The attenuation of impact vibrations at the interphalangeal joints and the metacarpophalangeal joint seems considerably less (12% and 9% respectively) leaving approximately 12% of the impact vibrations detectable at the level of the metacarpus (Willemen et al., 1999a). Nevertheless, the forces acting in different directions have the potential to damage the body (Fig. 8.9). Friction between the hoof and the ground and hardness of the ground affect the forces applied to the limb during the impact phase (Hjertén & Drevemo, 1993, 1994). The amplitude of impact vibrations at the level of the hoof wall is 15% higher in shod versus unshod hooves independent from the type of shoe that is used (shoes with or without pad). At the level of the first phalanx and the metacarpus the difference between shod and unshod vanishes (Willemen et al., 1999a).

The impulsive loading that occurs during impact has been implicated as a causative factor in arthritis in animals (Radin et al., 1981; Pratt, 1997; Radin 1999) and in humans (Folman et al., 1986; Ker et al., 1989). The time during which these forces have to be absorbed is reduced as speed increases. For example, the time taken to absorb impact shock at the canter (7 m/s) is 50% of that at the walk (1.6 m/s), which is a consequence of the shorter time the foot is on the ground. Back et al. (1995) found that during trotting on a treadmill the hoof was flat on the ground, and the vertical speed and acceleration were zero within 3% (20 ms) of the total stride duration. Surprisingly, it took 6% (40 ms) of total stride duration for the horizontal speed to reach zero, but as demonstrated by Gustås et al. (2001) the time lapse of this horizontal retardation of the hoof is an important factor in the attenuation of the impact.

The forelimbs appeared to land with a higher vertical velocity and the hind limbs with a higher horizontal velocity (Back et al., 1995). Thus, the forelimbs 'bounce', whereas the hind limbs 'slide'. On the other hand, Gustås et al. (2004) found no significant difference in

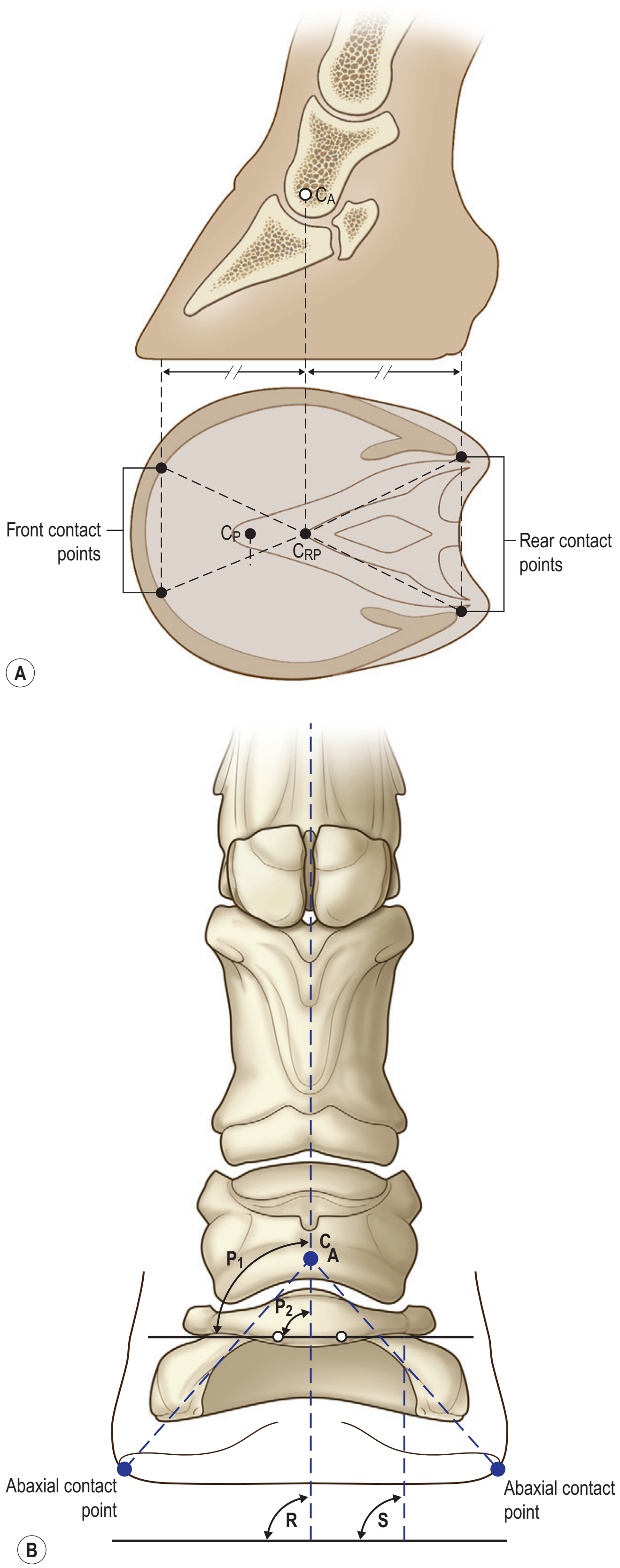

Fig 8.8 Schematic representation of foot balance showing the ideal equilibrium of the foot relative to the center of articulation in the distal part of the second phalanx. (A) Craniocaudal balance: Lateral and solar view and (B) mediolateral balance: heel view. C_A, center of articulation; C_P, center of pressure; C_{RP}, central reference point.

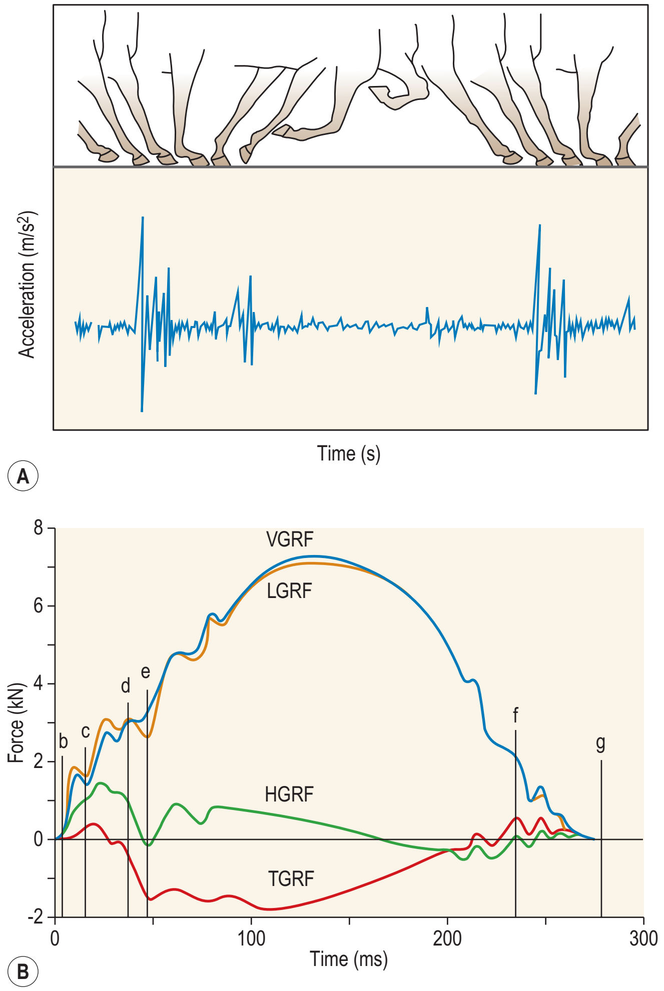

Fig 8.9 (A) The impact phase is the short period immediately following initial ground contact, in which the decelerating hoof is oscillating relative to the ground until hoof velocity has been reduced to zero. (B) During impact the vertical landing (VGRF) and horizontal braking (HGRF) forces acting on the hoof are transferred into longitudinal (LGRF) and transverse (TGRF) forces acting on the equine lower limb.

Reprinted from Hjertén, G. and Drevemo, S. (1994) Semi-quantitative analysis of hoof strike in the horse. J. Biomech. 17, 997–1004, with permission from Elsevier.

hoof deceleration between fore and hind limb using accelerometers mounted on the hooves. The sliding of the hoof in the sagittal plane has been measured for horses trotting on a treadmill; steel shoes slide for longer than rubber shoes and the hoof stops less abruptly on a coir mat than on a rubber belt (Roepstorff et al., 1994). It has been reported that the sliding of the hoof took 16 ms on a dirt track, whereas on a hard surface (asphalt or concrete) it took 21 ms for the unshod hoof and 32 ms for steel shoes (Back, 2001). Pardoe et al. (2001) could not demonstrate a significant difference in either slip time or distance between steel, plastic and rubber shoes, whereas Back et al. (2006) noted less gliding in freshly steel shod horses with protruding nails than in the same horses shod with plastic shoes.

The active neurophysiological response time is the time required for the muscles to respond to a stimulus. It has been estimated to be around 30 ms in humans (Nigg et al., 1981) and horses (Bowker et al., 1993; Hjertén & Drevemo, 1993). This suggests that the forces acting on the equine lower limb during the impact phase are determined mainly by passive factors like coordination and ground properties (Hjertén & Drevemo, 1993).

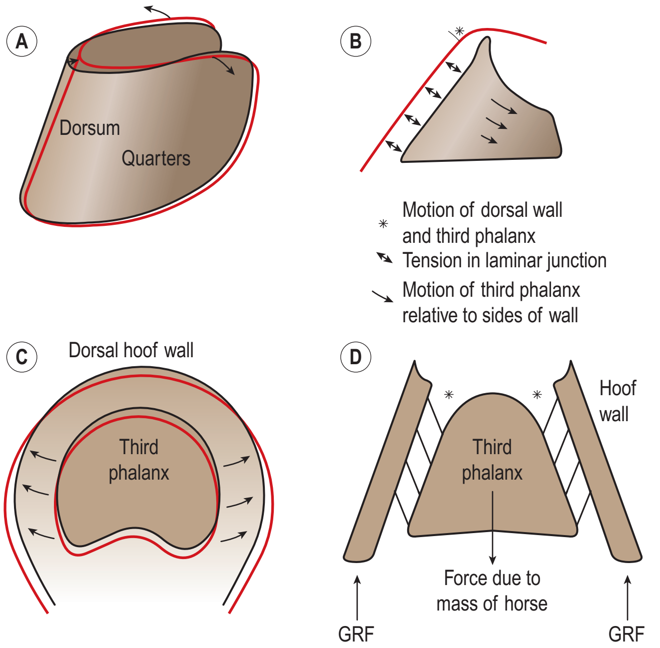

Fig 8.10 Schematic drawing of the hoof mechanism phenomenon. The solid line represents the unloaded hoof wall, the dashed line shows the change in shape that occurs during weight-bearing. Under load the dorsal wall flattens and moves palmarly, while the heels move laterally and caudally. GRF, ground reaction force.

Reprinted from Douglas, J.E., Biddick, T.L., Thomasson, J.J. and Jofriet, J.C. (1998) Stress/strain behaviour of the equine laminar junction. J. Exp. Biol. 201, 2287–2297, with permission from the Journal of Experimental Biology, http://jeb.biologists.org/content/201/15/2287.full.pdf+html

Hoof mechanism

Since the hoof shows more elasticity in the heel area than at the toes or quarters, its geometry changes when it is loaded: the proximal dorsal wall moves back, the quarters flare to the side and sole and frog perform a downward movement (Hinterhofer et al., 2000, 2001; Burn & Brockington, 2001; Hobbs et al., 2004, 2009); this is called the hoof mechanism (Fig. 8.10).

At impact the distance between the heels is wider than at rest, while at breakover, because of increased pressure in the toe area, the distance between the heels is narrower than at rest. Thus, the foot has three functional areas: the heels for damping; the wall, frog and sole for support; and the toe for propulsion (Barrey, 1990). Deformation of the foot during the stance phase optimizes these functions, and also enables the hoof to act as a pump for the blood circulation (Ratzlaff et al., 1985).

The hoof mechanism has been studied using strain gauges (Knezevic, 1966; Bayer, 1973; Dyhre-Poulsen et al., 1994; Summerley et al., 1998; Thomason, 1998; Thomason et al., 2001, 2002; Roepstorff et al., 2001), photoelastic material (Davies, 1997; Dejardin et al., 1997, 1999), optical systems (Roepstorff et al., 2001; Burn & Brockington, 2006), doppler (Hoffman et al., 2001; Pietra et al., 2004), and special horse boots (Barrey, 1990; Preuschoft, 1989). As hoof strain and limb loading are related, the GRF can be estimated from hoof strain data using artificial neural networks in experiments where force plates cannot be used (Savelberg et al., 1997). Photoelastic materials did not show any concentrations of colored fringes in the foot of the standing horse following trimming (Davies, 1996). Shoeing stabilized (Thomason, 1998) or even decreased hoof movements (Colles, 1989b; Dyhre-Poulsen et al., 1994). Shoes with 5° raised heels reduce hoof deformation compared to flat horseshoes (Hinterhofer et al., 2000) whereas the extra frog pressure provided by heart bar shoes does not influence hoof expansion in a consistent manner (Colles, 1989a). The latter is in contrast to more recent work of Roepstorff et al. (2001) demonstrating that increased pressure on the frog and sole does increase heel expansion, although some heel expansion still occurs when the frog and sole are unsupported. Surprisingly, the digital cushion has no active role in this heel expansion (Taylor et al., 2005). Shoes with a toe clip and two side clips placed behind the 3rd nail (type of shoe used in the treatment of a fractured P3) minimize the hoof mechanism (Kersjes et al., 1985; Hinterhofer et al., 2001).

Strains on the hoof wall are considerably higher at the trot than at the walk (Thomason, 1998) and are higher in the trailing limb than the leading limb at a gallop (Summerley et al., 1998). Surprisingly, riding decreases the strain in the quarters by 30%, while hoof wall strains are 20% higher on the medial side when the rider sits in the saddle and 20% higher on the lateral side for the forward seat (Summerley et al., 1998). Turning increases the hoof strain in the quarter that is on the inside of the turn by 40% (Summerley et al., 1998). A larger hoof angle and a longer toe length increased the strain at the toe, even when the length of the toe was proportional to the body size of the animals (Thomason, 1998). In the medial and lateral wall this relation was reversed: more upright feet were stiffer (Thomason, 1998). Elasticity of the hoof structures, however, is also affected by the moisture content: the wall consists of 82% keratin and 16% water, while the frog is 56% keratin and 42% water (Hertsch et al., 1996). Tubules are unlikely to be involved in the hydration status of the foot, but appear to have a more mechanical function in the hoof wall to redirect and resist cracks (Kasapi & Gosline, 1997, 1998).

Center of pressure

By tracking the path of the center of pressure in a craniocaudal plane it can be seen that immediately after initial ground contact it moves from the point of hoof contact to a position close to the apex of the frog (Barrey, 1990; Balch et al., 1997; Ovnicek, 1997; Van Heel et al., 2004). It remains there for most of the stance phase. At the end of the stance phase the center of pressure starts moving toward the toe. At toe-off it lies beneath the dorsal hoof wall at its breakover point (Barrey, 1990). Van Heel et al. (2005) studied the changes in location of center of pressure and hoof-unrollment pattern in relation to an 8-week shoeing interval and determined that horses can compensate to a certain extent for changes in hoof conformation that develop during 8 weeks on shoes. However, the capacity to compensate is less in the forelimbs and thus, the relative increase in loading of these limbs during a shoeing interval is larger compared to the hind limbs.

The location of the center of pressure in a mediolateral plane shows that when the horse is standing squarely the direction is concentrated on the medial quarters (Colahan et al., 1991). During locomotion more force is recorded on the medial hoof with force shoes (Ratzlaff et al., 1993; Balch et al., 1997; Kai et al., 2000; Rollot et al., 2004; Roland et al., 2003; 2005, Chateau et al., 2009a), and with force and pressure plates in horses and ponies (Van Heel et al., 2004; Oosterlinck et al., 2010a,b,c). Transverse forces as recorded with force plates are not consistent throughout the gaits in the fore and hind limbs (Merkens & Schamhardt, 1994; Merkens et al., 1994; Weishaupt et al., 2002). Furthermore, extrasagittal joint motions in the forelimb will show bilateral variation since horizontal moments around the hoof center of pressure are not symmetric (Colborne et al., 2009).

Changes in fetlock and coffin joint angulation affect strain in the palmar soft tissues that support the limb during the stance phase (Leach 1983; Bushe et al., 1987; Thompson et al., 1993; Riemersma et al., 1996a). The suspensory ligament (SL) and superficial digital flexor tendon (SDFT) are affected by the fetlock joint angle; strain increases as the fetlock extends. The distal accessory ligament (DAL) and deep digital flexer tendor (DDFT) are affected by the coffin

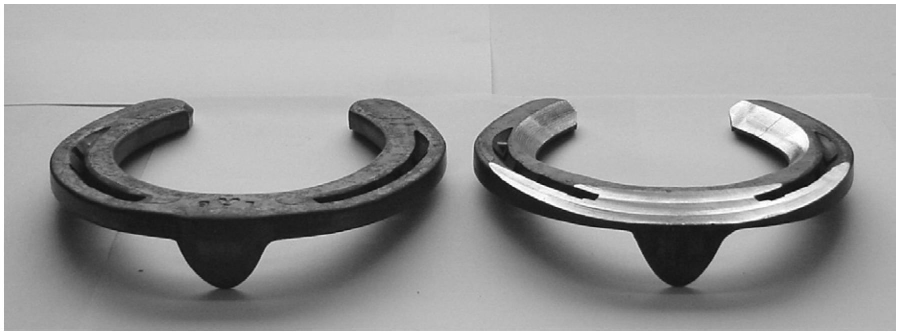

Fig 8.11 Shoes used to compare breakover. Left, a standard flat shoe (Mustad 22/10 LB); right and a shoe with a rolled toe (Mustad 22/10 equilibrium).
Reprinted from Van Heel, M.C., van Weeren, P.R., Back, W. (2006b) Shoeing sound warmblood horses with a rolled toe optimises hoof-unrollment and lowers peak loading. Equine Vet. Jour. 38 (3), 258–62, with permission of the Equine Veterinary Journal.

joint angle: strain increases when this joint extends. The load distribution between the tendinous structures changes with alterations in hoof balance: strain reduction in one tendon may result in an increased strain in another structure. Also the horse may compensate, to a certain extent, for hoof imbalances by adjusting the length of the muscle bellies of the SDFT and DDFT or by changing the configuration of the joint angles in the proximal limb, e.g. when it experiences navicular bone pain in the distal limb (Wilson et al., 2001).

Breakover

Breakover is the terminal part of the stance phase from heel-off to toe-off. Rotation of the hoof is brought about as a result of tension in the DDFT and DAL, and in the navicular ligaments (Schamhardt et al., 1991; Riemersma et al., 1996b). Farriery modifications that facilitate breakover may reduce tension in the DAL and in the navicular ligaments and also reduce pressure of the DDFT against the navicular bone. The onset and duration of breakover are sensitive to changes in hoof balance, especially hoof angle and toe length. Hooves trimmed with a low heel and long toe have a significantly longer breakover duration, although other stride variables like stride duration do not change significantly (Clayton, 1988, 1990a,b). On the other hand, rocker, rolled and square toe shoes (Fig. 8.11) did not significantly alter breakover duration of horses trotting on a hard surface (Clayton et al., 1991; van Heel et al. 2006b) or on a rubber floor (Willemen et al., 1996). However, breakover tends to occur earlier (Eliashar et al., 2002) and is smoother with a lower peak loading (van Heel et al., 2006b; Fig 8.12). In contrast to the effect of heel wedges, shoes that facilitate breakover do not reduce the peak distal interphalangeal joint moment nor the absolute force exerted on the navicular bone (Eliashar et al., 2002).

Off-center breakover has been associated with swing abnormalities of the foot that interfere with the opposite limb and contouring the hoof or shoe on one side are common techniques to correct for this. Recent research by Keegan et al. (2005) using gyroscopic sensors mounted on the hoof confirmed that shoes with a contoured lateral branch induce greater lateral roll during breakover. However, this effect was only observed at a trot and was limited to the first half of breakover.

Flight arc

The flight arc of the hoof represents the summation of all the joint movements in the limb (Fig. 8.13). The highest point in the flight arc occurs soon after lift-off with a second, smaller elevation, which may coincide with an upward flip of the toe, at the time of maximal protraction. This gives a slightly biphasic flight arc (Clayton, 1990a; Balch et al., 1991a, 1997; Back et al., 1995).

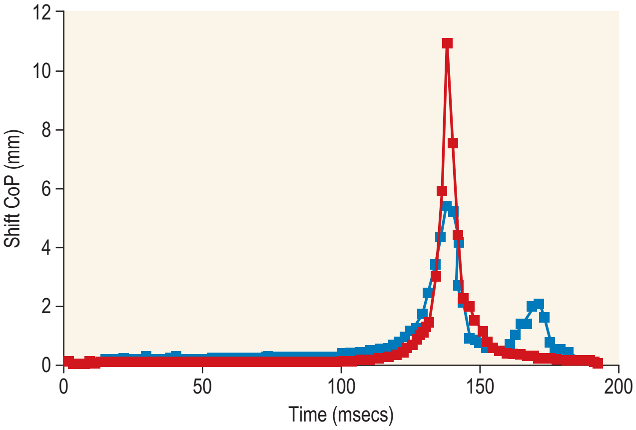

Fig 8.12 Craniocaudal displacement of the center of pressure (COP) from midstance to toe off in the same horse with a flat shoe (red line and squares) and a rolled toe (blue line and squares). The peak indicates heel lift. The higher peak in the flat shoe condition represents a more abrupt breakover process.
Reprinted from Van Heel, M.C., van Weeren, P.R., Back, W. (2006b) Shoeing sound warmblood horses with a rolled toe optimises hoof-unrollment and lowers peak loading. Equine Vet. Jour. 38 (3), 258–62, with permission of the Equine Veterinary Journal.

After the hoof leaves the ground, the limb swings forward to reach its position of maximal protraction, and is then retracted prior to contact with the ground. The final retraction is important for reducing the forward velocity of the hoof relative to the ground and so decreasing hoof deceleration at ground contact and preventing the horse from stumbling. Protraction of the limb is driven by muscles in the proximal limb, with the distal limb following passively (Back et al., 1995). In the forelimb the joints from the carpus proximally are driven by muscular action, while the fetlock, pastern and coffin joints move in response to inertial effects (Lanovaz et al., 1999). As maximal protraction is approached, the motion of the proximal limb is slowed and reversed by muscular action, while the distal limb continues moving forward until resisted by the passive structures (bones, ligaments, tendons). Swinging the limbs back and forth uses considerable energy, and a number of energy-saving mechanisms have evolved. One of the most important is the use of elastic structures as springs; energy is stored when elastic tissues are stretched as the limb is loaded during the stance phase, then released during unloading to bounce the limb off the ground and assist in flexing the joints. At the trot the SDFT, DDFT and SL are maximally stretched at midstance which corresponds with the time of maximal weight-bearing. Thus, the elbow, carpal and fetlock joints behave elastically during the stance phase at the trot (Clayton et al., 1998).

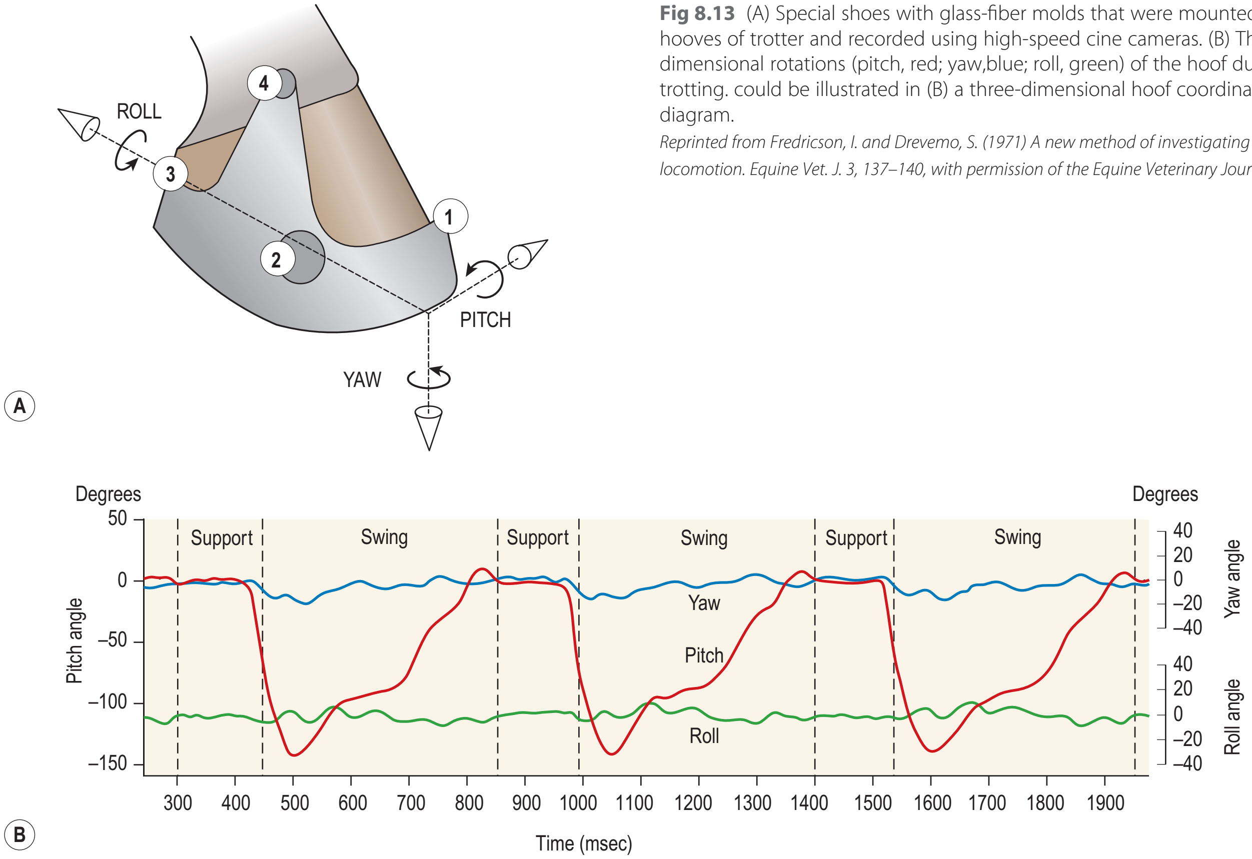

Fig 8.13 (A) Special shoes with glass-fiber molds that were mounted on the hooves of trotter and recorded using high-speed cine cameras. (B) Three-dimensional rotations (pitch, red; yaw,blue; roll, green) of the hoof during trotting. could be illustrated in (B) a three-dimensional hoof coordination diagram.

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Below the elbow and stifle joints the horse's limbs are designed to move in a sagittal plane, which is another energy-saving strategy. The distal limbs sometimes deviate from this ideal pattern by being abducted (winging) or adducted (plaiting) during protraction as a result of slight asymmetries in the articular surfaces, which also have a tendency to cause breakover to occur on the medial or lateral side of the toe. If horses that naturally show these deviations are shod in a manner that forces them to breakover the center of the toe, it creates torsional forces before and after breakover. As the hoof leaves the ground, these torsional forces cause it to deviate medially or laterally, depending on the type of asymmetry. Careful observation of the horse in motion, together with an examination of the wear pattern on the ground surface of the shoe or hoof, will reveal the preferred side of breakover. If the horse is shod to facilitate breakover at the preferred location, there will often be a marked reduction in winging or plaiting and this, in turn, affects the hoof's angle of approach to, and contact with, the ground.

Light-weight tactile stimulation devices attached around the pastern may increase the height of the flight arc and thus may represent a useful adjunct in physical therapy aiming at mobilization of joints and reinforcement of (atrophied) muscles (Clayton et al., 2011). However, short-term habituation does occur, especially in the forelimbs (Clayton et al., 2008). Application of the stimulators for short periods is recommended, although it is unknown how rapidly horses rehabituate to the effect of tactile stimulation of the pastern over different sessions.

Effects of hoof manipulations

Hoof angle

When a horse is trimmed with relatively long toes and/or short heels the hoof angle becomes more acute or sloping, while the pastern becomes more upright creating a broken-back hoof pastern axis (Bushe et al., 1987). Conversely, when horses are trimmed with a short toe and/or long heels, the hoof angle becomes more upright and the pastern angle becomes more sloping. Raising the heels decreases strain in the DDFT and DAL (Leach, 1983; Bushe et al., 1987; Thompson et al., 1993; Riemersma et al. 1996a), but increases strain in the SDFT and SL (Willemen et al., 1999b). One of the goals of hoof trimming is to achieve a flat landing with the objective of disseminating the forces on the foot as much as possible. When the hoof angle is more upright, the hoof has a more exaggerated heel first landing (Clayton, 1988; Back et al., 1995).

Barrey (1990) looked at the relation between hoof angle and force distribution: 75% of the weight was borne by the heels when the hoof angle was 39°, and this was reduced to 57% when the hoof angle was increased to 55° (Fig. 8.14). This agrees with the finding that a larger toe angle results in more strain of the hoof wall at the toe (Thomason, 1998). Nevertheless, the quarters experience higher forces during stance than the toe (Barrey, 1990).

Many racehorses are trimmed with an acute hoof angle because it is believed that the long toe low heel conformation enhances performance by increasing stride length. Comparison of the trot stride for a normal hoof angle versus an acute hoof angle showed no significant changes in stride length or suspension, and the flight arc of the hoof was almost identical with the two angulations (Clayton, 1990a; Balch et al., 1997; Girtler et al., 1995). However, the acute hoof angle was associated with an increased frequency of toe-first contacts, which was thought to be a consequence of the proprioceptive reflexes ensuring a fairly flat placement of P3 regardless of the shape of the hoof capsule (Clayton, 1990a). Since toe-first contacts are associated with a tendency to trip or stumble, this may be an undesirable effect. Decurnex et al. (2009) investigated the effect of training on proximal hoof circumference in young Thoroughbred racehorses being prepared for racing. Front hoof circumference immediately below the coronary

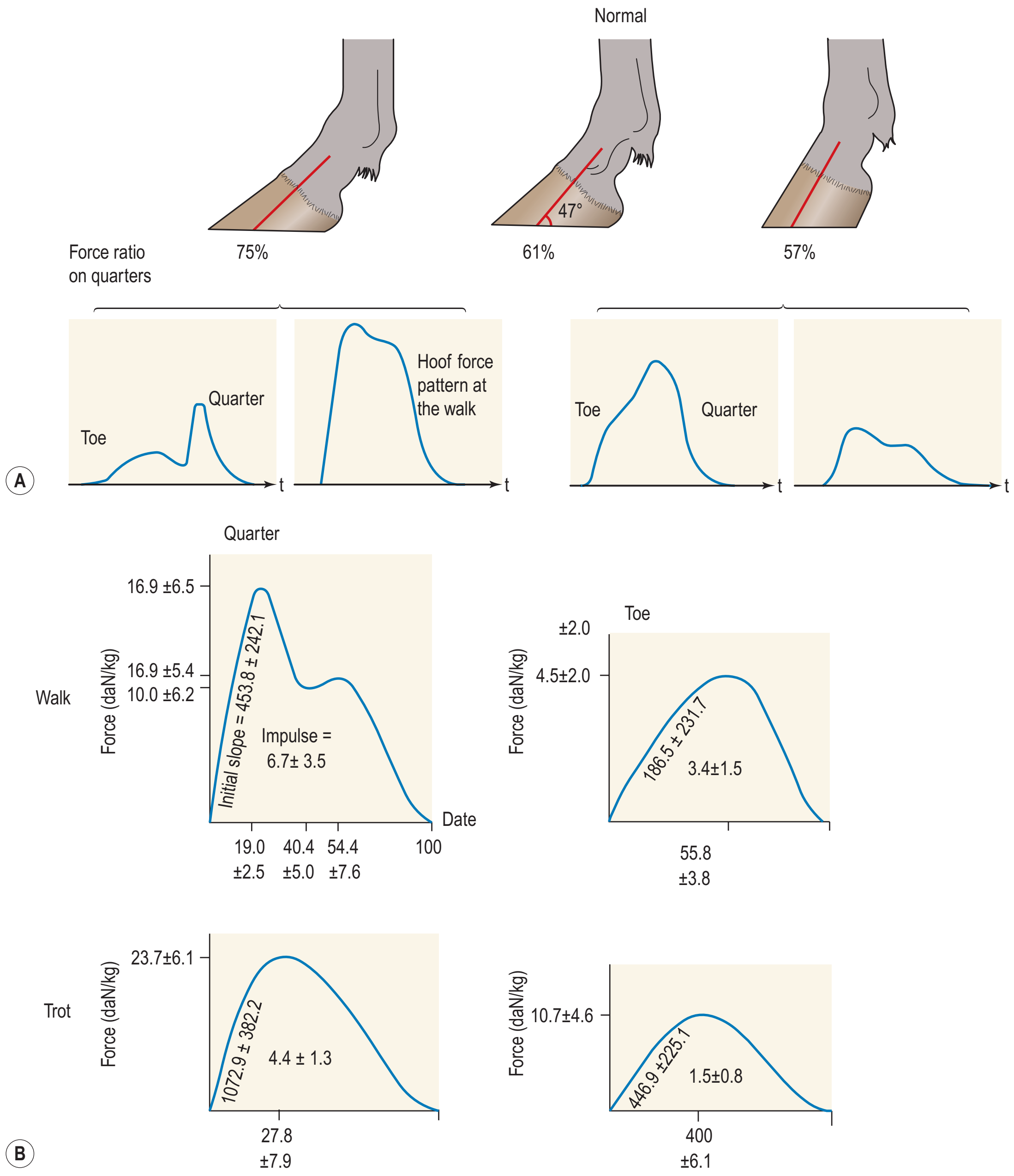

Fig 8.14 (A) The influence of foot axis on the individual vertical hoof force distribution at the toe and at the quarters. (B) Forces experienced at the medial toe and quarters at walk (above) and trot (below) in a group of 10 horses. Values on the graphs indicate mean +/– SD for force peaks, slope of initial slope, impulse and times of occurrence of the force peaks and troughs.

Reprinted from Barrey, E. (1990) Investigation of the vertical hoof force distribution in the equine forelimb with an instrumented horseboot. Equine Vet. J. 9 (Suppl.), 35–38, with permission from the Equine Veterinary Journal.

band was measured weekly with a measuring tape in all horses present at the stable. Most horses showed a similar pattern of change. The proximal hoof circumference decreased during the training periods and increased when the horse was rested. Apparently, horses showed a decrease in circumference during race training that reversed when they were rested, thus contributing to a possible 'environmental' explanation for the long toe low heel conformation often found in racehorses. Furthermore, measurement of front hoof circumference is a simple method to assess change in hoof shape. It provides an opportunity to investigate the relationships between specific training, hoof shape and soundness (Peel et al., 2006).

The duration of breakover was prolonged with the acute hoof angulation and the orientation of the limb segments at the start of breakover suggested an increased tension in the DAL and navicular ligaments (Fig. 8.15). The effects of an acute hoof angle on breakover may be mitigated on a softer surface that allows penetration of the toe during the terminal part of the stance phase, since flexion of the coffin joint reduces tension in the DAL and navicular ligaments.

The hoof wall grows approximately 1 cm every 6 weeks, with the wall at the toe growing faster than at the heels (Hertsch et al., 1996). When a horse is shod the hoof wears mainly in the heel region. Consequently, the hoof angle changes between farriery treatments and this is associated with alterations in the pressure on the navicular area (Hermans, 1984). Willemen et al. (1999b) calculated a decrease in force on the navicular bone of 24% when the angle was 6° more upright. The mean toe angle of the forelimbs of the 12 horses used in that study was 55°. At the end of an 8-week shoeing interval, the decrease in hoof angle results in a broken-back hoof-pastern axis thereby increasing extension in the distal interphalangeal joint and decreasing extension of the fetlock joint (Tacchio et al., 2002; Moleman et al., 2006; van Heel et al., 2006c). The deep digital flexor tendon has to compensate for this conformational change which puts the tendon at increased risk for injury. Therefore, horses should receive regular farrier treatment every 6–8 weeks or earlier when considerable changes in hoof angle can be expected in a particular horse. Recent studies also indicate that, by 2 weeks of age, foals already show a limb preference when grazing at pasture (Van Heel et al., 2006a; Fig. 8.16), and thus their hooves can become uneven (Kroekenstoel et al., 2006; Fig. 8.17).

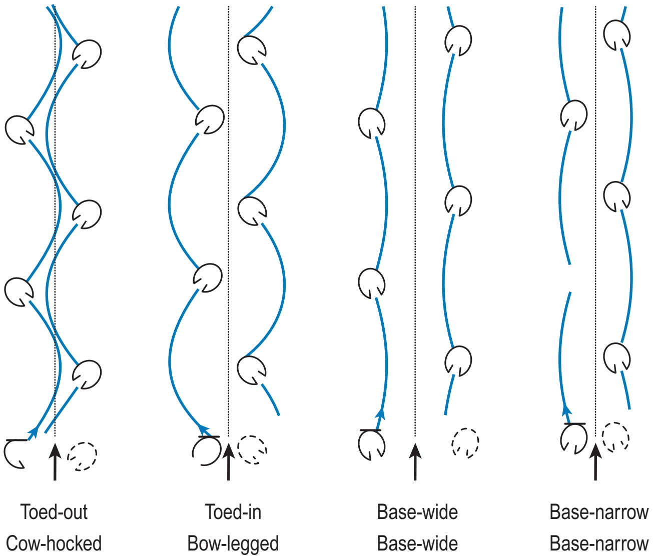

Fig 8.15 The influence of foot axis and conformation of the lower limb on the flight pattern of the hoof from above.

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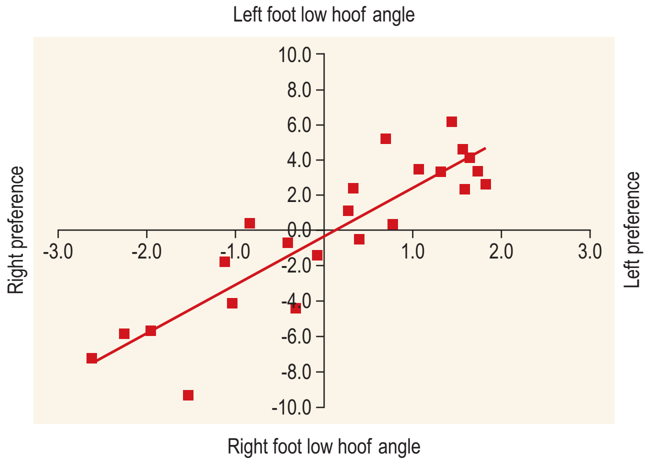


Fig 8.17 Relationship (r = 0.89) between the strength of preference during field observations and the degree of unevenness. On the x-axis the results of preference in the field, expressed as mean Z-value; on the y-axis unevenness in hoof angle at 27 weeks. Note that the Z-value is below the level of significance (1.96) in the majority of foals, which results from the inclusion of all observations of the first 31 weeks. In this period laterality developed and was not yet present in the first weeks. Inclusion of these observations decreased the mean Z-value while leaving the relationship of preference and hoof angle unaltered.

Reprinted from Van Heel, M.C.V., Kroekenstoel, A.M., Van Dierendonck, M., Van Weeren, P.R., Back, W. (2006a) Uneven feet in a foal may develop as a consequence of lateral grazing behaviour induced by conformation . Equine Vet. J. 38, 646–651, with permission from the Equine Veterinary Journal.

Fig 8.16 A foal grazing at pasture in the typical posture it has to adopt to reach the ground.

Reprinted from Van Heel, M.C.V., Kroekenstoel, A.M., Van Dierendonck, M., Van Weeren, P.R., Back, W. (2006a) Uneven feet in a foal may develop as a consequence of lateral grazing behaviour induced by conformation . Equine Vet. J. 38, 646–651, with permission from the Equine Veterinary Journal; picture courtesy of P.J.H.M. Meeus, DVM.

Hoof length

Long hooves, often augmented by pads and weights, are a feature of some gaited breeds in which they are used to give a showy, exaggerated elevation of the distal limbs during the swing phase.

In a study designed to investigate the effects of overall hoof length on the flight arc of the hoof, pads were applied to increase hoof length by 5 cm without changing the total weight of the shoe-pad combination (Balch et al., 1994). Compared with a normal hoof length, the long hooves were associated with a prolongation of stride duration, swing duration and breakover, but overall stride length and stance duration did not change. The flight arc of the hoof peaked earlier and higher with the longer hooves, but the normal movement pattern was re-established in the later part of the swing phase. Although stride length did not change, the prolongation of the swing phase may be esthetically pleasing. However, longer toes also lead to more strain on the dorsal hoof wall, which predisposes to hoof wall pathology (Thomason, 1998). Under natural social and environmental conditions, hoof length shows seasonal variations with 'self-trimming' attributable to periods of increased wear being an important phenomenon in the self-maintenance of the equine hoof (Florence & McDonnell, 2006).

Effects of shoe manipulations

Shoes are applied to protect against too much wear of the hoof wall, to improve performance and to provide additional support for the horse on slippery surfaces. On the other hand, shoes restrict the hoof mechanism, increase the weight of the distal limb and increase the impact shock (Hermans, 1984). When good-quality shoes are put on correctly, with the least number of nails and not too far backwards, and when adequate hoof care by a farrier takes place on a regular basis, then the aforementioned objections can be more or less compensated (Moyer, 1975). Nevertheless, quantitative evaluation of trimming and shoeing procedures identified significant differences between farriers in balancing a hoof (Kummer et al., 2009).

Shoe weight

The distal limb of the horse has evolved to become very light in weight. One of the goals when shoeing a horse is to keep the weight of the shoe as low as possible (Balch et al., 1997). This decreases its inertia, which reduces energy expenditure in protracting and retracting the limbs. When weight is added to the horse's limb, for example by the application of shoes or protective boots, the effect depends on the location of the weight (Fig. 8.18) and increases with a more distal placement. The weight of a shoe is likely to affect both the energetics and the kinematics of locomotion. Therefore, in racehorses, steel training shoes are replaced by aluminum plates for racing (Curtis, 1999). The increase in energy expenditure has been estimated to be the same for 1 oz (28.4 g) at the foot as for 30 oz (852 g) at the withers; the maximal weight that should added be to the hoof is 5–10 oz (142–284 g) (Butler, 1995).

Willemen et al. (1997) investigated the influence of shoeing on stride kinematics of young horses that were shod the first time (Table 8.1). The average weight of the horses was 516 kg and the average weight of the shoes was 478 g. With shoes there was an increase in the maximal height of the flight arc of the hoof and greater flexion of the coffin, fetlock and carpal joints during the swing phase, which improved the quality or 'animation' of the trot. Stride duration and the relative swing phase duration were longer in the shod horses, but stride length was not significantly different. During the stance phase the load on the navicular bone increased by 14% when shod, probably as a consequence of these swing phase adaptations which were achieved with a less protracted forelimb. The increase in maximal vertical ground reaction force when shod was also found by Roepstorff et al. (1999).

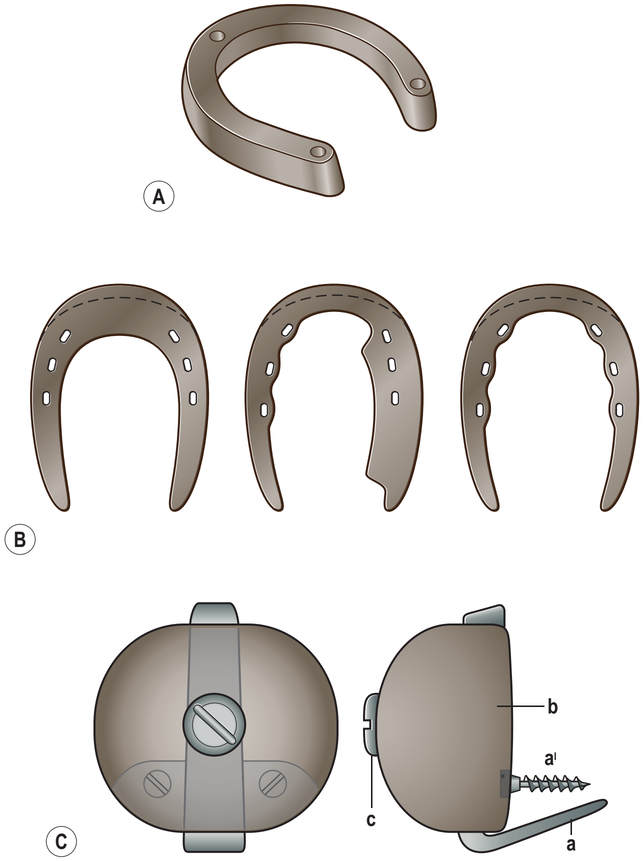


Fig 8.18 Basic principles to increase the weight of the shoe–foot combination. (A) Double shoe; (B) toe (left), side (middle) and heel (right) weighted shoes; (C) extra toe or heel weight attached to hoof wall.

Balch et al. (1996) doubled the weight of the shoe from 348–417 g to 724–869 g, and did not find any changes in stride length, stride duration or breakover time, but again there were increases in the maximal heights of the hoof, fetlock and carpus during the swing phase, with the peak height of the flight arc tending to occur later in the swing phase. The hoof and pastern segments had a more acute angle at initial ground contact, probably as a result of the increased momentum of the distal limb during the swing phase.

The location of the weight on the hoof may also have an influence on its effect.

Butler (1995) stated that toe weight would improve fold and heel weight would improve reach. Willemen et al. (1994) applied 88-g toe weights to the fore hooves of Standardbreds. During trotting on the treadmill the flight arc was elevated with the extra weight. Interestingly, the effects of toe weights on stride kinematics varied with the individual locomotion pattern: horses that initially showed too little carpal flexion showed more flexion, whereas those with adequate carpal flexion did not show a significant change. The effect on stride length was doubtful and there were no significant changes in stride duration or relative stance duration.

When egg bar shoes were put on young horses, the increased 'animation' effect was less than that found in horses wearing flat shoes. It has been speculated that it might be an effect of the increased weight distribution over the heels of this bar shoe (Willemen et al., 1997).

The Seattle shoe was designed to increase the energetic efficiency of locomotion but its main effect appeared to be due to its weight

Table 8.1 **Kinetic comparison of unshod versus shod conditions in a group of 12 horses trotting on a treadmill at 4 m/s**

Variable	Unshod	Shod
Stride length (cm)	2.78 ± 0.12	2.82 ± 0.12
Stride duration (ms)	694 ± 31	706 ± 28*
Stance phase duration (%)	37.0 ± 1.3	36.0 ± 1.2*
Range of pro/retraction (°)	43.5 ± 1.6	42.7 ± 1.3*
Maximum protraction (°)	112.0 ± 1.3	111.2 ± 0.8*
Maximum retraction (°)	68.5 ± 1.8	68.5 ± 1.5
Swing phase retraction (%)	9.8 ± 3.7	6.9 ± 3.4*
Range of carpal motion (°)	86.7 ± 7.1	98.2 ± 6.1*
Maximum carpal flexion (°)	80.6 ± 6.5	92.5 ± 6.0*
Range of fetlock motion (°)	81.2 ± 8.3	91.5 ± 8.8*
Maximum fetlock extension (°)	25.5 ± 2.7	24.3 ± 3.5
Maximum fetlock flexion (°)	55.6 ± 8.3	67.2 ± 8.5*
Range of vertical displacement hoof (cm)	10.0 ± 3.6	17.4 ± 4.5*
Range of vertical displacement fetlock (cm)	18.0 ± 3.9	20.0 ± 3.7*
Range of vertical displacement carpus (cm)	11.0 ± 3.4	13.9 ± 3.0*
Maximum total moment coffin joint (Nm)	158 ± 30	175 ± 48
Maximum total moment fetlock joint (Nm)	862 ± 124	835 ± 148

*Indicates a statistically significant difference between unshod and shod ($p < 0.05$). Nm, Newton meters. Values are mean ± SD.

Reprinted from Willemen, M.A., Savelberg, H.C.C.M. and Barneveld, A. (1997) The improvements of the gait quality of sound trotting warmblood horses by normal shoeing and its effect on the load on the lower forelimb. Livestock. Prod. Sci. 52, 145–153, with permission from Elsevier.

Table 8.2 **Kinetic comparison of three shoe manipulations of a group of 12 horses trotting on a treadmill at 4 m/s**

Variable	Unshod	Flat shoe	Egg bar
Maximum GRF (N)	6364 ± 600	6421 ± 647	6477 ± 699
Vertical displacement at scapular spine (cm)	7.2 ± 1.8	8.0 ± 1.5	7.9 ± 1.5
Maximal total moment at coffin joint (Nm)	158 ± 30	175 ± 48	175 ± 46
Maximal total moment at fetlock joint (Nm)	862 ± 124	835 ± 148	829 ± 100
Maximal moment at fetlock joint of DDFT (Nm)	211 ± 40	231 ± 67	231 ± 63
Maximal moment at fetlock joint of SDFT and SL (Nm)	726 ± 115*	676 ± 110	674 ± 97
Force on navicular bone by DDFT (N)	3060 ± 438*	3546 ± 526	3504 ± 459

*Indicates a statistically significant difference compared with the value of the flat shoe ($p < 0.05$). DDFT, deep digital flexor tendon; GRF, ground reaction force; Nm, Newton meters; SDFT, superficial digital flexor tendon; SL, suspensory ligament. Values are mean ± SD.

Reprinted from Willemen, M.A., Savelberg, H.C.C.M. and Barneveld, A. (1997) The improvements of the gait quality of sound trotting warmblood horses by normal shoeing and its effect on the load on the lower forelimb. Livestock. Prod. Sci. 52, 145–153, with permission from Elsevier.

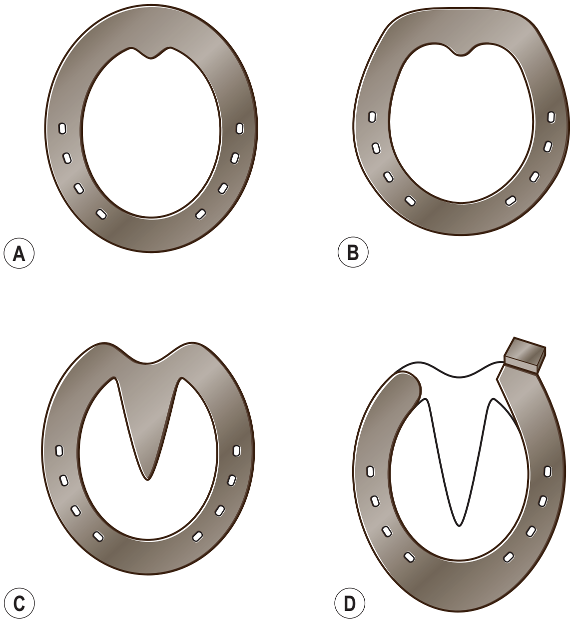


Fig 8.19 Shoes to support the caudal heel at stance. (A) Egg bar; (B) straight bar; (C) (adjustable) heart bar; (D) trailer with caulk at the lateral heel.

of 310–325 g compared with control shoes weighing 76–85 g (Wilson et al., 1992).

Weight attached to the feet increases the height to which the feet are lifted from the ground through greater limb flexion. This is a well-known effect used to improve the performance of gaited, carriage horses. Effects related to the location of the weight on the foot (heel/toe), or direct beneficial influence on stride length, remain speculative. Empirically, young trotters can find their balance more easily using weights, and interference can be prevented.

Shoe length

The hoof is more elastic in the heel area and its geometry changes when loaded: the heels expand and sink caudally, while the toe retracts (Douglas et al., 1998). Lengthening the heels of the shoe depending on foot conformation in routine shoeing automatically allows for this change in shape (Balch et al., 1997).

The extended heel of an egg bar shoe does not change the position of the center of pressure within the hoof during the stance phase. Compared with flat shoes, however, it reduces the torque at the fetlock joint by changing the orientation of the GRF vector so that its line of action is closer to the fetlock joint on its dorsal side (Auer & Butler, 1986; Willemen et al. 1999b) (Table 8.2). The net effect is that egg bar shoes have a negligible effect on tendon strain patterns in sound ponies at a walk (Riemersma et al., 1996a). Bouley shoes, which have a lengthened heel, may be effective, however, in cases of severed tendons, especially if the DDFT or DAL is involved (Figs 8.19 & 8.20).

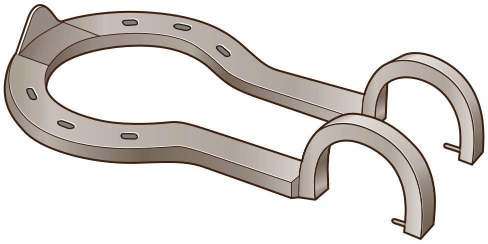


Fig 8.20 The longer heels of a Bouley shoe support a dropped fetlock joint caused by severe flexor tendon lacerations.

In the absence of tension in the DDFT, the hoof rotates to such an extent that the point of application of the GRF vector is directly below the center of rotation of the coffin joint. The tip of the toe lifts up and the hoof rolls back onto the heels, which puts the hoof in an unstable position. In these cases, egg bar shoes stabilize the hoof, and provide pain relief in horses with injury of the DDFT or DAL, laminitis or navicular disease (Auer & Butler, 1986). Bar shoes may also be useful to prevent lifting of the tip of the toe on soft ground (Wright & Douglas, 1993).

In horses trotting on a rubber floor there was no significant difference in limb loading between egg bars and flat shoes (Willemen et al., 1999b), although the 'animation' effect was more pronounced with flat shoes. Egg bar shoes, as a result of having more ground support and stability, should prevent the heels from sinking into the ground and allow reestablishment of heel growth leading to an increased toe angle (Scheffer & Back, 2001, Chateau et al., 2006b). Furthermore, it has been proven indirectly that the dorsal laminar blood flow is enhanced by egg bar or heart bar shoes in laminitic horses, as a result of distributing the weight more caudally and thus protecting the toe region of the foot (Ritmeester et al., 1998). It should be remembered that egg bars on the fore hooves are more likely to be stepped on and torn off by overreaching. Bell boots can be applied to the forelimbs to prevent this.

Bar shoes in general provide more ground support and thus might reduce limb rotation and pain in horses that are lame due to bone spavin. This effect can also be achieved using a unilateral trailer (heel extension) at an angle of 45° (Stashak, 1987; Balch et al., 1997; Martinelli & Ferrie, 1997). Trailers are also supposed to give more medial or lateral support and to change the mediolateral landing pattern depending on whether they are applied on the inside or outside. In foals with contracted flexor tendons toe extensions are used to stretch the DAL and DDFT at the end of the stance phase.

Shoe width

As mentioned previously, the geometry of the hoof changes when the hoof is loaded: the heels expand and sink caudally, and the toe retracts (Douglas et al., 1998). Increasing the width of the shoe accommodates for these movements (Balch et al., 1997). Another application for widening the shoes is in foals with angular limb deformities. The goal is to bring the weight-bearing surface of the limb, and thus the point of application of the GRF, under the fetlock joint as opposed to under the hoof capsule.

Hoof pads

Shoes increase pressure on the navicular region (Willemen et al., 1997, 1999b). Compared with horses that are bare-footed, shod horses have less damping of the impact forces and both the median and maximal amplitudes of the frequencies are higher (Balch et al., 1991b; Benoit et al., 1993; Dyhre-Poulsen et al., 1994).

Benoit et al. (1993) explored the shock absorbing damping effect on the hoof wall of different combinations of shoes and pads. For unshod hooves the impact shock had a velocity of 450 m/s^2 and this increased to 800 m/s^2 when steel shoes were applied, which is in accordance with Hertsch et al. (1996) and Back et al. (2006). Various shock-absorbing pads have been developed to decrease the amount of shock transmitted to the limb (Marks et al., 1971). Good attenuation of the impact shock was achieved using an aluminum shoe combined with a polyurethane pad, which had a value of 200 m/s^2. Benoit et al. (1993) recommended using a shoe with a pad of rubber or polyurethane and working the horse on soft footing to reduce the risk of lameness. A polyurethane/elastomer/viscoelastic hoof pad is a much better shock absorber than rubber (Marks et al., 1971; Vasko & Farr, 1984; Rooser et al., 1988; Back et al., 2006). For an optimal effect, hoof pads or silicone should be put under pressure to prevent it moving and to show increased shock damping (Jörgensen & Ekstrand, 1988). This is also ideal for increasing the surface area to disseminate high-frequency oscillations at impact.

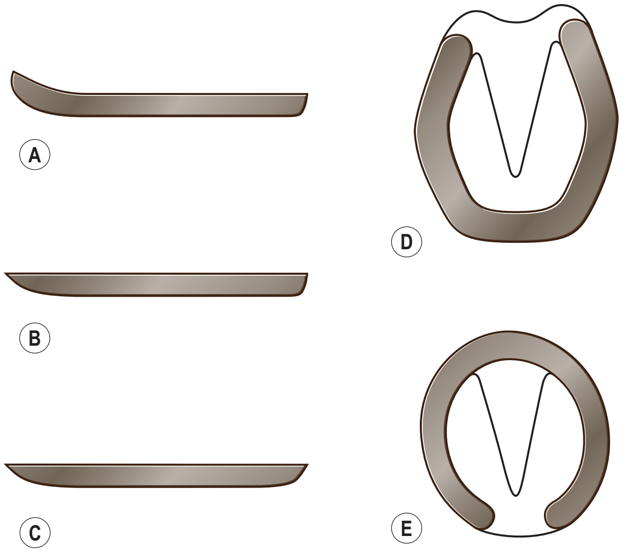


Fig 8.21 Toe manipulations of shoes to reduce breakover time. (A) Rolled shoe; (B) rocker toed shoe; (C) full roller motion shoe; (D) square toe shoe; (E) reversed shoe.

An additional benefit is that increased deformation of the hoof also leads to an increase in the hoof mechanism and thus circulation.

It should be noted that most of the studies of the effects of shoes and pads on impact shock have evaluated the effects at the level of the hoof wall. Little information is available regarding attenuation of the amplitude or frequency of the vibrations within the hoof. *In vitro* studies have suggested that the hoof acts as a filter to protect the more proximal bones and joints from the potentially damaging effects of impact shock (Dyhre-Poulsen et al., 1994; Lanovaz et al., 1998; Willemen, 1998).

Toe of the shoe

Breakover is defined as the time from the moment of heel-off to toe-off. In theory, the speed of hoof rotation during breakover can be enhanced by shoes that facilitate the movement of the hoof in rolling over the toe or by raising the heel (Fig. 8.21). For horses trotting even on a hard surface, however, the duration of breakover was no different for a rolled toe, a rocker toe or a square toe, compared with a flat shoe (Clayton et al., 1991; Willemen et al., 1996). A possible disadvantage, particularly with the square-toed shoes, is that they direct the breakover point to the middle of the toe, which is not the natural position in all horses. This might enhance the likelihood of lameness, especially at high speeds when rapid movements of the hoof occur (Clayton, 1990a; Wilson et al., 1992). Therefore, Caudron et al. (1997b) successfully used a full roller motion shoe to provide easy breakover in all directions for horses with poorly balanced hooves, whereas the principle behind these shoes was proven by Van Heel et al. (2006b).

Wedges

Side wedges

Wedges are applied to one or both heels for specific reasons. In horses with bone spavin, a lateral wedge is used to relieve pressure from the medial side of the hock. In horses with upward fixation of the patella, lateral wedges should enhance inward rotation of the hoof and promote rolling over the medial toe. In the light of evidence-based medicine, Back et al. (2003) studied the effect of lateral heel wedges on sagittal and transverse plane hind limb kinematics. It was found that lateral heel wedges cause significant changes in the transversal plane angles of all joints in the hind limb. Just before the end of the stance phase, the stifle joint becomes more adducted whereas the tarsal and fetlock joint become more abducted, in fact a more 'cow hocked' position of the tarsal joints. Conceivably, lateral heel wedges relieve tension from the medial patellar ligament and decrease pressure on the medial side of the tarsal joint. However, the fetlock joint experiences considerably more out of plane stress (Back et al., 2003) while digital imbalance puts the horse at risk for interphalangeal joint injury (Chateau et al., 2002).

Colahan et al. (1991) and Wilson et al. (1998) found that lateral wedges shifted the center of pressure to the lateral side of the hoof. Firth et al. (1988) put lateral wedges under the feet of foals and found a rapid compensation of bone strain to this alteration. Lateral corrective trimming restored the mediolateral balance of 15 horses with chronic digital lameness using a radiological protocol to assess the imbalance of the foot (Caudron et al., 1998).

Heel/toe wedges

Heel wedges facilitate rolling over the toe and are used to relieve pressure from the heels, as in navicular disease. A wedge of 6° resulted in a 24% load reduction on the navicular bone in trotting horses (Willemen et al., 1999b). Heel wedges caused only slight changes in strain of the SDFT, DDFT and SL during walking (Riemersma et al., 1996a,b), though a larger increase in SDFT strain has been recorded at the trot (Stephens et al., 1989). Using *in vivo data* and an accurate subject-specific model, Lawson et al. (2007) calculated that at walk and trot, heel wedges decrease DDFT peak strain and increase SL peak strain. Calculated SDFT peak strain, however, increases at a walk but not a trot. With heel wedges there is an earlier shift of the center of pressure from the mid-hoof to the toe and the unloading of the heels is enhanced, whereas toe wedges delay the forward shift of the center of pressure and the unloading of the heels is delayed (Riemersma et al., 1996a,b; Wilson et al., 1998; Crevier-Denoix et al., 2001). Heel wedges affect the sagittal plane kinematics of the digital joints both *in vitro* (Deguerce et al., 2001) and *in vivo*. A wedge of 6° significantly increases maximal flexion of the proximal (PIPJ) and distal (DIPJ) interphalangeal joints while decreasing maximal extension of these joints at heel-off both at a walk and at a trot (Degueurce et al., 2001; Chateau et al., 2004, 2006a). Inverse effects were observed with the use of toe wedges (except for PIPJ maximal extension at a trot). In the same studies, it was found that heel wedges significantly increase maximal extension of the metacarpophalangeal joint at a walk (Chateau et al., 2004) but not at a trot (Chateau et al., 2006a). The latter finding is in contrast with the study of Scheffer and Back (2001) that found a decrease in maximal fetlock extension when horses were shod with heel wedges. However, in that study the PIPJ was not taken into account, which may have affected the accuracy of the measurements.

With a toe wedge, strain in the DDFT and DAL increases, whereas strain in the SDFT and SL decreases both at a walk and a trot (Thompson et al., 1993; Lawson et al., 2007). Since the DAL has no muscular component that can actively change its length, strain in this structure is totally dependent on limb configuration, especially the angle of the coffin joint. The DAL is normally maximally strained at the start of breakover, which is when heel wedges have their greatest effect on the GRF (Fig. 8.22). This emphasizes the importance of the DAL in influencing limb forces and movements in the final part of the stance phase. Raising the heels seems appropriate in DAL injury, though this may slightly increase SDFT loading. During recuperation from DAL injury, however, the limitations on exercise make it unlikely that the safety margin of the SDFT will be exceeded even with heel wedges in place. Toe wedges are used clinically as a passive flexion test in lameness examination.

Nevertheless, one should realize that a balanced foot is the ideal. Altered foot orientation as a result of the use of wedges influences intra-articular pressure and articular contact area at the level of the distal interphalangeal joint. A study by Viitanen et al. (2003a) has demonstrated a significant increase in distal interphalangeal joint pressure and pressure on the dorsal side of the joint by elevating the heels by 5°.

Toe grabs and heel caulks

On a soft, slippery surface, caulks are screwed into the horse's shoes, where they act in a similar manner to spikes in a runner's shoes (Thompson & Herring, 1994). Toe grabs are used in racing Thoroughbreds with the objective of increasing the propulsion at the toe. There have not been any studies to prove these beneficial effects. However, results of a preliminary study indicate that landing and breakover in horses with toe grab shoes occurs much more abruptly which could represent an increased risk for injury (Ryan et al., 2006; Schaer et al., 2006). A correlation has been shown between the presence of toe grabs and the incidence of breakdowns involving the suspensory-sesamoidean apparatus (Kane et al., 1996). The higher the toe grab, the greater the risk of injury. Thompson and Herring (1994) found also a decrease in the dorsal metacarpophalangeal, and an increase in the dorsal inter phalangeal joint excursion in the sagittal plane during the stance phase, while in the transverse plane the distal limbs appeared to take a limb conformation similar to a varus limb.

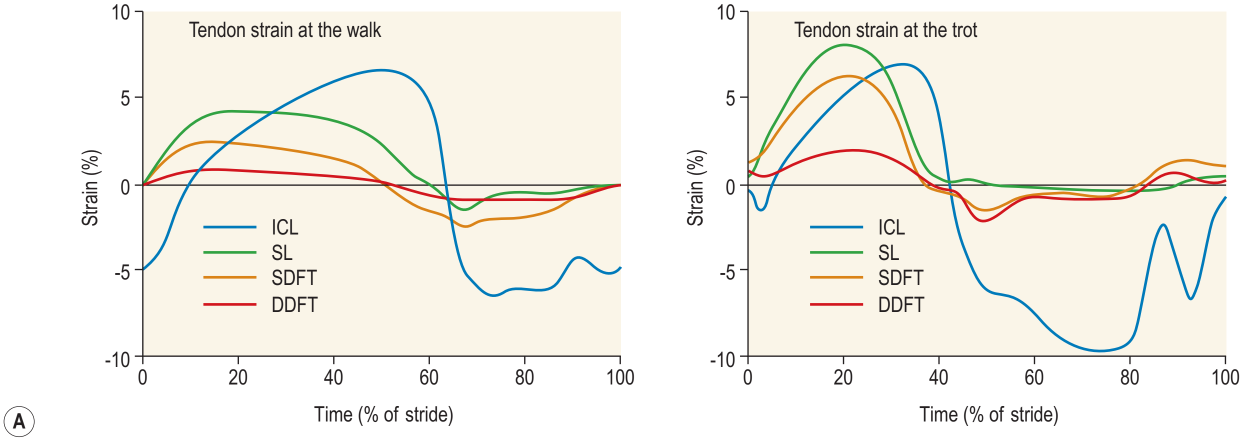
Rims, clips and nails

A minimum number of nails should be used, usually 6–8, to minimize damage to the hoof wall and to reduce blocking the hoof mechanics to a minimum (Balch et al., 1997). Therefore nailing should be done from the toe to the widest part of the hoof, with the clinches being formed one-third of the way up in a line parallel to the ground. Clips and rims reduce the shearing stress upon the nails especially when more traction is needed, for example in barrel racing and polo (Stashak, 1987; Balch et al., 1997; Martinelli & Ferrie, 1997).

Effect of footing

Properties of the ground

The hoof–ground interaction has been found to be the major determinant in studies relating track properties to limb pathology, both in horses (Kane et al., 1996) and in humans (Folman et al., 1986). Two important phenomena play a role: the banking and the surface type.



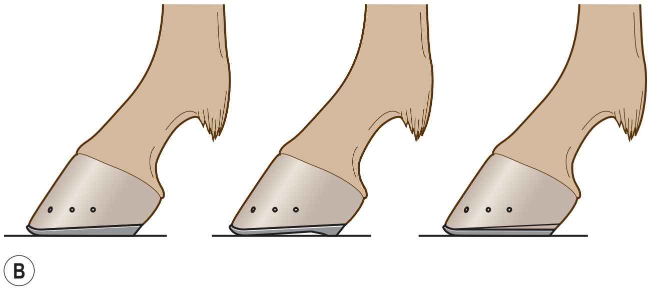


Fig 8.22 (A) Strain in the palmar soft tissues at walk (left) and trot (right) (Schamhardt et al., 1991); SL, suspensory ligament; ICL, inferior check ligament; SDFT, superficial digital flexor tendon; DDFT, deep digital flexor tendon. (B) Some examples of wedged shoes used to change strain distribution among the palmar soft tissues. Left, shoe with wedged heel; center, shoe with heel calk; right, shoe with wedge pad.

(A) Reprinted from Schamhardt, H.C., Hartman, W., Jansen, M.O. and Back, W. (1991) Biomechanics of the thoracic limb of the horse. Swiss Vet. 8, 7–10, with permission from Swiss vet. (B) Reprinted from Wright, I.M. and Douglas, J., Biomechanical considerations in the treatment of navicular disease. Vet. Rec. 7, 109–114, Copyright© 1993 with permission from BMJ Publishing Group Limited.

Fredricson et al. (1971, 1975 a,b) made three recommendations for banking to improve racetracks for trotters: increase the banking of the curve, incorporate a transition curve and eliminate slopes in the straight part of the track. Davies (1997) also stressed the importance of the track shape to prevent shin soreness. She found a considerable increase in dorsal bone strain when horses gallop through turns.

Most tracks and arenas are constructed with two layers: a looser cushion on top of a firmer base. Variations in the depth and quality of the base and the cushion affect both performance and soundness of the horses (Thomason & Peterson, 2008). Running on a rough instead of smooth track surface changed the vertical hoof force and balance of the resultant hoof forces (Kai et al., 1999). Hard surfaces absorb little energy, which leads to fast race times, but they are associated with a high incidence of lameness (Cheney et al., 1973; Pratt, 1997). The hardness of the ground is related to the impact time: the harder the surface, the shorter the impact time (Drevemo & Hjertén, 1991). Ratzlaff et al. (2005) found a significant correlation between track rebound rate and negative vertical hoof acceleration peaks. Any factor that reduces phase of the hooves will increase stride efficiency by allowing a smoother transition from braking to propulsion. Hence, track dynamic properties are important in determining the safety of racing surfaces.

A loose top layer of 5 cm or more can give dynamic response values that reduce impact by 40–60% (Cheney et al., 1973). Reduction of impact forces and enhancement of energy absorption can be achieved using a layer of wood shavings (Barrey et al., 1991; Drevemo & Hjertén, 1991). Wood products are effective shock absorbers but are sufficiently resilient that little impulse is lost. Wood products (shavings, mulch, chips) mixed with sand give good shock damping with lower vibration frequencies (Barrey et al., 1991). Rubber chips from recycled tires can also be mixed with sand to reduce impact shock without losing much impulse. Differences were found for horses trotting on a concrete track compared with a rubber or a sand track: stride and swing duration were longer on the softer track due to the lower impact shock combined with more elastic rebound (Buchner et al., 1994; Riemersma et al., 1996b). Newer track surfaces like synthetic all-weather waxed tracks further reduce the impact shock by 50% compared to sand tracks (Robin et al., 2009; Chateau et al., 2009a,b). Furthermore, all-weather waxed tracks smooth horizontal braking as a result of decreased friction. As a drawback, they reduce stride length and acceleration of the hoof at breakover. Hence, the all-weather waxed track seems an ideal training track but is most likely less efficient for performing at racing speed.

Barrey et al. (1991) categorized the damping properties into three types: no damping (asphalt), friction damping (sand) and structural damping (wood). Sand tracks can have different properties depending on the moisture content, dry density and depth of the layers (Ratzlaff et al., 1997). Apart from damping, sand tracks allow a forward rotation of the hoof at midstance and thus relief of pressure in the navicular area (Scheffer & Back, 2001). Surprisingly, the same study observed a concurrent decrease in maximal fetlock extension and thus unloading of the fetlock joint.

In wild horses, hoof growth appeared to be related to hoof wear. By natural selection only horses with good hoof quality survive. Ovnicek et al. (1995, 1997) found differences between the hooves of the wild horses that had lived for a prolonged period on one of three surfaces: sand, gravel or firm soil (Fig. 8.23). The form of the hoof adapts to the surface (Hampson et al., 2011). On sand, less shock damping was needed so the hoof wall carried more weight. The hooves did not show more wear as one would have expected, but on both sides of the wall spikes were formed at the quarters to give more grip in the sand ('natural caulks'). The hoof angle was about 55°. On a firmer surface of gravel, the hoof angle was more upright at the toe but the spikes at the quarters were lower, so the angle was again 55°. On firm soil the hoof wall was worn flat without a heel spike, which would not be useful in this type of ground. Again the hoof angle was 55°. Regardless of the type of surface the horse moved over, the toe was always rolled (Ovnicek et al., 2003).

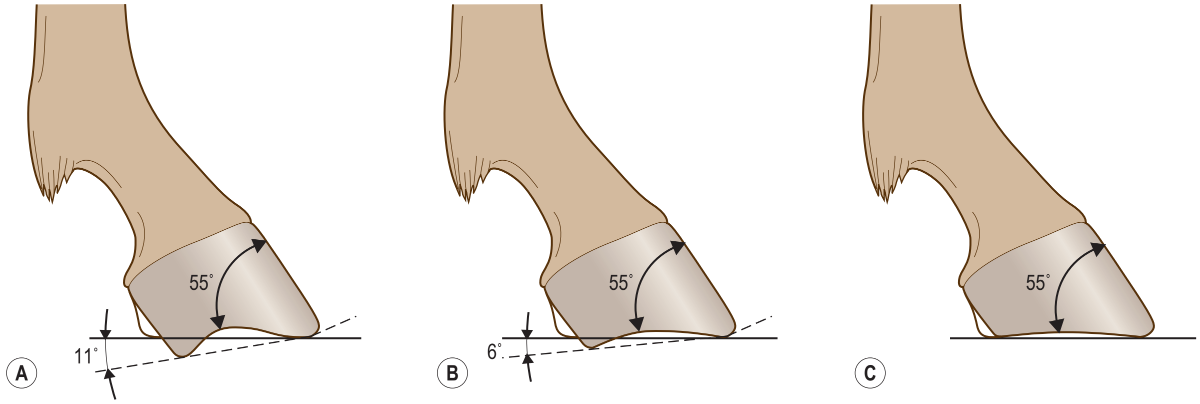


Fig 8.23 Hoof conformation of wild horses living on different ground surfaces. (A) Soft, (B) medium and (C) hard surfaces.
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Practical applications to performance

Interference

Horses trimmed with normal angles in their fore hooves and acute angles in their hind hooves showed a prolonged breakover time and delayed lift-off in the hind hooves (Hermans, 1984; Clayton, 1990b). However, the hind limbs were protracted more rapidly to re-establish the normal sequence of limb placements by the time of ground contact (Clayton, 1990a,b). Therefore, delaying breakover in the hind hooves seems unlikely to have a beneficial effect in horses that interfere (Curtis, 1999).

A more effective solution to interference problems may be to hasten breakover and lift-off in the fore hooves. Furthermore, another solution is to put on square toe shoes more towards the heels of the hind hooves so that the hoof wall instead of the shoe hits the forelimbs (toe preventer shoe). Also, weights are used to balance horses moving at high speed and thus prevent interference.

Action

It is recognized among horse trainers that heavier shoes give horses more action. Double shoes are applied in trotters just before the race to encourage them to lift the limbs higher, in spite of the fact that heavier shoes require greater energy expenditure to overcome inertia at the start of the swing phase and to overcome momentum at the end of the swing phase. Young trotters are shod with heavier shoes in the forelimb than in the hind limb to improve their balance (Hermans, 1984; Butler, 1995; Ruthe et al., 1997). Too little folding of the forelimb allows interference by the hind limbs; too much folding results in elbow hitting. Mediolateral imbalances leads to knee hitting by the contralateral limb, which can also be compensated for by lateral weights on the hind limbs so that their forward swing is outside the forelimbs.

Willemen et al. (1994) found that the effect of toe weights on the flight arc dependent on the individual locomotion pattern of the horse. Horses that normally trotted with too little carpal flexion showed more action with toe weights. Stride duration and relative stance duration did not change at high speeds (10–11 m/s), and it is doubtful whether there was any effect on stride length.

In young horses shod for the first time the weight of the shoes increased the maximal heights of the hoof, fetlock and carpus during the swing phase, which thus resulted in a longer, more 'animated' swing phase at the trot (4 m/s). This is the desired effect of double shoes applied in harness horses just before the race (Balch et al., 1996; Wilson et al., 1992; Willemen et al., 1997).

Practical application to lameness

Lameness is caused by pain, a mechanical deficit, a shortage of oxygen or a neurological problem. Therapeutic trimming and shoeing can be used to improve lameness by reducing pain or influencing limb mechanics (Stashak, 1987; Martinell & Ferrie, 1997; Aoki, 1999; Eliashar, 2007). This section highlights some practical applications to treat specific lameness conditions, thereby illustrating the aforementioned principles.

Hoof cracks

Hoof wall defects can be very painful in the acute stages, which makes the horse reluctant to bear weight on the affected foot. Cracks should be relieved from hoof wall pressure and should be repaired with the objective of minimizing movement and propagation of the crack using mechanical or composite material (Wilson & Pardoe, 1998). Cracks are stress raisers and can be detected using photo-elastic material (Davies, 1997). The hoof wall tubules seem to play a major mechanical role in resisting and redirecting these hoof-cracks (Kasapi & Gosline, 1998). Full hoof support, including frog and sole using polyurethane hoofpads, is one of the treatment options, as by using this technique the loading pressure on the hoof is significantly relieved from the nails and the hoofwall, and disseminated over the whole supported foot surface (Van Heel & Back, 2006).

P3 fracture

Fractures of P3 can be stabilized successfully by reducing hoof movements during weight-bearing. Heel expansion can be stabilized by using a full bar shoe with quarter and heel clips (Hermans, 1984; Colles, 1989a,b; Thomason, 1998), and the effect can be enhanced by applying a rigid cast over the clip shoe (Kersjes et al., 1985). However, frequent trimming does not help to prevent P3 fractures from developing in foals (Kaneps et al., 1998).

Laminitis

Laminitis, an aseptic pododermatitis mainly caused by endotoxins and gastrointestinal disorders, affects the laminae primarily on the dorsal aspect of the foot. The avascular damage to those laminae and thus to the connection between P3 and the hoof wall can lead to rotation and sinking of P3 within the hoof capsule. Quantification of limb load distribution using force platforms seems a promising screening method for detecting acute laminitis, grading severity of lameness and monitoring rehabilitation of horses with chronic laminitis (Hood et al., 2001b). An important parameter is the load distribution profile (LDP), which is an index of the frequency of redistribution of load over the four limbs of a horse during a 5-min measuring period. In acute laminitis, a decreased LDP is observed indicating unwillingness to move and even normal weight shifting is avoided as much as possible. In chronic laminitis, LDP increase with the severity of disease mostly as a result of cycling of load between forelimbs. Except for brief periods during motion, horses seem physically incapable of shifting substantial weight to the hind limbs.

Basic principles of shoeing treatment in laminitic horses are to protect the foot and damp impact shock, to facilitate breakover and thus relieve tension on the dorsal laminae, and to prevent sole pressure in the toe region by posterior support of the frog and heels (Goetz, 1987; Olivier et al., 2001; Oosterlaan-Mayer et al., 2002; Hansen et al., 2005). One of the ensuing factors in P3 rotation is deep digital flexor tendon tension. However, once rotation of P3 did occur, deep digital flexor tendon force is much reduced until late stance where it nears normal values again (McGuigan et al., 2005). From this observation, farriery in laminitic horses with P3 rotation should focus on regimens that reduce the force in the deep digital flexor tendon at the end of stance.

In chronic founders it is important to restore normal hoof conformation by corrective trimming. A reversed shoe laid back from the toe facilitates breakover, relieves pressure from the dorsal laminae and gives caudal heel support. The use of a pad protects the sole and damps oscillations (White & Bagget, 1983; O'Grady, 1997). Substantial clinical improvement following therapeutic shoeing of horses with chronic laminitis should not be expected during the first 7 days (Taylor et al., 2002). Dorsal hoof wall resection and the use of adjustable heart bar shoes, however, still remain somewhat controversial (Eustace & Caldwell, 1989a,b; Peremans et al., 1991; Jurga, 1997).

Navicular syndrome

Navicular syndrome comprises pathological changes to the navicular bone, its ligaments and the DDFT caused by mechanical overloading and/or vascular obstruction (Wright et al., 1998; Trotter, 2001). Recent histological examination confirms that lesions in the navicular bone occur predominantly on the fibrocartilage side and are comparable to osteoarthritis (Wright et al., 1998; Viitanen et al., 2003b). Pain is due to pressure of the DDFT on the navicular bursa and bone, tension in the navicular ligaments, and elevated intramedullary bone pressure in the navicular bone (Pleasant et al., 1993). According to Wilson et al. (2001), horses with navicular disease experience higher compressive forces on the navicular bone compared to normal horses. This finding is attributable to a contraction of the deep digital flexor muscle in early stance and the increased stress on the flexor surface of the navicular bone puts the horse at risk for progression of the disease. Regional analgesia of the palmar digital nerves lowers the compressive forces on the navicular bone indicating that horses with navicular disease attempt to unload their heels in response to pain (McGuigan & Wilson, 2001). Hence, the whole mechanism identifies navicular disease as a possible end point for a variety of heel related painful conditions. According to Williams (2001), however, horses with navicular disease have abnormal limb-loading force patterns that are not altered by loss of sensation in the palmar digital region and thus some horses seem predisposed to develop the disease as a result of an inherently abnormal gait pattern.

The navicular bone in the forelimb is significantly larger than in the hind limb, probably to compensate for the larger forces in the forelimb (Gabriel et al., 1997; Bentley et al., 2007), while the shape of the navicular bone has been related to the biomechanical risk of developing lameness (Dik et al., 2001). Smaller feet seem to have a higher risk of developing navicular disease (Balch et al., 1997) and navicular bone forces are well correlated to the ratio between heel and toe height and to the angle of the distal phalanx with the ground (Willemen et al., 1999; Eliashar et al., 2004). Bowker et al. (2001) found a significant increases in contact area and contact load at dorsiflexion in the joints between the distal phalanx and navicular bone and between the middle phalanx and navicular bone, when the digit was subjected to a load. This may explain the biomechanical background of morphological changes in the navicular bone.

Table 8.3 **Growth plate closure times and periods of rapid growth for equine long bones**

Growth plate	Age at closure	Rapid growth period
Distal radius	24–30 months	<8 months
Distal tibia	24 months	<6 months
Distal McIII/MtIII	12 months	<3 months
Proximal Ph I	6 months	<3 months

Mc, metacarpal; Mt, metatarsal; Ph, phalanx

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Shoeing principles for horses with navicular syndrome aim to reduce concussion and facilitate breakover by elevating the heels and rolling the toe. When the horse is bare-foot, pressure of the DDFT on the navicular bone is 14% lower than when flat shoes are applied (Willemen et al., 1999b). Therefore, it might be beneficial for shod horses suffering for navicular pain to have their shoes removed; this will also decrease concussion. Elevation of the heels using heel wedges may be beneficial (Wintzer, 1971; Leach, 1983; Turner, 1986, 1988; Bushe et al., 1987; Ratzlaff & White, 1989; Wright & Douglas, 1993; Keegan et al., 1998) due to the reduced net joint moment at the coffin joint (Willemen et al., 1999b) (Table 8.3). Wedge shoes promote breakover but the increased pressure at the heels may have a long-term negative effect on the growth and health of the heels (Rogers & Back, 2007). Empirically, the use of a rolled toe/rocker toe shoe is promoted, although this type of shoeing did not reduce breakover time in sound horses (Clayton et al., 1991; Willemen et al., 1996), but breakover tends to occur earlier (Eliashar et al., 2002) and more smoothly with a lower peak loading (van Heel et al., 2006b). Egg bar shoes may prevent hyperextension of the coffin joint on a soft surface and rotation of the foot, thus avoiding high stresses on the navicular region (Østblom et al., 1984; Auer & Butler, 1986; Wright & Douglas, 1993). By preventing the heels from sinking into the ground, they increase both distal and proximal interphalangeal joint flexion by several degrees at the beginning of stance while decreasing distal interphalangeal joint extension by almost 4° at heel-off (Chateau et al., 2006b). Further, egg bar shoes promote a more gradual loading of the hoof (flatter loading curve) with lower peak pressures, particularly at the heel region (Rogers & Back, 2007). Egg bars in combination with mixed sand tracks allowed a forward rotation of the hoof at midstance and thus relief of pressure in the navicular area (Scheffer & Back, 2001).

Arthrosis and arthritis

The high-frequency oscillations together with rapid loading of the joints experienced at impact promote the development of osteoarthrosis (Radin et al., 1981, 1999). Prevention and treatment aim to reduce these impact oscillations with a shock-absorbing pad (Marks et al., 1971; Benoit et al., 1993). *In vitro* tests, however, revealed that the hoof capsule (Willemen, 1998) and the distal limb were able to attenuate impact shock quite considerably (Dyhre-Poulsen et al., 1994; Lanovaz et al., 1998). A polyurethane/elastomer/viscoelastic pad is a much better shock absorber than rubber (Marks et al., 1971; Vasko & Farr, 1984; Rööser et al., 1988; Back et al. 2006). A leather pad is more susceptible to variations in moisture content of the ground (Stashak, 1987). For arthritis of the distal interphalangeal joint, Caudron et al. (1997a,b, 1998) used a special full roller motion shoe to facilitate breakover and to reduce stress and thus pain from the ligaments and the joint capsule while adapting to the breakover path of the particular horse, using a similar principle as Van Heel et al. (2006b).

Spavin

Bone spavin is an aseptic osteoarthritis on the dorsomedial aspect of the distal intertarsal joint or the tarsometatarsal joint (Stashak, 1987). The rationale behind treating bone spavin by lowering the medial side of the hoof or elevating the lateral heel is that it may relieve pressure from the medial side (Firth et al., 1988; Colahan et al., 1991). Indeed, Back et al. (2003) proved that when using lateral heel wedges in the hind limb, the tarsal joint becomes more abducted just before the end of the stance phase, in fact a more 'cow hocked' position of the tarsal joints. Conceivably, lateral heel wedges decrease pressure on the medial side of the tarsal joint. It has also been suggested that heel wedges and rolled toes prevent the hind limb from hyperextending the distal intertarsal and/or tarsometatarsal joints. Trailers have been used in selected cases to reduce rotation of the distal limb, but this can also exacerbate the symptoms (Stashak, 1987; Balch et al., 1997; Martinelli & Ferrie, 1997).

Patellar fixation

In horses with patellar fixation, lateral heel wedges and rolled toes prevent hyperextension and outward rotation of the stifle and thus avoid locking the patella (Stashak, 1987). Most affected horses are aged 3–5 years. When corrective trimming and shoeing are combined with training of the appropriate muscles, symptoms often disappear. Back et al. (2003) confirmed that practical experience in his study on the effect of lateral heel wedges on sagittal and transverse plane hind limb kinematics. It was found that by using lateral heel wedges the stifle joint becomes more adducted, and thus these lateral heel wedges would relieve tension from the medial patellar ligament. Empirically, some horses, especially trotters, respond better to a medial wedge than a lateral wedge, as this would also prevent them from interfering.

Flexural limb deformities

The greatest threat to the young foal's locomotor system is the foal itself. In the first 4–5 months of its life a foal grows as much as during the rest of its life. Just recently, it has been hypothesized that foals from older mares, that are poorly developed at birth because of the smaller placenta but then receive a surplus of milk, are prone to develop pathology in their locomotor system. Asynchronous bone–tendon growth results in flexural deformities.

Contraction of the DDFT is responsible for a hyperflexed coffin joint found at 1–6 months of age, while at 1 year of age SDFT contraction leads to a hyperflexed fetlock joint (Fig. 8.24). Treatment options depend on the severity of the contraction. Possible treatments for DDFT contraction include lowering the heels, extending the toe of the shoe using a cast, and desmotomy of the distal accessory (check) ligament. For SDFT contraction a wedged pad would be an option. So-called 'weak' flexor tendons are often seen in premature foals and lead to hyperextension of the distal limb. If this does not have a traumatic origin, the initial treatment can be supported by shoes with longer heels (Curtis, 1992a; Ellis, 1998).

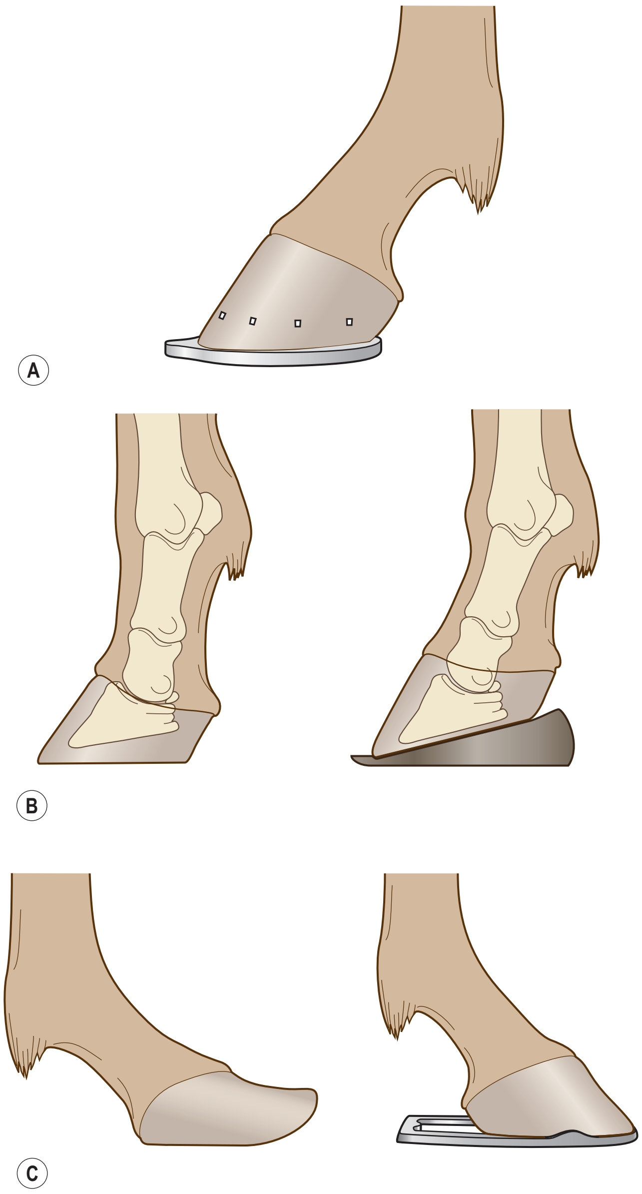

Fig 8.24 Shoeing principles for flexural deformities in foals. (A) Toe extension for contracted deep digital flexor tendon (left) treated with a raised heel (right). (B) Contracted superficial digital flexor tendon. (C) Flaccid flexor tendons (left) treated with a heel extension and appropriate hoof trimming (right).

Angular limb deformities

In the rapidly growing young foal asymmetric bone growth, caused by congenital or acquired factors can lead to angular limb deformities. They should be corrected at the fetlock joint before 3 months of age, while in those at the carpus/tarsus region this should be corrected before 6–8 months of age (Table 8.3). At that time the growth plates start to close. Treatment options of first choice are corrective wall/toe rasping, a medial/lateral extension shoe (Dallric, Dallmer Salzhausen-Putensen, Germany; Baby Glu, Mustad Hoofcare SA, Bulle, Switzerland) and a limited exercise regime (Curtis, 1992b, 1999). The objective is to center the hoof-bearing surface under the fetlock joint (Fig. 8.25).

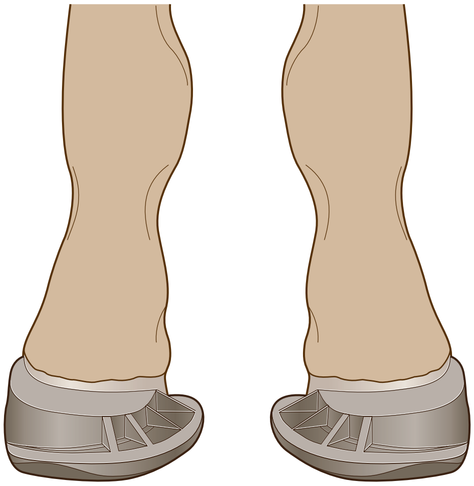

Fig 8.25 Diagram of a foal with a fetlock valgus deviation (left) treated with a medial extension glue-on shoe (right).

Conclusion

The major effects of farriery are similar in most horses of a group, but there are likely to be minor differences in the response of individual horses. Basic farriery considerations that influence locomotion are toe angle and weight of the shoe, which interact with the type of footing. The mechanisms by which trimming and shoeing affect locomotion and lameness involve relieving pain, altering the mechanics of the stance phase and influencing inertia during the swing phase. In experimental studies the mean effect of a particular modification on the kinetics and kinematics is often smaller than the differences between individuals. Therefore, individual responses may have to be taken into account when evaluating farriery effects.

In young foals, regular trimming is necessary from 1 month of age (every 4–6 weeks). If pathological deformities or hoof unevenness start to develop, therapeutic trimming should be performed at least every 2 weeks. Prevention of these deformities is the best option, of course, because forced correction of conformation by trimming and corrective shoeing at an older age will lead to lameness sooner or later.

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CHAPTER 9

Gait adaptation in lameness

H. H. Florian Buchner

Introduction

Horses are kept as domestic animals due to their outstanding locomotor skills, which have been employed for military use, transportation and sports. Perfect athletic performance, of course, needs a sound locomotor system. Maintenance of soundness and detection of lameness are of prime importance for horse owners. The ability to study the gait of horses and assess the small deviations associated with locomotor problems is limited by the physiological ability of the human eye. Therefore, locomotion research in horses started very early with studies of the gait of lame horses. Already in 1899, Muybridge published series of photographic plates of both sound and lame horses in his fascinating book, *Animals in Motion*. These nice studies were the start of modern kinematic research about lameness in horses, which is and, will continue to be, a central theme of equine locomotion analysis (Leach & Crawford, 1983).

Definitions

Lameness is not a disease but a symptom of a locomotor disturbance. Generally, lameness can be defined as an alteration of the normal gait due to a functional or structural disorder in the locomotor system (Wittman, 1931; Knezevic, 1982; Stashak, 1987; Wyn-Jones, 1988; Speirs, 1994; Wilson & Keegan, 1995). A detailed description of the locomotion pattern is a central part of each lameness examination. The goal is to localize the cause of the lameness and to make a diagnosis that is as specific as possible as a basis for the veterinary therapy.

Classification of lameness

In a clinical setting various classifications of lameness are used to differentiate various pathological gait patterns. Such classifications provide only a rough framework and a real lameness cannot always be fitted into a single category. Nevertheless, placing a lameness in one of the categories is a first step for the clinician in reaching a diagnosis. Locomotion analysis, on the other hand, should provide specific details of the various lamenesses as well as fundamental relations and principles. These can be used to understand the different types of lameness and to provide the scientific basis for interpreting the observations made during lameness examinations. Figure 9.1 shows the traditional classifications for lameness. The cause of the lameness is most often pain in one or more limbs. Sometimes diseases of peripheral nerves, blood vessels or muscles cause specific lameness and occasionally purely mechanical restrictions can be found. The type of lameness describes the phase of the stride when the disturbance is caused. A supporting limb lameness is caused by pain during the stance phase, while swinging limb lameness is caused by problems during the swing phase. Pure swinging limb lameness without pain during the stance phase is extremely rare and is most often a component of mixed lameness with features of both supporting and swinging limb lameness. The third classification describes the site of the lameness as a fore or hind limb lameness, or as a bilateral lameness when both fore limbs or both hind limbs are affected.

If a specific structure can be proven as the origin of lameness and a specific diagnosis is established, locomotion analysis techniques can be used to define the associated locomotor patterns. A special situation is represented by induced lameness, which has been used in several clinical studies for evaluations of diagnostic or therapeutic regimes. Lameness models have been reported to induce hoof lameness (Merkens & Schamhardt, 1988a; Foreman & Lawrence, 1991; Keegan et al., 2000), arthritis of the carpal joint (Auer et al., 1980; Firth et al., 1987; Peloso et al., 1993) and tendonitis (Silver et al., 1983; Williams et al., 1984). The ability to induce a more or less transient lameness in groups of sound horses offers an important and reliable method to study the locomotor pattern in horses with specific, well-defined lameness in a controlled manner that minimizes individual variations.

Locomotion research can provide information regarding several aspects of equine locomotion. This chapter will describe the results of locomotion research in the area of lameness during the past century from different viewpoints and with different objectives:

1. Firstly, the kinematics that are specific to different types of lameness will be described. This will provide a more complete insight into the gait adaptations and how horses deal with and compensate for pain in a limb. The complete picture of movement changes of all body parts due to fore or hind limb lameness makes it possible to distinguish the original and compensatory lameness. The findings are of fundamental importance for the orthopedic specialist.
2. The effectiveness of the locomotor adaptations in terms of load reduction in the painful limb and load redistribution will be evaluated using kinetic methods. The connection of kinetic and kinematic findings allows an analysis of the mechanisms by which a horse manages a lameness.
3. The patterns of some well-defined lameness will be presented and analyzed to determine their specific signs, which will serve as a diagnostic database.
4. The possible use of locomotion analysis techniques in clinical settings, such as the documentation of diagnostic or therapeutic regimes or the diagnosis of insidious lameness, will then be described and discussed including the pros and cons of these methods.

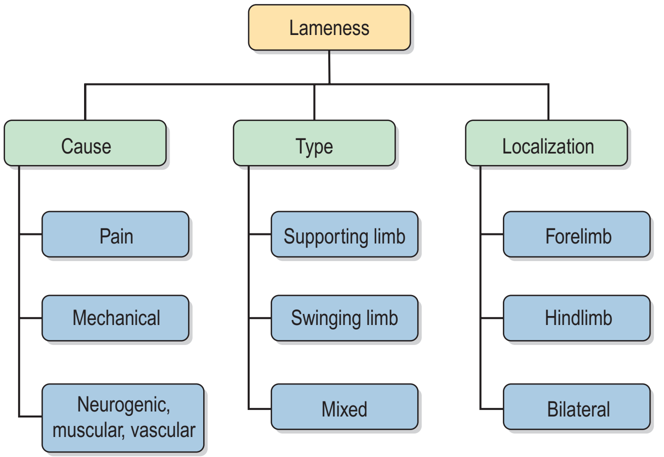

Fig 9.1 Classification of lameness.

5. Finally, the effects of several frequently used diagnostic or therapeutic aids will be evaluated. In these studies locomotion analysis technology is used to evaluate the proposed effects and to support or to reject their use based on scientific fundamentals.

Kinematics of lameness

The judgment of an observer as to whether a horse is lame or not is based on a comparison of the gait or details of the locomotion pattern with a sound reference. Such a reference for an objective determination of a lameness can be found using three different approaches:

1. A comparison with the 'normal' locomotion pattern in the population, which is based on the experience of the clinician. This requires a sufficient number of observations in sound horses to establish a standard and to eliminate the problem of individuality. This 'standard horse', however, may not be the best method for kinematic assessments due to the small differences caused by lameness compared to the wide interindividual variation in sound horses.
2. A comparison using the horse's own pattern as an individual control. Since the sound pattern of the individual is usually unknown during lameness examinations, diagnostic nerve blocks serve as a tool to restore kinematics that are close to the sound pattern during a clinical evaluation. In a research setting similar comparisons are possible using lameness models, where the sound locomotion pattern of each horse before lameness induction serves as an individual control and minute deviations due to lameness can be easily differentiated from the small intraindividual variations.
3. An assessment of the movements of the left and right sides of the body in terms of locomotor symmetry or asymmetry within an individual horse. This approach allows an immediate comparison of affected and unaffected limbs independent of individual characteristics.

Using one of these three methods several general characteristics of supporting limb lameness and swinging limb lameness have been described.

Supporting limb lameness

Lameness that results from the efforts of the horse to avoid pain during the stance phase is defined as supporting limb lameness and often originates in ailments of the hoof or the distal limb. These ailments cause pain during loading and the horses try to minimize the pain by changes in various aspects of the locomotor pattern, which can be described within four categories: the temporal stride pattern, the movement of the hoof, the angular pattern of the limb joints and head and trunk movements.

Temporal stride pattern

Many studies (Hugelshofer, 1982; Clayton, 1986b; Girtler, 1988a,b,c; Tietje, 1992; Buchner et al., 1995a; Keegan et al., 1997; Weishaupt et al., 2006) have tried to find relationships between types of lameness and the timing of the limb placements, described as stride variables. However, these studies did not find typical changes or asymmetry patterns. This is in contradiction to subjective impressions, where some observers describe that a shortening of the loading phase of the lame limb seems to be a typical sign for a supporting limb lameness (Wittmann, 1931; Ratzlaff et al., 1982; Hajer et al., 1988). Nevertheless, some general temporal patterns can be seen if the lameness is moderate or severe. Slight or 'subclinical' lameness, on the other hand, does not show significant temporal deviations from the sound stride pattern (Buchner et al., 1995a; Weishaupt et al., 2006).

Generally, lame horses tend to move with a slower velocity. This is of utmost importance for the interpretation of the stride pattern in lame horses, because all stride variables are heavily dependent on velocity (Dusek et al., 1970; Leach & Cymbaluk, 1986; Leach & Drevemo, 1991). Furthermore, the lameness degree is influenced by speed, as moderate lameness increases with speed (Peham et al., 2000). Comparisons of different assessments, for example before and after diagnostic anaesthesias, are valid only if recorded at the same velocity or using statistical correction methods (Kübber et al., 1994). Horses reduce their velocity by decreasing stride duration, stride length and all the dependent variables, such as stance duration or contralateral advanced placement. On the other hand, when horses are forced to maintain a constant velocity on the treadmill, variable results regarding stride duration and stride length in lame horses have been reported (Buchner et al., 1995a; Pollhammer-Zeilinger, 1996; Keegan et al., 1997). When showing different degrees of hoof lameness, provoked by the screw model of Merkens & Schamhardt (1988a), horses maintained the velocity by taking shorter, but quicker, strides than in the sound condition (Table 9.1) (Buchner et al., 1995a; Galisteo et al., 1997; Weishaupt et al., 2006). However, in horses suffering from navicular disease no consistent changes in stride duration and stride length were found between the lame pattern and the sound pattern after diagnostic anesthesia (Pollhammer-Zeilinger, 1996; Keegan et al., 1997).

Generally, a consistent feature in all studies is a shortening of the swing duration in lame horses compared to the same horses without lameness (Hugelshofer, 1982; Tietje, 1992; Buchner et al., 1995a; Keegan et al., 1997). In other words, horses lengthen the stance phase duration rather than shortening it to diminish the pain. This is in contradiction to the opinions that shortened stance durations are indicative of supporting limb lameness (Ratzlaff et al., 1982; Clayton, 1986a). Furthermore, there is no difference in stance duration between the lame and the sound limb (Girtler, 1988c; Tietje, 1992; Buchner et al., 1995a; Weishaupt et al., 2006). The horses maintain their symmetry; both limbs are kept on the ground longer with increasing lameness, while both swing durations decrease. This does not contradict the findings of differences in stance durations between left and right limbs in some particular horses. Absolute symmetry is nearly impossible in nature and significant left/right differences as sign of handedness or leggedness are found in various breeds (Drevemo et al., 1987; Deuel & Lawrence, 1987; Meij & Meij, 1980). Asymmetry in stance duration is therefore not a sign of a supporting limb lameness, but a typical individual characteristic.

Table 9.1 Mean and standard deviation of stride variables in 11 horses evaluated when sound and with two degrees of induced forelimb lameness in the hoof at the trot (3.5 m/s)

Variable	Lameness degree		
	0	1	2
Stride duration (ms)			
	715 (36)	707 (42)	693 (53)[c]
Stance duration (ms)			
Lame forelimb	312 (17)	313 (15)	318 (16)
Sound forelimb	307 (16)	306 (15)	312 (15)[c]
Ipsilateral hind limb	291 (20)	287 (25)	290 (22)
Diagonal hind limb	291 (17)	284 (20)[a]	285 (19)[c]
Relative stance duration (%)			
Lame forelimb	43.7 (2.4)	44.3 (2.4)	46.0 (2.8)[bc]
Sound forelimb	43.0 (2.4)	43.4 (2.8)	45.3 (3.4)[bc]
Ipsilateral hind limb	40.7 (3.1)	40.7 (3.7)	42.0 (3.8)[bc]
Diagonal hind limb	40.7 (2.9)	40.3 (3.3)	41.3 (3.2)
Advanced placement (ms)			
Lame diagonal	0 (18)	–9 (19)[a]	–16 (26)[c]
Sound diagonal	3 (22)	–2 (24)	–10 (24)[bc]
Lame to sound forelimb	360 (20)	358 (26)	341 (28)[bc]
Sound to lame forelimb	355 (18)	350 (19)	352 (28)
Ipsilateral to diagonal hind limb	358 (19)	357 (20)	359 (21)
Diagonal to ipsilateral hind limb	357 (18)	351 (24)	335 (36)[bc]
Suspension (ms)			
Lame diagonal	36 (24)	35 (26)	14 (29)[bc]
Sound diagonal	39 (20)	38 (20)	32 (27)

Significant differences between the values of a variable for different lameness degrees are indicated by superscripts: [a], degree 0 versus 1; [b], degree 1 versus 2; [c], degree 0 versus 2. Diagonal advanced placement is positive when the hind limb precedes the forelimb and vice versa.

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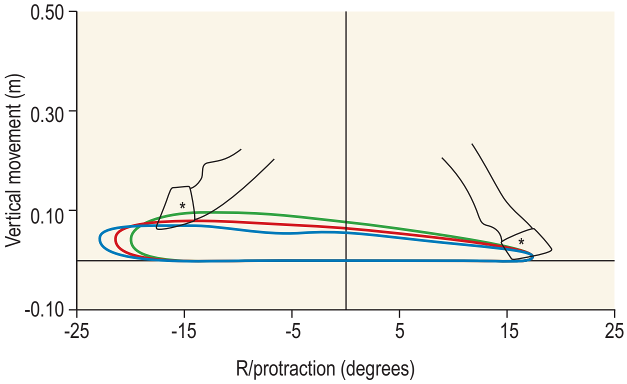

Fig 9.2 Hoof trajectory of a lame forelimb during different degrees of forelimb lameness. (blue line) Lameness degree 0 (sound); (red line) lameness degree 1; (green line) lameness degree 2.

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In forelimb lameness, a real asymmetry due to lameness can be found in the suspension phase at the trot (Table 9.1) (Clayton, 1986a; Buchner et al., 1995a; Weishaupt et al., 2006). The suspension phase following the lame diagonal stance phase, which means the time when none of the limbs is on the ground after the stance phase of the lame forelimb and diagonal hind limb, is significantly shortened in lame horses. This is a sign of reduced propulsion during the stance phase of the lame limb. The suspension following the sound diagonal, on the other hand, is nearly unchanged. This asymmetry can only be seen in forelimb lameness, not in hind limb lameness. The asymmetric suspension phase in forelimb lameness has some implications for the co-ordination of the placements of the different limbs. The duration of the step from the lame to the sound forelimb is shorter than the contralateral step or than the step duration without lameness (Table 9.1) as a result of the clearly shortened suspension between the lame and sound diagonals.

An interesting pattern is seen in the diagonal advanced placement. As already mentioned, during forelimb lameness, the stance phases of the forelimbs tend to increase, with the fore hooves being placed earlier and lifted later. This results in an earlier placement of the forelimbs in relation to the diagonal hind limbs. Sound horses place their diagonal limb pairs almost synchronously or even place the hind limbs earlier than the forelimbs (positive diagonal advanced placement). The latter sequence may be indicative of superior gait quality in dressage horses (Holmström et al., 1994). Lameness reverses this pattern. Similarly, horses on a treadmill show this earlier forelimb placement, perhaps due to a need for longer ground contact, possibly as a sign of a remaining insecurity even after a long period of habituation to the treadmill (Buchner et al., 1994).

During hind limb lameness, generally the same temporal pattern is found in most stride variables, however, the amount of changes in limb timing is much less in hind limb lameness. Stride frequency increases as in forelimb lameness, but the increase in relative stance duration is small and both diagonal advanced placement and suspension phases do not change at all (Buchner et al., 1995a). Horses with hind limb lameness keep this variable constant and perfectly symmetrical.

There are two possible explanations for this temporal stability. Firstly, load damping may be more effective in the hind limbs as a result of greater tarsal flexion during loading of the lame limb. And secondly, a lower percentage of the body weight is carried by the hind limbs (46.8%, trot) compared with the forelimbs (53.2%) (Merkens et al., 1993), which may facilitate the management of a supporting limb lameness.

Summary

Horses with supporting limb lameness tend to have longer stance durations in both, lame and contralateral sound limb, but provide less propulsion during the stance phase of the lame limb, so that the following suspension phase is reduced. This is an important method of reducing the peak loads on the limbs, which will be discussed in detail in a later paragraph.

Hoof movement

Hoof movement can be visualized as the hoof trajectory during the stride. Figure 9.2 shows the trajectory of a fore hoof on a treadmill seen from the right side. The stance phase is characterized by a constant vertical position on the treadmill belt during the horizontal movement from right to left in the figure. After lift-off, the flight arc of the hoof shows the elevation during the swing phase and ends with the hoof landing at the start of the next stance phase.

Different features can be seen in this figure showing typical changes in the hoof trajectory due to various degrees of forelimb lameness. The maximal height of the hoof during protraction of the limb is said to be lower during both supporting limb lameness and swinging limb lameness (Stashak, 1987). In supporting limb lameness, a lower flight arc might reduce pain on impact. In swinging limb lameness, difficulties in flexing the joints may cause a lowering of the flight arc. However, this could not be confirmed in recordings of horses suffering from navicular disease. Several authors investigated this lameness for characteristic patterns, but did not find consistent changes in maximal hoof height (Ratzlaff & Grant, 1986; Pollhammer-Zeilinger, 1996; Keegan et al., 1997). In experimentally induced forehoof lameness (Buchner et al., 1996a) as well as in patients with forelimb lameness (Girtler et al., 1987) a higher flight arc was found in the sound forelimb and an unchanged height in the lame limb (Fig. 9.2). During hind limb lameness, a lower flight arc was found in the lame limb, while the sound limb had an unchanged flight arc (Buchner et al., 1996a). Both patterns give the same impression, the hoof of the lame side is lower than the contralateral hoof. In induced toe pain lameness, a shift of the instant of maximal hoof height nearer to midswing has been found (Keegan et al., 2000).

Changes in the pro- and retraction of the limbs of lame horses are visible at the walk. Retraction of the forelimbs is slightly reduced during forelimb lameness. For the interpretation of this pattern a comparison with the changes in hind limb movement during hind limb lameness is interesting. Lame hind limbs show a reduction in protraction rather than retraction. Perhaps the position of the limb relative to the body center of mass influences this feature. During walking vertical ground reaction forces of the forelimbs reach peak values in the second half of the stance phase, when the limb is retracted, which brings it closer to the body center of mass. On the other hand, the position of the hind limbs relative to the body center of mass causes peak loading in the first half of the stance phase (Merkens et al., 1986). The changes in pro- or retraction, which are more obvious during walking than trotting, might reduce the total load on the lame limb by shortening the period of high load.

The changes in the temporal stride pattern also have implications for the linear stride variables. The distances between hoof placements of sound and lame limbs and vice versa, which are called the step lengths, might give information about the cause of the lameness. A shortening of the step length from the lame to the sound limb is said to be typical for a supporting limb lameness (Wittmann, 1931; Stashak, 1987). Horses with sesamoiditis (Clayton, 1986b) and hoof lameness (Buchner et al., 1996a) showed this feature. This shortening corresponds with the temporal variables in terms of the shorter advanced placement between lame and sound forelimbs as well as the clearly shortened suspension phase following the lame diagonal. The linear stride variables offer further proof of reduced propulsion during the stance phase of the painful limb.

Few studies have described specific changes in the hoof-landing pattern due to lameness. Toe first or heel first might give information about the localization of the pain, in the heel or toe region (Ratzlaff & Grant, 1986; Stashak, 1987; Clayton, 1988; Tietje, 1992; Wilson & Keegan, 1995). Measurements of induced hoof lameness, caused by pressure-inducing screws on the sole, did not influence the hoof-landing angle (Buchner et al., 1996a), which may have been due to the position of the screws in the middle between toe and heel. The study of Keegan et al. (2000) inducing the hoof pain at the toe showed an increased protraction of the lame limb, but the hoof-landing pattern could not be distinguished. Differences in the hoof position and motion just before landing were described by Knezevic et al. (1982) for a horse with carpal lameness. Changes in limb movement during the swing phase may also cause changes in the hoof-landing pattern. However, a lack of quantitative data for different lameness causes still precludes making precise conclusions at this time. To differentiate between individual landing patterns and specific lameness patterns, it will be necessary to perform studies with a number of horses that have a similar diagnosis or the same induced lameness.

Summary

The hoof flight is slightly lower in the lame limb compared to the sound limb. Forelimb lameness causes reduced retraction and sometimes increased protraction of the lame limb; hind limb lameness shows a reversed pattern. The reduced swing duration also leads to a shorter step length from lame to sound limb but slightly higher flight arc in the sound limb.

Limb movement and joint angle patterns

The joint movement patterns of the equine limbs are important indicators of both physiologic locomotor capacity (Holmström et al., 1994; Back et al., 1994) and disturbances of the gait due to lameness (Adrian et al., 1977; Ratzlaff & Grant, 1986; Back et al., 1993; Peloso et al., 1993; Buchner et al., 1996a; Keegan et al., 1997). The amount of hyperextension of the fetlock joint and flexion of the carpal and tarsal joints correlated very well with subjective judgments of gait quality in the areas of suppleness and strength (Back et al., 1994). In lame horses, the proximal (shoulder, carpus, stifle, tarsus) and distal (fetlock, coffin) joints reflect different aspects of limb motion and show different changes due to lameness.

During supporting limb lameness the horse tries to reduce the load on the painful limb. The amount of loading can be measured directly using a force plate, and it can be assessed indirectly from the distal joint patterns during the stance phase. At the trot, after landing the fetlock joint shows increasing hyperextension until the moment of maximal loading in the middle of the stance phase at (Fig. 9.3A). The hyperextension then decreases gradually until the end of the stance phase. The fetlock joint angle during the stance phase is determined by and resembles the pattern of the vertical ground reaction force as measured in sound horses with a force plate (Riemersma et al., 1988) or a force shoe (Ratzlaff et al., 1993). This relationship is valid also in lame horses, when changes in the fetlock and coffin joint patterns correspond to a decrease in the vertical ground reaction force in the lame limb and a compensatory increase in the contralateral sound limb (Merkens & Schamhardt, 1988b). The correlation of the ground reaction forces with the distal limb joint angle pattern is even used to calculate limb forces based on kinematic data of distal limb length (Bobbert et al., 2007).

During supporting limb lameness, both the fetlock and coffin joint patterns change distinctly with increasing lameness (Table 9.2) (Buchner et al., 1996a). In the lame limb, fetlock hyperextension at the middle of the stance phase is reduced with each degree of lameness (Fig. 9.3A). In contrast, fetlock hyperextension in the contralateral sound limb shows increased maximal values (Fig. 9.3B). This asymmetry indicates a compensation of the reduced loading of the lame limb by the contralateral sound limb. Similarly, coffin joint flexion is reduced, but the effects are a little less obvious and occur earlier in the stride cycle (Fig. 9.3C,D). Based on this strong correlation, the fetlock joint pattern can be used as indicator of a supporting limb lameness or the supporting limb component of a mixed lameness (Back et al., 1993). However, the range of fetlock joint motion proved to be less sensitive in detecting slight lameness (Peloso et al., 1993), probably due to the higher variability in swing phase flexion. Therefore, maximal fetlock hyperextension during stance, which resembles the clinical assessment of fetlock sinking, is a sensitive measure of a supporting limb lameness. The

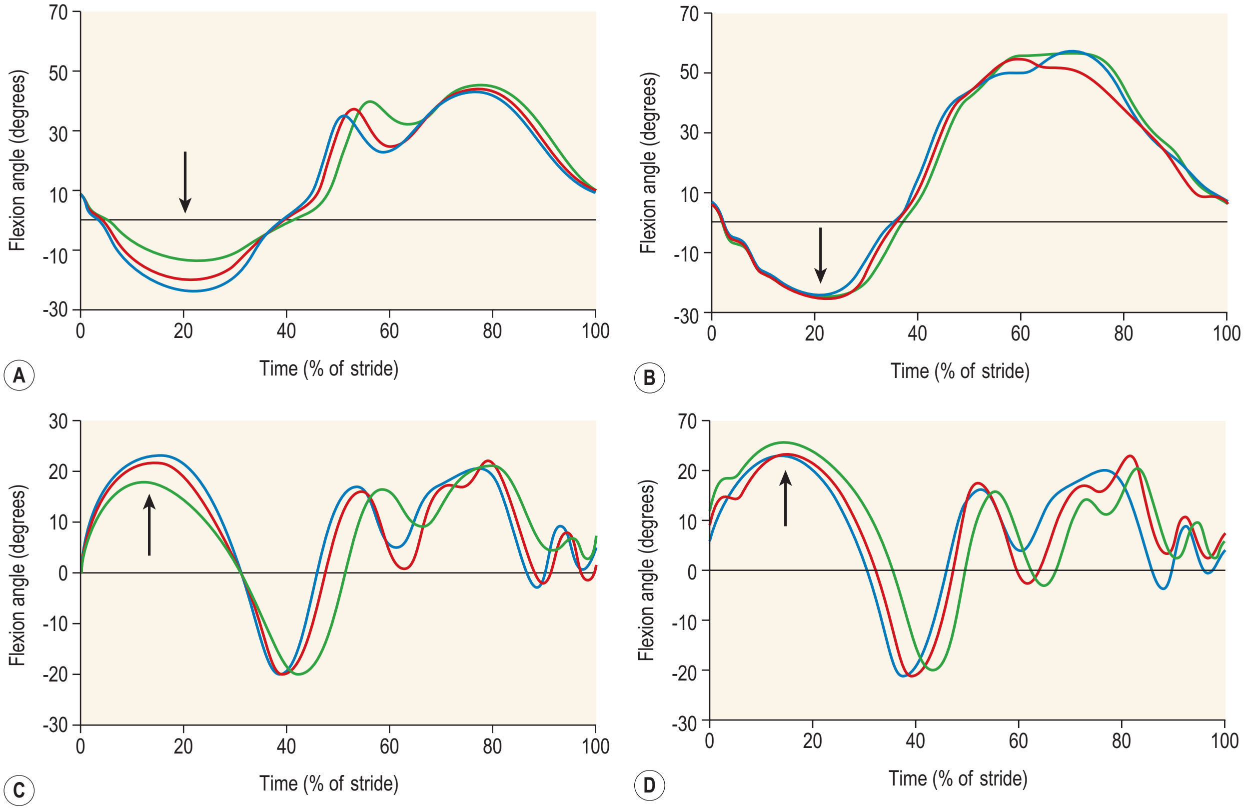

Fig 9.3 Joint angle pattern of the fetlock (A) and coffin (C) joints of a lame forelimb, and the fetlock (B) and coffin (D) joints of the contralateral sound forelimb during different degrees of forelimb lameness. (blue line) Lameness degree 0 (sound); (red line) lameness degree 1; (green line) lameness degree 2. Arrows indicate hyperextension (fetlock joint) or flexion (coffin joint) during the middle of the stance phase.

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Table 9.2 Joint angle variables of the forelimbs of 11 horses at the trot when sound and with two degrees of induced forelimb lameness (3.5 m/s)

Variable	Limb	Lameness degree		
		0	1	2
Maximal carpal flexion	Lame	80.3 (7.7)	81.1 (6.3)	79.4 (5.2)
	Sound	79.8 (10.4)	80.1 (10.0)	78.3 (11.2)
Maximal fetlock hyperextension	Lame	−19.1 (4.0)	−17.0 (4.1)[a]	−11.5 (5.2)[bc]
	Sound	−20.0 (3.7)	−21.2 (3.4)[a]	−21.9 (3.9)[c]
Maximal coffin flexion	Lame	23.6 (3.3)	22.8 (3.5)	20.4 (3.4)[bc]
	Sound	23.5 (4.0)	24.6 (4.1)	27.3 (3.5)[bc]

Data are presented as mean (SD), and are expressed in degrees. Significant differences ($p < 0.05$) between different lameness degrees are indicated by superscripts: [a], degree 0 versus 1; [b], degree 1 versus 2; [c], degree 0 versus 2.

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asymmetric pattern of lame and contralateral sound limbs can be used as a symmetry variable for lameness quantifications.

In contrast to the distal joints, the proximal joints play a more active role in lameness management. The shoulder and tarsus normally flex as the limbs are loaded, but movements of these joints are more dependent on muscular control than the fetlock joint, where passive support by the interosseous (suspensory) ligament is the most significant factor. In contrast to the distal joints, flexion of the proximal joints during loading of the limbs is increased rather than reduced in the lame limb (Buchner et al., 1996a). In the shoulder joint of the lame forelimb this increase is rather small, but tarsal flexion changes more distinctly, which may indicate an increased functioning of a shock absorbing mechanism (Fig 9.4A–D) (Hjertén et al., 1994; Back et al., 1995b). These increases in shoulder and tarsal joint flexion during the stance phase of the lame limb are not due to increased loading. They are the result of a more gentle braking of the flexion by the extensor muscles. Consequently, loading of the lame limb with the body weight occurs more gradually, and this reduces the peak forces in the hoof. This finding corresponds with the changes in the ground reaction force pattern in lame horses: there is a marked decrease in the first peak of the vertical ground reaction force in a lame limb at the walk, while the forces at midstance are slightly higher (Merkens & Schamhardt, 1988a). This increased damping is expressed more in the hind limb than the forelimb, which is thought to be related to the considerably greater range of motion in the tarsal/stifle joint complex compared with the shoulder/elbow joint complex (Back et al., 1995a, b).

Summary

The proximal joint pattern shows the efforts of the horse to smooth limb loading, while the distal joint pattern reflects an absolute decrease in loading of the lame limb. This decrease in limb loading cannot be achieved by changing the limb movement pattern. It is the result of adaptations in head and trunk movements.

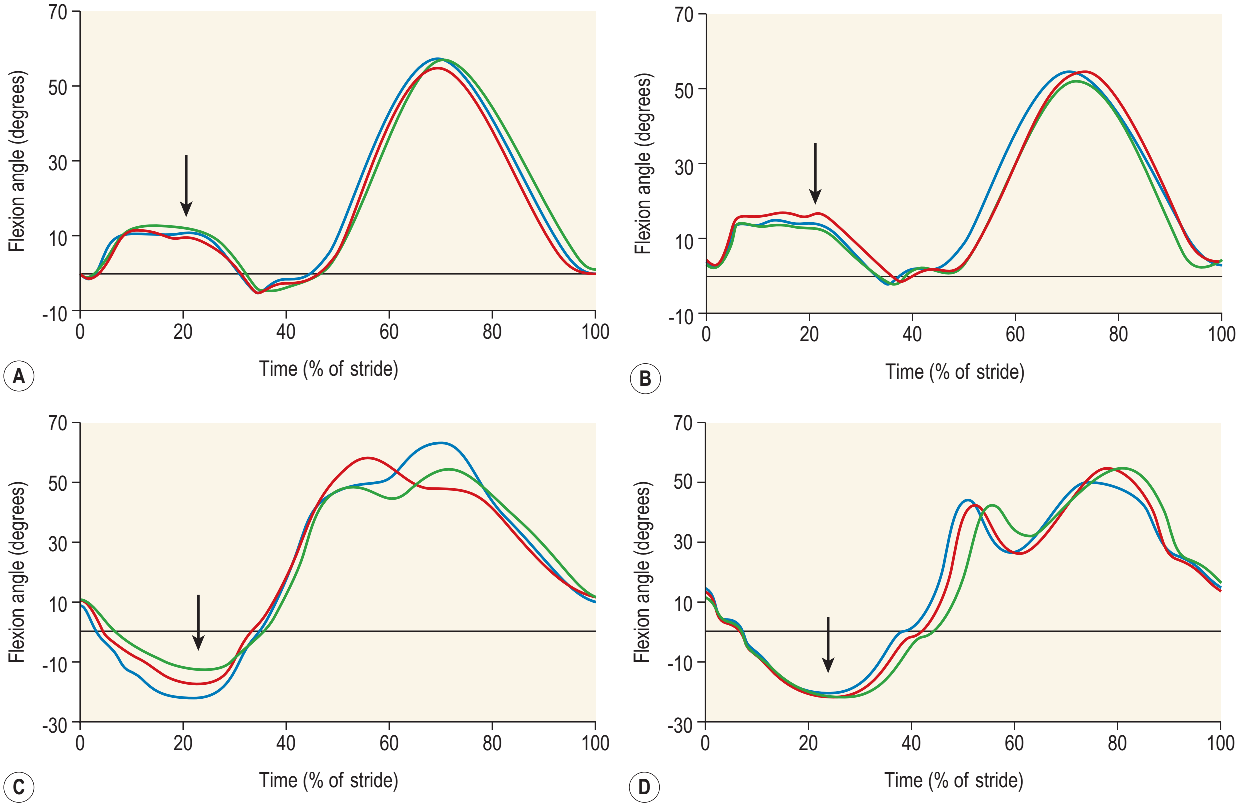

Fig 9.4 Joint angle pattern of the tarsal (A) and fetlock (C) joints of a lame hind limb and tarsal (B) and fetlock (D) joints of the contralateral sound hind limb during different degrees of hind limb lameness. (blue line) Lameness degree 0 (sound); (red line) lameness degree 1; (green line) lameness degree 2. Arrows indicate flexion (tarsal joint) or hyperextension (fetlock joint) during the middle of the stance phase.

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Head and trunk movement

The simplest, most sensitive, and most frequently used indicator for the clinical diagnosis of lameness is the characteristic vertical movement of the horse's head and trunk (Stashak, 1987; Wyn-Jones, 1988). A more or less asymmetric pattern of head movement is the starting point for each student to diagnose a forelimb lameness and, similarly, croup or hip movement is used to diagnose a hind limb lameness. Sound horses at a trot show a perfect sinusoidal pattern for all midline body locations including the head, withers and croup (Girtler & Floss, 1984; Buchner et al., 1996b). During one stride, two symmetric waves can be seen (Fig. 9.5A), which occur almost synchronously in all three body parts. The height of these structures falls from the beginning of the diagonal stance phase reaching the lowest position at midstance, then rising to their highest level at or shortly after the end of the stance phase. During the suspension phase, the body starts to fall again into the next diagonal limb stance phase. These sinusoidal cycles are repeated twice in each stride. The derivatives of this vertical movement, vertical velocity and vertical acceleration of the head or withers, show similar sinusoidal patterns, but shifted by 12.5% per derivative to the left (Fig. 9.5B, C). Vertical velocity reaches minimal values shortly after the beginning of the stance phase and maximal values shortly before the end of stance. Acceleration is maximal in the middle of the stance phase and minimal during the suspension phase when it falls to its minimum value which is equal to gravitational acceleration. All midline body locations, head, withers and croup raise and sink simultaneously, they are in phase.

During lameness, characteristic changes in the patterns of all these body segments occur. The most obvious of these is the vertical head movement pattern (Girtler & Floss, 1984; Peloso et al., 1993; Buchner et al., 1996b; Keegan et al., 1997). The lowering and lifting of the head during the stance phase of the lame limb decreases, with a compensatory increase in both movements during the stance phase of the contralateral sound forelimb (Fig. 9.5). These changes are proportional to the degree of lameness and in severe lameness the first wave may not be visible, there is no lifting of the head anymore. The sinusoidal pattern with two cycles per stride then changes to show a single cycle during each stride (Girtler & Floss, 1984). Vertical velocity of the head changes in accordance with the vertical movement. Both minimal and maximal vertical velocity during the lame stance phase decrease. During the sound stance phase both values increase, which also results in a more positive velocity of the head at the start of the subsequent lame stance phase. This means that, at impact, the head shows less downward movement with increasing lameness. During severe forelimb lameness, the head may even be lifted slightly at the instant of impact of the lame limb. Finally, vertical acceleration of the head also changes from a symmetrical pattern to an asymmetrical pattern (Fig. 9.5C). For a quantitative analysis of the lameness, the acceleration values are even more useful than the head movement pattern, since vertical acceleration is less sensitive to changes in absolute head height. Furthermore, changes in the acceleration peaks quite accurately represent changes in the vertical forces acting on the limbs, since forces (F) are determined by the mass (m) of a body and its vertical acceleration (a): F = ma. Therefore, reduced vertical acceleration of the head and trunk during the stance phase of the lame limb results in a lower vertical force, or less loading of the lame limb.

During forelimb lameness the withers and croup show the same vertical movement pattern and the same timing as the head, but the

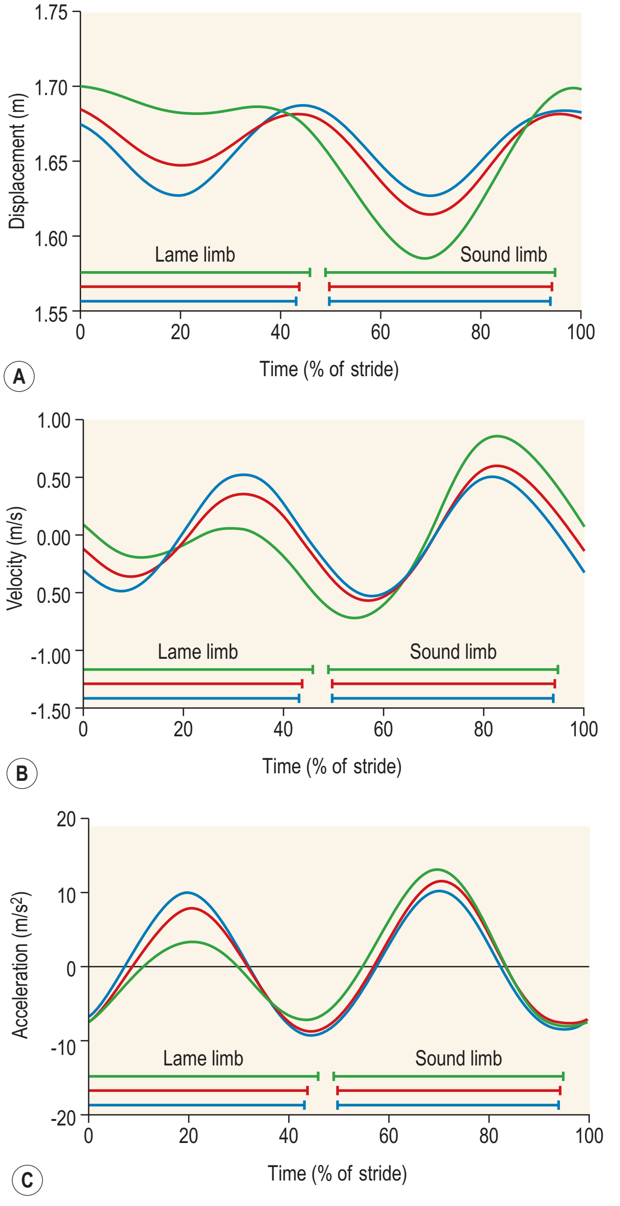

Fig 9.5 Head movement pattern during different degrees of forelimb lameness: (A) vertical displacement, (B) vertical velocity, (C) vertical acceleration. The horizontal bars indicate the stance phases of the limbs. (blue line) Lameness degree 0 (sound); (red line) lameness degree 1; (green line) lameness degree 2.

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oscillations are less pronounced (Buchner et al., 1996b). This means less lowering of the croup simultaneously to the withers and head during the lame diagonal stance and more lowering during the sound stance phase. Looking from behind the horse with moderate forelimb lameness this resembles a slight lameness of the diagonal hind limb, a diagonal 'compensatory' lameness (see later in this chapter). Nevertheless, there is a large decrease in the vertical acceleration of the trunk depending on the degree of lameness. Due to the mass of the trunk, which accounts for about 65% of total body mass (Buchner et al., 1997), this causes a highly significant decrease in limb loading.

An interesting hypothesis is stated by Keegan (2005), who describes four different patterns of head movement during forelimb lameness characterized by different relative heights of the head during the various instants of the stride. He proposed that different instants of maximal pain, e.g. after landing and the first half of the stance or before breakover, may lead to these four different patterns of head movement. This specific head movement pattern would lead to a more specific local lameness diagnosis than only limb and lameness degree, but has still to be proven by the analysis of a number of horses with known lameness cause.

The locomotion patterns of the head, withers and croup during hind limb lameness are similar to those of a forelimb lameness, but show some distinctive characteristics. The os sacrum, which lies on the midline, shows a perfectly sinusoidal up and down motion in sound horses. During lameness, it shows less lowering and lifting during the stance phase of the lame limb, which is exactly the same as the motion of the withers during forelimb lameness (Buchner et al., 1996b). The tuber coxae, however, which is more laterally placed, has an asymmetric locomotion pattern even in sound horses (Buchner et al., 1993). The amplitude of motion, which is measured as the distance between lowest and highest positions of the tuber coxae, is smaller during the stance phase of the ipsilateral hind limb, than during the contralateral stance phase (Fig. 9.6A). Rotation of the croup around the sagittal axis through the hip joint causes different displacements in the ipsilateral and contralateral tuber coxae. The sum of the rotational movement and the vertical translational movement of the whole trunk causes this typical asymmetric vertical movement pattern of the tuber coxae even in sound horses. In hind limb lameness, the asymmetry on the lame side of the body increases. This means that vertical motion of the left tuber coxae during left hind limb lameness is diminished or absent during the left hind limb stance phase (Fig. 9.6B) and increased during the right hind limb stance phase (May & Wyn-Jones, 1987; Buchner et al., 1996b). These large motion amplitudes of the tuber coxae are more easily detected by many people compared with midline movements of the os sacrum. However, the pattern of the os sacrum is similar to head and withers movement and is, therefore, easier to describe.

Movement of the withers during hind limb lameness is similar to, but less pronounced, than os sacrum movement. Head movement, on the other hand, shows a different pattern and different timing than withers or sacrum movements. While the head movements are unchanged or even increased during the stance phase of the lame hind limb, the displacement amplitude of the head decreases during the stance phase of the sound hind limb. This means that head and trunk motion is out of phase, the small vertical amplitude of the croup during the stance of the lame hind limb is associated with a large head amplitude and vice versa. In other words, in moderate-to-severe hind limb lameness the head drops on the diagonal forelimb. This is to allow the horse to reduce some of the load on the lame hind limb due to the changed moment of head and neck. This load redistribution mechanisms will be discussed in more detail in a subsequent section.

Compensatory lameness

Dropping of the head as a compensating mechanism for a hind limb lameness mimics the head movements in a supporting limb lameness of the ipsilateral forelimb and, consequently, is described as sagittal compensatory forelimb lameness (Uhlir et al., 1997). A compensatory or false lameness is an apparent lameness in the opposite end of the body in a quadrupedal animal due to the kinematic changes caused by pain in one limb, the primary lameness (Uhlir et al., 1997; Kelmer et al., 2005). During a moderate hind limb lameness, the dropping of the head during the lame diagonal stance phase resembles an ipsilateral (or sagittal) forelimb lameness. A different situation can be seen during moderate forelimb

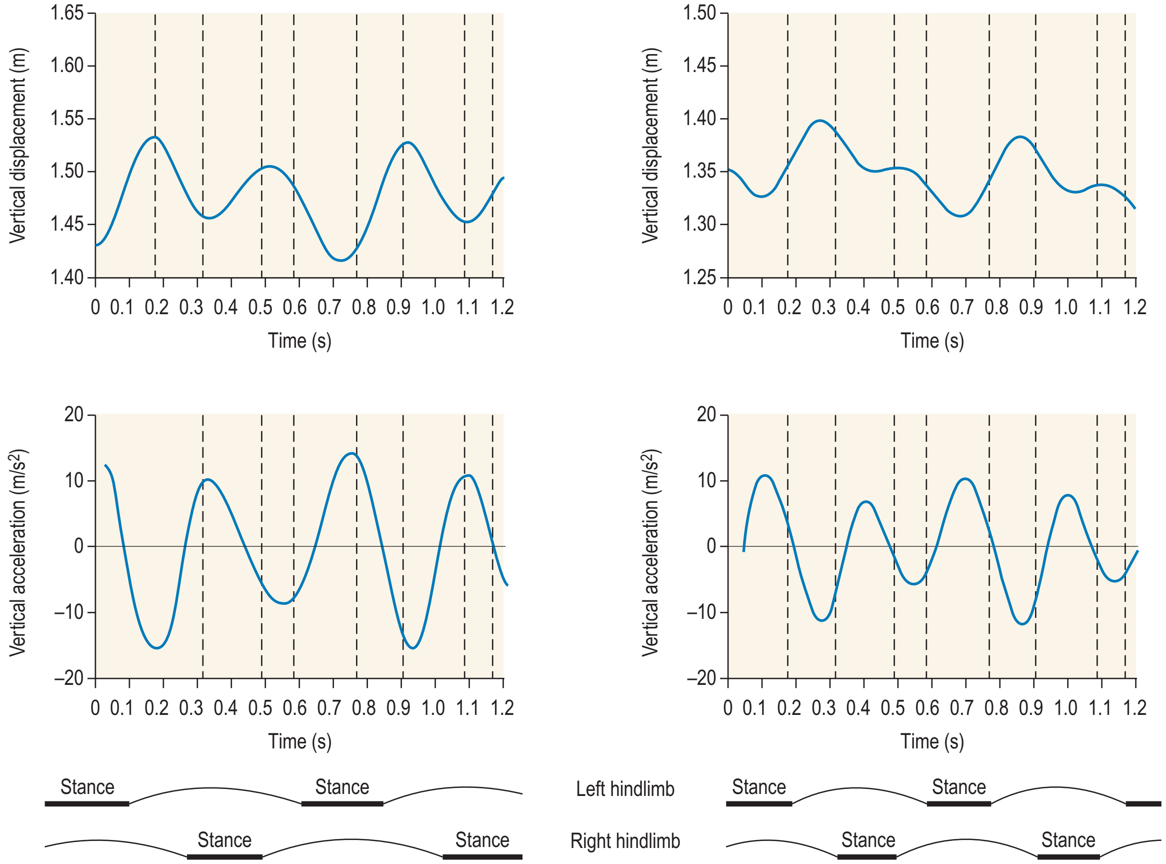

Fig 9.6 Vertical displacement and vertical acceleration of the right tuber coxae in a sound horse (A) and in a horse with a moderate lameness of the right hind limb (B) at the trot. The horizontal bars indicate the stance phases of the hind limbs.

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lameness. In that case the croup movements change simultaneously with the head movements, dropping of both head and croup, and resemble a diagonal hind limb lameness. A compensatory lameness can be differentiated from a real or true lameness by diagnostic anesthesias. For example, a positive diagnostic anesthesia in the lame hind limb reduces the sagittal compensatory forelimb lameness too. A true forelimb lameness, on the other hand, will not be significantly changed by the hind limb anesthesia.

Summary

The pattern of head and croup movements in lame horses allows localization of the lame limb and assessment of the degree of lameness. The asymmetric movements of head and trunk enable significant unloading of the painful limb. Based on a knowledge of these principles and the interactions between trunk and head movement patterns, an accurate quantification of the lameness using several mathematical methods are possible which will be discussed later in the chapter.

Swinging limb and mixed lameness

Pure swinging limb lameness, which is caused by pain during the swing phase without pain during the stance phase, is extremely rare. The two major reasons for a pure swinging limb lameness are a mechanical problem, such as an advanced ankylosis of a limb joint, or a neural problem such as paresis of the radial nerve. Adrian et al. (1977) published goniograms of a 9-year-old stallion with an osseous ankylosis of the metacarpophalangeal joint. Flexion testing in this limb did not cause pain, but the limb showed hardly any flexion or extension during the entire stride. The author has observed a similar locomotion pattern in horses with ankylosis of the stifle or talocrural joint. In all cases, the affected limb could support the body without pain, but also without any flexion or extension during the stride.

Much more common and of clinical significance is the mixed lameness, where pain or pain reactions are obvious during both stance and swing phases. Typical examples are shoulder and carpal lameness or stifle and tarsal lameness. The most extensive information is available for carpal lameness. Several clinical studies in patients (Ratzlaff et al., 1982; Ratzlaff & Grant, 1986; Clayton, 1986a, 1987a, b) as well as studies using lameness models (Morris & Seeherman, 1987; Back et al., 1993; Peloso et al., 1993) investigated the locomotion pattern of horses with carpal joint problems. In these studies the various symptoms can be differentiated into signs that are typical of a supporting limb lameness and other signs that are typical of swing phase problems. The temporal variables do not show a consistent pattern in the different studies. Clayton (1986a, 1987a, b) studied three horses, suffering from a shoulder, carpal and tarsal problems. She found in all three cases shorter stance phase durations in the lame limb compared to the sound limb. Ratzlaff et al. (1982), focusing on carpal lameness, found variable results regarding stance duration and suggested that a shortened stance duration occurred with a predominance of the supporting limb lameness component, while a lengthened stance duration indicated a predominance of the swinging limb lameness. Of course, the variability of the patient histories, even in horses suffering from carpal lameness, precludes making general conclusions. Three studies provoked carpal lameness using toxins (Back et al., 1993), antibiotics (Peloso et al., 1993) or surgical manipulation (Morris & Seeherman, 1987). If trotting velocity was checked to be constant, no significant changes were found in the stance phase duration between the sound and lame limbs, or between the same limb before and after lameness induction (Morris & Seeherman, 1987; Peloso et al., 1993). Obviously, individual left/right differences play the major role compared with the influence of a mixed lameness. In most cases, a high degree of symmetry is maintained and the right/left differences in temporal variables do not help to diagnose a specific lameness.

The characteristics of the caudal and cranial phases of the stride might be a useful criterion to distinguish between swinging and supporting limb lameness (Wittmann, 1931; Hajer et al., 1988). In swinging limb lameness the cranial phase is said to be shorter in the lame limb due to pain during the swing phase and its effect on protraction. Indeed, Clayton (1986a, 1987b) found shorter cranial phases in shoulder and tarsal lameness, but in a horse with carpal lameness (Clayton, 1987a) both phases were equal. Therefore, reduction of the cranial phase is indicative of some swing phase problems, but lack of such a reduction does not exclude a swinging limb lameness.

Equivocal results were found regarding the joint angle pattern in horses with mixed lameness. Looking at the different limb joints, a very clear differentiation between swing phase and stance phase problems can be made. During the swing phase, flexion of the affected joint (carpal, tarsal) was decreased in all studies. The restriction can be seen in both the maximal flexion and the total range of motion. The limb gives the impression of moving stiffly with a lower flight arc of the hoof. This is most obvious during carpal lameness (Back et al., 1993), but is also found in tarsal (Clayton, 1987b; Khumsap et al., 2004) and shoulder lameness (Clayton, 1986a). This feature is clearly different from a supporting limb lameness, where the carpal joint angle during the swing phase was unchanged, and the tarsal joint angle was even increased (Buchner et al., 1996a). Therefore, the presence and degree of left/right differences in flexion of a carpal or tarsal joint seem to be useful indicators for the swinging limb component of a mixed lameness, as Back et al. (1993) proposed. The decreased flexion of a painful joint results from the horse's efforts to avoid painful positions. This effort can be detected even earlier in the stride cycle at the start of the swing phase; when flexion of the carpus begins, the angular velocity of this joint is reduced (Ratzlaff et al., 1982).

The characteristics of the supporting limb lameness component of the mixed lameness have already been described. In general, all variables typical for a supporting limb lameness can also be seen in mixed lameness (Clayton, 1986a; Peloso et al., 1993). The most significant features are that fetlock hyperextension in the lame limb is reduced as sign of less loading, which is achieved by reduced head and trunk displacement. The contributions of the supporting and swinging limb lameness components to the individual lameness pattern are quite variable depending on the individual condition.

The combined angle-angle graph of both joints illustrates the changes during various lameness degrees very clearly. Fetlock hyperextension and carpal flexion give useful information about both aspects of the lameness, but not necessarily about its location. Though the proximal limb joints are more at risk for swinging limb lameness, distal limb problems more often show supporting limb lameness. The coupling of different joints, such as the tarsal and stifle joints, impedes the ability to localize the disease. Furthermore, slow protraction due to joint pain causes similar decreases in the range of joint motion in the coupled joint regardless of whether the pain is in this joint or the neighboring joint.

Summary

Carpal and tarsal or stifle lameness are typical examples of mixed lameness. Reduced flexion of a proximal joint during the swing phase is indicative of the swinging limb lameness component, while reduced fetlock joint hyperextension during the stance is indicative for the supporting limb lameness component.

Bilateral lameness

A special situation and a challenging task for a veterinarian is the presence of a bilateral lameness. A number of orthopedic diseases, such as navicular disease, distal limb arthrosis and bone spavin, may be present in both limbs to a more or less similar extent. The presence and degree of bilateral problems are often difficult to assess, because of the lack of the typical asymmetric pattern associated with unilateral lameness (Seeherman, 1991). The locomotion of horses suffering from bilateral lameness has been described as stiff, short, or shuffling (Stashak, 1987). Such characteristics are difficult to distinguish from the normal locomotor pattern of the individual horse, which is usually unknown to the veterinarian. In this situation, local diagnostic anesthesia is used to detect locomotor asymmetries by eliminating pain in one limb and thus facilitate the detection of pain in the contralateral limb. However, this diagnostic method is complicated by gait changes seen also in sound horses with desensitized limbs. In a study on the effects of local anesthesia in sound horses, they showed changes in the locomotion pattern too, perhaps due to the changed proprioception in the anesthetized limb (Kübber et al., 1994). Therefore, in mild cases it is difficult to decide whether a change in locomotion pattern is due to bilateral lameness, or just to the lost sensitivity in one limb.

Quantitative locomotion analysis in bilaterally lame horses suffers from the same problems as the clinical assessment. If the horse does not show left-to-right asymmetries and if there are no individual control data for the horse when it was sound, it is impossible to make a diagnosis of lameness (Hugelshofer, 1982). The use of a bilateral hoof lameness model showed some gait adaptations that allowed the horses to reduce their discomfort, even when the usual transfer of weight to the contralateral limb was impossible (Buchner et al., 1995b). The adaptations were similar to those seen in unilateral supporting limb lameness: stride duration was reduced, while relative stance duration increased. The most distinct change in temporal co-ordination, however, was in the diagonal advanced placement. During slight bilateral lameness, horses placed their forelimbs earlier than the hind limbs compared with the sound situation. Again this variable proved to be a reliable indicator for unilateral or bilateral locomotor problems.

A second variable that is indicative of bilateral pain is fetlock hyperextension, which was reduced equally in both forelimbs during an induced bilateral lameness. By changing the temporal stride pattern and slightly reducing the vertical displacement of the trunk, the horse achieved the same amount of load reduction (and pain relief) as seen in unilateral lameness.

Summary

Horses are able to relieve the pain in bilateral lameness even when the typical asymmetric, contralateral compensation is not possible. Adjustments in temporal stride patterns and vertical trunk movement reduce the peak forces of all limbs. Diagnosis of bilateral lameness remains difficult, especially in mild cases. Repeated measurements using diagnostic anesthesia or by screening the horses over longer periods can be used to monitor fetlock joint angle and diagonal advanced placement to detect mild gait deficits.

Kinetics of lameness

If horses feel pain in a limb when moving, they adjust their locomotion pattern to diminish the pain. The various kinematic changes described in the previous sections are components of the overall effort to achieve pain reduction. In a supporting limb lameness, pain reduction means reducing the load on the affected limb. The success of the efforts of the load-reducing strategy can be assessed by measuring the ground reaction forces (GRFs) using a force plate (Gingerich et al., 1979; Morris & Seeherman, 1987; Merkens & Schamhardt, 1988a, b; Weishaupt et al., 2004, 2006), force shoes (Hugelshofer, 1982) or the EGA-system (Tietje, 1992). A unique technology to record continuously the vertical ground reaction forces of horses is the instrumented treadmill developed in Zürich/Switzerland, which allows to measure continuously vertical forces of all four limbs independently during treadmill locomotion (Weishaupt et al., 2002). A synchronous view of kinetic and kinematic findings provides a more complete picture of how horses manage a lameness and gives a better understanding of the mechanisms that redistribute the load away from the lame limb without serious overloading of the sound limbs.

Load reduction in the lame limb

As lameness increases, horses show progressive reductions in their vertical and longitudinal deceleration forces. These differences can be seen in the GRF tracings at the walk (Merkens & Schamhardt, 1988a) as well as at the trot (Morris & Seeherman, 1987; Clayton et al., 2000a; Weishaupt et al., 2004, 2006). At the walk the peak vertical force decreases, while the GRF pattern becomes smoother: the dip between the two vertical force peaks diminishes in mild lameness and disappears in moderate lameness at the walk (Fig. 9.7) (Merkens & Schamhardt, 1988a). At the trot, the shapes of the vertical and longitudinal GRF force curves in the lame limb resemble those of sound horses, however with characteristic decreases in the force amplitudes. Generally, with increasing lameness, horses show a reduced impact force, a reduced rate of loading during the first half os stance and a reduced peak vertical force (F_{zmax}). (Clayton et al., 2000a; Weishaupt et al., 2006). Already in only a subtle lameness, F_{zmax} is significantly reduced by 4%. This reduction reached 9% in mild lameness and 24% in moderate lameness (Weishaupt et al., 2006). Similar results are reported by Morris and Seeherman (1987) which measured 11.5% decrease of F_{zmax} in a easy observable carpal lameness, or Clayton et al. (2000a) with 27% less F_{zmax}, in horses with an induced tendinitis. However, these horses, showing moderate to severe lameness also reduced their running velocity by 10%, which contributes to the overall load reduction.

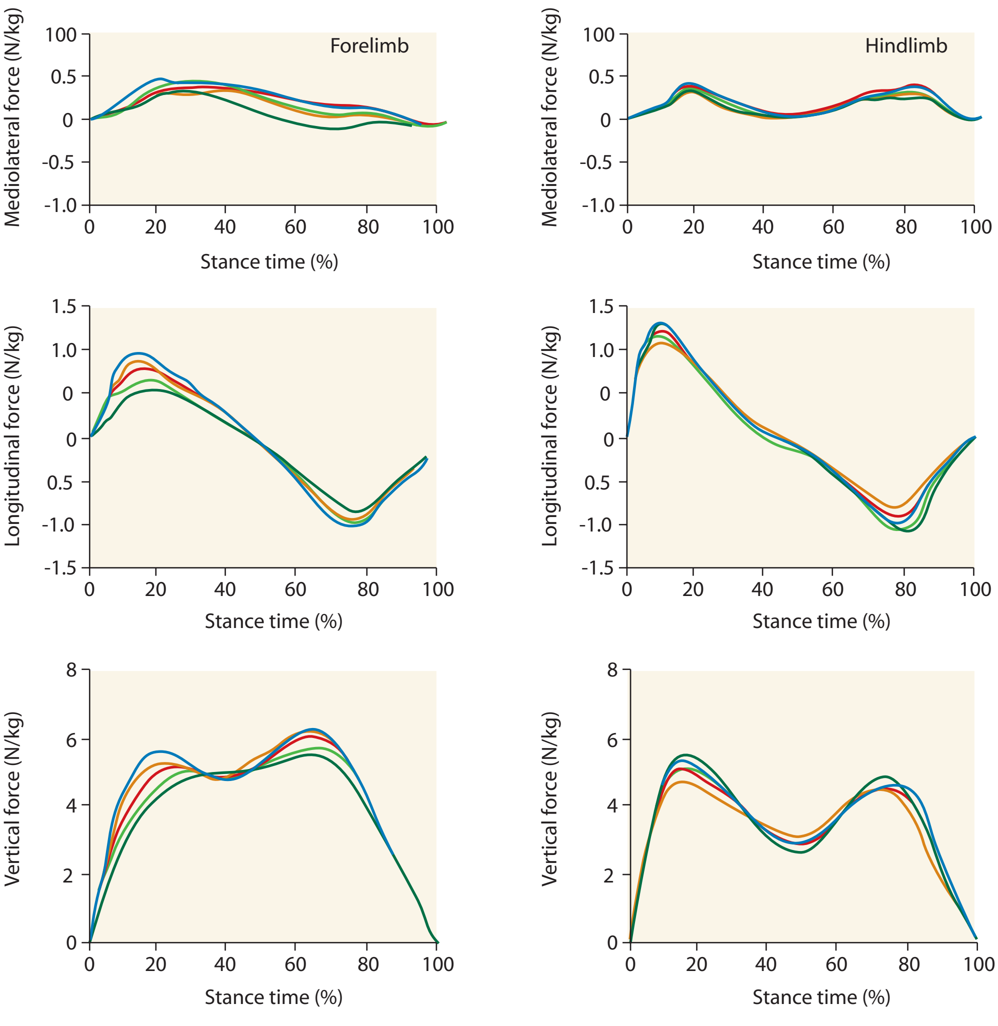

Fig 9.7 Ground reaction force patterns of left fore limb (left panel) and left hind limb (right panel) at the walk during different degrees of left forelimb lameness. The forces are expressed in N/kg body mass during a standardized stance time. Control session (blue line); only lame at the trot (red line); mild lameness at the walk (green line); moderate lameness at the walk (dark green line); digital nerve block (orange line).

Reprinted with permission from: Merkens, H.W., Schamhardt, H.C., 1988a. Evaluation of equine locomotion during different degrees of experimentally induced lameness. I. Lameness model and quantification of ground reaction force patterns of the limbs. Equine Vet. J. (Suppl.) 6, 99–106.

Similar reduction of loading can be found in the braking longitudinal force, where several local peaks of the longitudinal force are reduced in the lame limb. The third parameter used to describe limb loading is the vertical impulse (I_z) of the limb, which represents the time integrated force during one stance phase. While the vertical force decreases continuously with increasing lameness, the vertical impulse is less affected. The increase in relative stance duration is responsible for this smaller increase in vertical impulse. Compared to the 24% decrease of F_{zmax} in moderate lameness, I_z decreased only by 20% (Weishaupt et al., 2006). This difference between F_{zmax} and I_z is an important feature for the lameness management of horses who try to maintain their normal locomotion pattern as much as possible together with maximal pain reduction, which will be discussed in the next paragraph. If lameness is more severe, the load is reduced progressively to zero load in a non-weightbearing lameness.

In lame horses, the fetlock joint angle time diagram (Back et al., 1993; Buchner et al., 1996a) resembles the vertical force pattern shown by Morris and Seeherman (1987) or Clayton et al. (2000a). The reduction of the fetlock hyperextension of about 8° in a grade 2 lameness might be quite comparable to the reduction of fetlock extension by about 10% that was reported in horses with an easily observable lameness by Morris and Seeherman (1987). Similarly, Clayton et al. (2000a) found a decrease in fetlock hyperextension of 11° corresponding to the decrease in the F_{zmax} of 27%.

Summary

Maximal vertical force, assumed to be responsible for the pain during loading, is effectively reduced in the lame limb. Vertical impulse is reduced too, but due to an increased stance duration less than maximal vertical force.

Mechanisms of load reduction

Based on the kinematic analyses, the reduced loading in a lame forelimb can be explained by two major mechanisms: 1) a smoother loading of the lame limb and 2) decreased vertical movements of the head and trunk.

The loading is smoothed by small adjustments in several aspects of limb timing. The swing duration of the forelimbs is reduced, while the relative stance duration is increased. The longer ground contact distributes the effort required to lift the body over a longer period. Furthermore, the earlier placement of the lame forelimb, seen in a changed diagonal advanced placement of the lame limb (Buchner et al., 1995a; Weishaupt et al., 2006), allows it to accept the body load at a time when the trunk is at a higher point in its sinusoidal motion cycle and has a relatively low downward velocity. This reduces the effort required to lift the body as discussed in the second mechanism. Additionally, braking of the descending body is smoothed by slightly more flexion of the shoulder joint.

The second mechanism to reduce peak load involves the vertical displacement of the body. During the stance phase of the lame limb the head and neck and, to a lesser extent, the trunk, are not lowered as normal. Keeping the body at a more constant height needs less maximal vertical acceleration and results in a decreased peak vertical force in the lame limb. Additionally horses adjust their head and neck movement to control the load distribution in all limbs. Since the head and neck are heavy, representing about 10% of total body mass (Buchner et al., 1997), and they have a long lever arm relative to the body center of mass, their position has a relatively large effect in loading or unloading the forelimbs. This influence of head and neck movement has been evaluated using an inverse dynamics model (Vorstenbosch et al., 1997). The dynamic forces acting on the trunk and then on the limbs were calculated from the kinematics of head and neck, their inertial properties and the geometric properties. Differences of only 10 cm in vertical amplitude of the head during the stance phases of lame and sound limbs caused differences in the vertical force of nearly 500 N and differences of about 230 Nm in the sagittal torque acting on the trunk. Therefore, the head is an effective tool for redistributing the load from the painful limb to the other limbs. These dynamic influences of the head and neck movements should not be confused with the relatively small static influences on the position of the body center of mass (BCM) due to different head positions. If the head and neck move caudally by 10 cm, the BCM shifts caudally by only 1 cm. For a 500-kg horse, assuming a distance of 100 cm between fore and hind limbs, this means a transfer of only 50 N from fore to hind limb. This assumption is substantiated by Buchner et al. (2001) finding a caudal translation of the BCM during midstance of the lame limb in a grade 2 lamenesss of only 9 mm. Therefore, the dynamic influences of the asymmetric head and neck movement in lame horses have about 10 times more effect than the static component.

Summary

Summing up all details, the body receives less vertical impulse during the stance phase of the lame limb despite the small prolongation of the stance duration. This smaller vertical impulse leads to a distinct reduction in the duration of the subsequent suspension phase and the contralateral limb has to cope with the need for a higher vertical impulse associated with the descending trunk and head.

Redistribution of the load

The reduction of the peak load in the lame limb is not accompanied by equivalent increases of peak loads in the sound limbs. This remarkable fact has been observed both in kinematic studies that evaluated the fetlock joint pattern of all limbs and in kinetic studies of the vertical loads on all four limbs. Using the maximal hyperextension of the fetlock joint as a load indicator, at the trot a decrease of 7.6° in the lame limb was accompanied by an increase of only 1.9° in the contralateral forelimb, no change in the diagonal hind limb and a 2.6° decrease in the ipsilateral hind limb (Buchner et al., 1996a). Simultaneous kinetic recordings of the vertical forces on the instrumented treadmill allowed for the quantification of the effective load changes in all four limbs with increasing fore or hind limb lameness (Weishaupt et al., 2004, 2006). As already seen in the kinematic analyses, the contralateral limb does not get a higher peak load at the trot. F_{zmax} of the contralateral limb was nearly unchanged during subtle or moderate lameness. Similarly, peak load in the diagonal hind limb was nearly constant, and it was only during moderate lameness a slight increase of 2% could be found. The ipsilateral limb shows more changes, but it is loaded less rather than more (6% less in moderate lameness). In fact, hardly any compensatory increase of peak load can be found in the nonlame limbs. This is true also for hind limb lameness, which is even more stable: while peak load in the lame limb gradually decreases with increasing lameness, no change in F_{zmax} could be found in the three other limbs (Weishaupt et al., 2004).

The same relationships were found by Morris and Seeherman (1987) and Tietje (1992).

Analysis of the characteristic head and trunk movements combined with model calculations (Vorstenbosch et al., 1997) offer an explanation for the way horses redistribute the body load. The reduction of maximal head acceleration during the lame diagonal stance phase reduces the load on the lame forelimb, but increases the load on the diagonal hind limb due to a reduced torque at the neck-trunk connection. At the same time, reduced acceleration of the whole trunk adds to the reduction of loading of the lame forelimb, but counteracts and equalizes the torque effects of the head on the diagonal hind limb. During the sound diagonal stance phase, the trunk acceleration hardly changes. Increased head movements, however, slightly increase the loading of the contralateral forelimb and decrease that of the ipsilateral hind limb.

The fact that the reduction of the peak load in the lame limb is not compensated by higher peak loads in the other limbs raises the question as to where the load is going. Two phenomena are involved in answering this question:

1. A redistribution of the load within the limbs
2. A decrease of total load of all four limbs during the whole stride cycle.

The redistribution within the limb is based on an earlier placement of the limb, the prolonged stance duration and the increased damping in the proximal limb joints. These movement adaptations smooth the loading of the lame limb and enable the horse to reduce the peak load significantly more than the vertical impulse. As already mentioned for a moderate forelimb lameness, peak vertical load reduction was 24% compared to a reduction of vertical impulse of only 20%. Similar results were found for a carpal lameness by Morris and Seeherman (1987) whose results showed 11.5% reduction in peak force, but only 8.4% reduction in impulse in the lame limb. In severe induced tendonitis, a decrease of 27% in F_{zmax} corresponded to 15% reduction in the vertical impulse (Clayton et al., 2000a) (Fig. 9.8). The same principle works in the contralateral limb. More or less unchanged peak loads during a prolonged stance phase led to increases in vertical impulse in the contralateral limb of 7% (Weishaupt et al., 2006) or 4.7% (Morris & Seeherman, 1987).

The remaining difference in impulses between lame and sound limbs can be explained by the second phenomenon, the reduction of the sum of the load of all four limbs, the total load or total stride impulse. This has already been suggested by Morris and Seeherman (1987) and is later confirmed by results of kinematic and kinetic studies. When forced to keep a constant velocity on the treadmill, horses increase their stride frequency by reducing the duration of the swing phase. In this way the horses reduce the load within one stride by distributing it over a larger number of strides.

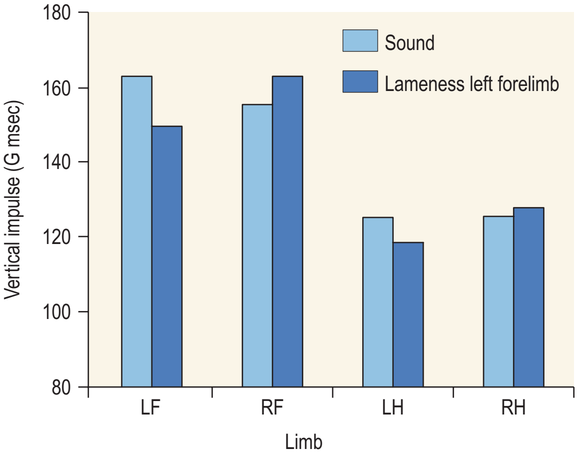

Fig 9.8 Redistribution of vertical impulse from the lame forelimb to the other limbs during induced superficial digital flexor tendinitis in one forelimb.

Data from Clayton, H.M., Schamhardt, H.C., Willemen, M.A., Lanovaz, J.L., Colborne, G.R., 2000a. Kinematics and ground reaction forces in horses with superficial digital flexor tendinitis. Am J Vet Res 61, 191–196. ©American Veterinary Medical Association. Reprinted with permission from: Merkens H.W., Schamhardt H.C., 1988a. Evaluation of equine locomotion during different degrees of experimentally induced lameness. I. Lameness model and quantification of ground reaction force patterns of the limbs. Equine Vet J (Suppl.) 6, 99–106.

These results show that a lameness in one limb will not necessarily increase the risk of damaging the contralateral limb or the other sound limbs. If high peak forces are responsible for compensatory injuries, the mechanisms described above enable a maximal decrease of peak force in the lame limb together with a minimal increase of risk in the sound limbs.

Summary

There is no redistribution of peak load from the lame to the sound limbs and only a little redistribution in vertical impulse. A lower total stride impulse is compensated by a higher stride frequency.

Specific lameness

The most ambitious aim in the use of locomotion analysis for the diagnosis of lameness in horses is the exact localization of the ailment within a limb thus making the diagnosis of a specific disease (Leach & Crawford, 1983; Clayton, 1986a). A precondition for such a specific diagnosis is a database that includes kinematic patterns of various specific diseases, based on sufficient measurements to eliminate the variation due to individual locomotion patterns. Recordings have been made in small groups of horses with specific ailments, and studies have been performed in groups of horses with equal, induced lameness. Analysis of the results of these studies showed two major problems that impede formulation of a definition of characteristic lameness patterns in specific lameness:

- The individual locomotion pattern: Several studies found a high level of reproducible individuality in the locomotion pattern of horses (Drevemo et al., 1980; van Weeren et al., 1993) seen as a low intraindividual variation compared to the high interindividual variation. The low intraindividual variation allows for repeated, reliable assessments of the locomotion pattern after diagnostic or therapeutic manipulations. The accurate measurement techniques enable the detection of really small, but significant, differences due to the various kinds of lameness. However, these differences are often smaller than differences between horses due to their individual locomotion pattern.
- The wide variety of orthopedic diseases: Many horses suffer from more than one disease. Even horses suffering from very similar diseases or syndromes, such as navicular disease or carpal lameness, show a variety of orthopedic and radiological findings. In two studies analyzing seven horses with carpal lameness syndrome seven different specific diagnoses were reported (Ratzlaff et al., 1982; Clayton, 1986a). Navicular disease seems to be more uniform, but additional ailments can occur. In the thorough study of Girtler (1988a,b,c) six out of seven horses with navicular disease had additional problems, such as arthrosis, tendinitis, sesamoiditis or bone spavin. This problem might have existed, though it was not described, in other studies of horses with navicular disease by Pollhammer-Zeilinger (1996), Hütter (1997) and Keegan et al. (1997). Therefore, it is difficult to use horses with naturally occurring lameness to extract specific patterns for a specific ailment. General conclusions can be drawn only by analysis of a large number of horses suffering from more or less the same disease. Then general symptoms have to be separated from specific symptoms. Large numbers of horses have been studied for only a few diseases and in these diseases the general symptoms dominate over specific details.

Navicular disease

There are five studies reporting kinematic data from horses with navicular disease (Ratzlaff & Grant, 1986; Girtler, 1988a,b,c; Pollhammer-Zeilinger, 1996; Keegan et al., 1997; Hütter, 1997).

Comparing their results with those from other lameness studies, the same general characteristics as described for supporting limb lameness can be found. There is a tendency to longer stance durations, but this feature is not shown by all horses (Pollhammer-Zeilinger, 1996). Fetlock joint hyperextension is reduced and vertical head movement shows some of its characteristic asymmetric pattern, which depends on the degree of asymmetry of the pathologic process in both limbs. Even hoof landing, as described by Ratzlaff and Grant (1986), does not show a consistent pattern in all horses (Hütter, 1997). Keegan et al. (1997) found also a reduced maximal flexion in the carpal joint during the swing phase, which he explained as a general symptom of a reduced loading followed by a less energetic protraction of the limb. Therefore, no really specific kinematic patterns for navicular disease could be found to differentiate navicular disease from other types of supporting limb lameness.

However, locomotion analysis studies using the advanced methodology of inverse dynamic analysis, which combines kinetic and kinematic measurements, offered additional insights into the specific locomotion pattern of horses suffering from navicular disease (or low palmar foot pain) (Wilson et al., 2001; McGuigan & Wilson, 2001). These studies calculated the moment arm of the coffin joint and the compressive force of the deep digital flexor tendon (DDFT) on the navicular bone. The most surprising and significant finding was an increase in compressive force shortly after landing and during the whole stance phase in horses suffering from navicular pain. Sound horses start with a low DDFT force and a low navicular compressive force, which increases during the stance phase reaching a peak shortly before heel-off. The lame horses with navicular pain show a paradoxical increase in this force, which is expected to increase their pain too (Fig. 9.9). Obviously, while they try to decrease heel loading by tension in the DDFT, they increase pressure on the navicular bone and thereby even contribute to a progression of the disease. This obvious inability of the horse to unload the diseased structure might explain the bad prognosis of navicular disease and also the positive effects of mechanical support offered by orthopedic shoeing, such as raised heels, facilitation of break over, or protection from overextension of the coffin joint by extended heels (egg bar shoes).

Another interesting approach was described by Williams et al. (1999) using the pattern of the GRF. When they performed a principal component analysis of the vertical and longitudinal forces specific differences between sound horses and horses suffering from SDF tendonitis could be found especially at the beginning of the stance phase. These very promising results for a specific lameness diagnosis, however, are based on a quite sophisticated analytic method that has not been pursued.

Laminitis

A similar inverse dynamic study as for navicular disease was performed in ponies with chronic laminitis (McGuigan et al., 2005). These ponies all had rotations of the distal phalanx of 6–13° and a stilted gait at the trot. Ground reaction forces (GRF) showed similar typical signs of bilateral lameness, with lower F_{zmax} and a prolonged stance duration. The most interesting detail was the change in the moment arm of the GRF at the coffin joint. The moment arm was below zero until about 40% of the stance phase, and in the later part of stance was still significantly shorter than the moment arm in sound ponies. As a consequence of this situation there was no tension in the DDFT until nearly midstance. In the second half of the stance phase, DDFT force gradually increased, but reached only 64% of the peak values in sound ponies at heel-off (Fig. 9.10). This shows nicely how displacement of the distal phalanx reduces tension in the DDFT, which means that rotation of the distal phalanx during the laminitis is a self-limiting process. When the rotation reaches a critical amount around 15–20°, there is no tension in the DDFT and therefore no rotational force on the distal phalanx.

Carpal and tarsal lameness

Carpal lameness is the most intensively studied orthopedic syndrome using locomotion analysis techniques. Both patient studies (Ratzlaff et al., 1982; Clayton, 1987a) as well as studies of induced, uniform carpal lameness (Auer et al., 1980; Morris & Seeherman, 1987; Back et al., 1993; Peloso et al., 1993) serve as a database for a detailed analysis. As in navicular disease, there are reliable general signs of lameness, including reduced fetlock hyperextension and a head movement pattern that are indicative of the supporting limb lameness component. Reduced carpal flexion is a consistent sign of the swinging limb lameness component. Ratzlaff et al. (1982) also described changes in the angular velocity as a good indicator to differentiate swinging and supporting limb lameness.

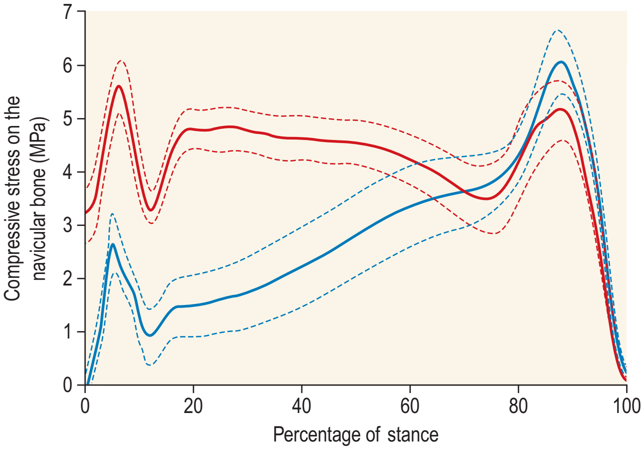

Fig 9.9 Compressive stress on the navicular bone by the DDFT during trot in normal horses (red lines) and horses with navicular disease (blue lines). Values are mean (solid lines) and SD (broken lines).

Reprinted with permission from: Wilson A.M., McGuigan M.P., Fouracre L., et al., 2001. The force and contact stress on the navicular bone during trot locomotion in sound horses and horses with navicular disease. Equine Vet J 33, 159–165.

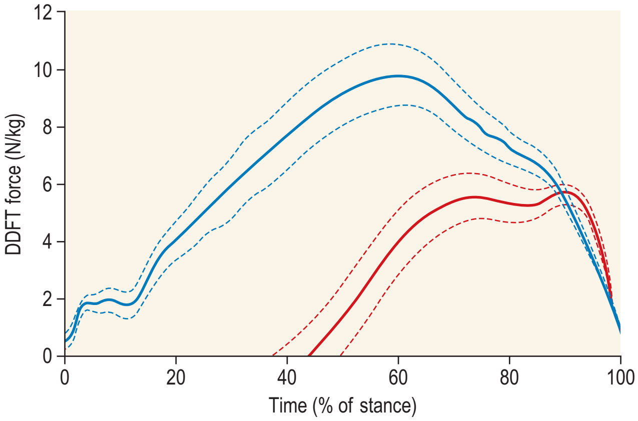

Fig 9.10 Mean force in the deep digital flexor tendon (N/kg body mass) during the stance phase in normal horses (blue lines) and horses with navicular disease (red lines). Values are mean (solid lines) and SD (broken lines).

Reprinted with permission from: McGuigan M.P., Walsh T.C., Pardoe C.H., et al., 2005. Deep digital flexor tendon force and digital mechanics in normal ponies and ponies with rotation of the distal phalanx as a sequel to laminitis. Equine Vet J 37 (2), 161–165.

Clayton (1987a) described a specific detail in the vertical movement pattern of the carpal region in a horse with a fracture of the third carpal bone. This involved lowering of the lame limb at lift-off and during the early swing phase. This pattern is visible also in the horse recorded by Ratzlaff and Grant (1986) as well as in one horse of Girtler (1988b). Another horse in the study of Girtler (1988b), that was suffering from tendinitis, showed the same carpal pattern, which might point to a common phenomenon of pain during maximal extension of the carpal joint and the wish to flex and unload the lame limb as early as possible.

Several studies analyzed the gait in induced arthritis of the distal tarsal joints (Clayton, 1987b; Kramer et al., 2000; Khumsap et al., 2003; Khumsap et al., 2004). Osteoarthritis of the distal tarsal joints is known as bone spavin, a very common degenerative joint disease in the horse. Like carpal lameness, characteristics of both supporting limb lameness as well as swinging limb lameness were found. Typical load reduction, seen as reduced vertical force and impulse or reduced fetlock joint hyperextension was measured. Tarsal flexion was reduced during midstance as well as midswing. Furthermore, a net power analysis revealed reduced negative joint work during early stance and reduced positive work at push-off at the tarsal joint (Khumsap et al., 2003). Another study by Khumsap et al. (2004) offered even more insight reporting from three-dimensional joint movement pattern in tarsal synovitis. These results pointed to movements like proximodistal or craniocaudal translation of the metatarsus, which, while coupled to tarsal flexion and extension to a major part, show some additional movements.

Tendinitis

An integrated study of the kinematics and GRFs before and after the induction of superficial digital flexor (SDF) tendinitis in one forelimb (Clayton et al., 2000a) showed typical signs of a supporting limb lameness, e.g. a lower peak vertical GRF in the lame limb together with less flexion of the coffin joint and less hyperextension of the fetlock joint in the lame limb during midstance compared with the compensating limb. Carpal joint kinematics did not change. At the lame evaluation the compensating limb had a more protracted orientation throughout its stance phase, though its total range of limb rotation from ground contact to lift-off did not change. This facilitated a smooth transfer of body weight from the lame to the compensating limb without the need to raise the body mass into a suspension. In association with its more protracted orientation, the compensating limb had a higher braking longitudinal force and impulse than the lame limb, while the propulsive components of the longitudinal ground reaction force did not differ between limbs. The center of pressure began to move rapidly toward the toe relatively early in the stance phase in the lame limb, which was interpreted as a consequence of the lower GRFs in the lame limb. The lame limb also showed significant reductions in the peak values for the net joint moments on the palmar aspect of the fetlock, carpal and elbow joints, which are the joints crossed by the SDF musculotendinous unit. The total mechanical energy absorbed was significantly lower at every joint in the lame limb compared with the compensating limb (Clayton et al., 2000b).

In the early stance phase, oscillations in the longitudinal force peaks correspond approximately with changes in the vertical loading pattern of the limb, and it has been suggested (Dow et al., 1991) that changes in the slope of the vertical ground reaction force during phase periods corresponds to a reduced rate of loading of the fetlock as this joint reaches its full extension. Unfortunately, findings from the lame and compensating limbs were not differentiated by Dow et al. (1991), but all horses whose values for the vertical force slope for one or both limbs were outside the 95% confidence limits of the population under study had an SDF injury. Clinical lameness was only apparent when the deviation of the vertical force slope was outside the 99% confidence limits of the population. Clayton et al. (2000a) also found a significant difference in the slope of the vertical ground reaction force that was indicative of a greatly reduced loading rate in the lame limb and a more rapid loading rate in the compensating limb. It coincided with a divergence between the angles of the coffin and fetlock in the two limbs as a consequence of the differences in loading. However, the large variations in the force curves between and within horses are likely to preclude their use as a diagnostic tool.

Ataxia

Several attempts were made during recent years to find an objective documentation for ataxic movements, which are symptoms of neurological disturbances in horses. The diagnosis of this gait pattern is based primarily on subjective gait changes, like in coordination, weakness or dysmetria. Clayton et al. (2003) and Bialski et al. (2004) introduced the force plate as a tool to assess postural sway as an indicator of neurological disease. The horses stood with both fore or both hind feet on the force plate, without and with a blindfold and movements of the center of pressure were tracked over a period of time. Variables that were measured include the radius and velocity of the movements of the center of pressure, and the craniocaudal and mediolateral range of motion. The findings are plotted graphically as a stabilogram (Fig. 9.11). Increases in the measured variables have been detected in horses with various neurological diseases including cervical vertebral stenosis (wobblers), equine protozoal myelitis and vestibular disease. The agreement boundary of the center of pressure movement was described to be a sensitive parameter to distinguish between sound horses or those having balance deficiencies. Keegan et al. (2004) used the kinematics of 21 markers on the trunk and limbs together with a sophisticated mathematical procedure using a fuzzy clustering to distinguish between sound and spinal ataxic horses. They found the movement pattern of one body marker on the back together with one marker each at on a fore and hind limb sufficient to achieve a correct classification of the horses. Another kinematic method was used by Strobach et al. (2006), which used the autocorrelation and cross correlation of hoof movement successfully to evaluate the consistency of the gait.

Peculiar lameness

There are some rare orthopedic diseases in which the locomotion pattern is so unique that it will be recognized by everybody who

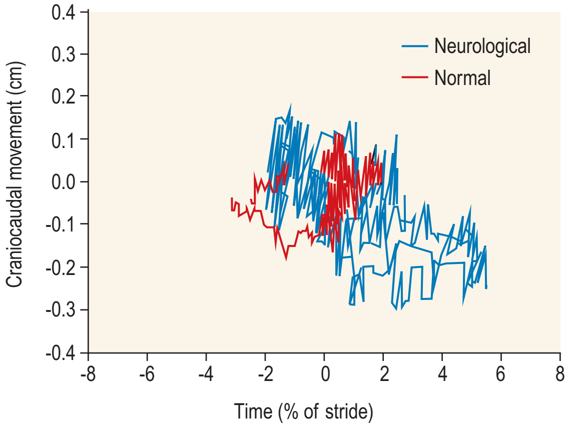

Fig 9.11 Stabilogram showing craniocaudal and mediolateral movements of the center of pressure of the two forelimbs in a normal horse (red line) and a horse with vestibular disease (blue line). Measurements were made over a period of 10 s at a sampling frequency of 2000 Hz.

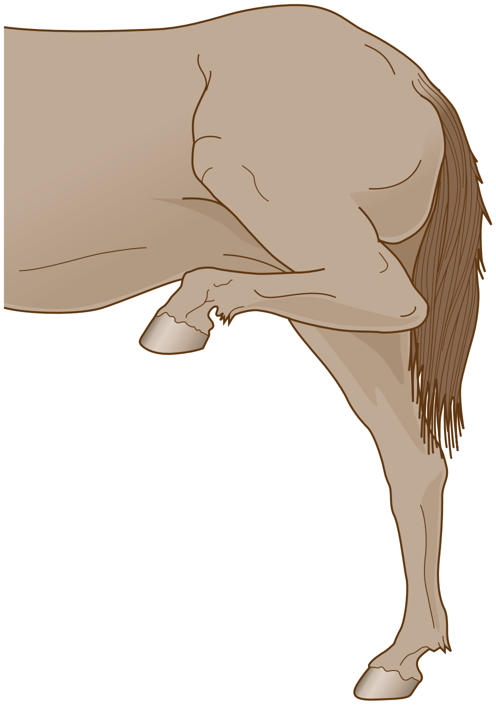

Fig 9.12 Typical high elevation of the hind limb during the swing phase in a horse at the walk suffering from stringhalt.

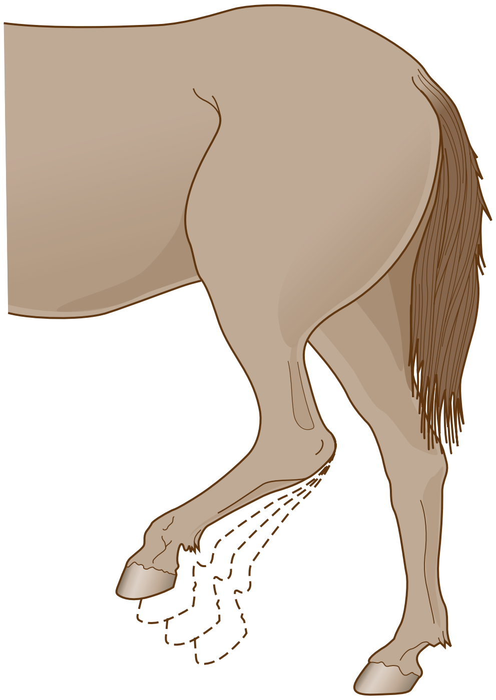

Fig 9.13 Typical movement pattern of a hind limb in a horse at the walk suffering from fibrotic myopathy of the semitendinosus muscle. The foot jerks backward and downward just before landing.

Reprinted from Stashak, T.S., 1987. Adam's Lameness in Horses, with permission from John Wiley and Sons, Inc.

has seen it previously. Two of these specific lamenesses have been described kinematically in detail.

Stringhalt

This extraordinary locomotion pattern can be seen in horses often without a known underlying cause (idiopathic stringhalt), probably due to a neurologic impairment with disturbed spinal motorneuron regulation. This pattern is characterized by the exaggerated lifting of one or both hind limbs during the swing phase (Fig. 9.12). Girtler (1988c) presented the flight arc and temporal data of such a patient. The hoof was lifted to a maximum height of nearly 60 cm instead of the normal height of 15–20 cm, with the peak of the flight arc being reached quite late during the swing phase and the hoof then being lowered nearly vertically to the ground. In the affected limb, the stance phase was shortened and the swing phase was prolonged, whereas the sound limb showed the opposite changes. Step duration from the sound to the lame limb was longer than the contralateral step. This strange locomotion pattern is much more obvious at the walk than at the trot, even at very slow velocities. Recently, both kinematic as well as surface EMG techniques were used to document these typical gait characteristics of horses with stringhalt and the effects of an intramuscular botox therapy (Wijnberg et al., 2009).

Fibrotic myopathy

Like stringhalt, the typical locomotion pattern of fibrotic myopathy is more obvious at the walk than at the trot. Fibrosis of torn muscle fibers of the semitendinosus muscle impedes protraction of the hind limb at its most cranial position, when the muscle is maximally stretched. At the walk, the hind hoof jerks backward and downward just before landing instead of a smooth forward movement to impact (Fig. 9.13). Clayton (1988) analyzed a typical example of a horse with this ailment and described some kinematic details for the trot. The flight arc stopped its forward movement at 84% of the swing phase and the hoof contacted the ground toe first after being lowered almost vertically rather than being retracted prior to contact. Consequently, the diagonal distance was shorter for the affected diagonal limb pair. These differences were found even at the trot, in which the characteristics are less obvious than at the walk, because at the walk more hind limb protraction is seen than at the slow trot (Buchner et al., 1996a).

Summary

Kinematic or kinetic analyses of lameness in different ailments show patterns that allow for a reliable classification into supporting or swinging limb lameness. More specific patterns could not be detected using these techniques alone, probably as a consequence of the quite uniform way horses react to pain in a limb, due to the limited degree of freedom in their locomotion patterns. Inverse dynamic analyses allow more specific characteristics of a lameness to be identified, including changes in functional units like the deep digital flexor tendon (including its check ligament and the navicular bone). Therefore, specific lameness diagnosis using gait analysis techniques is still a hot topic and field for further research in the future.

Clinical use of locomotion analysis

Accurate and objective assessments of locomotor disturbances using locomotion analysis techniques provide the veterinarian with valuable tools for advanced diagnostics in a clinical setting. Both qualitative and quantitative methods can be used to assess lameness objectively, to augment diagnostic procedures or to verify therapeutic effects. Qualitative assessments use slow motion video-recordings to detect changes in hoof motion and landing as well as locomotor asymmetries (Seeherman, 1991, 1992). The big advantage of qualitative gait analysis is the low technical effort and the simplicity of

Table 9.3 Symmetry indices using kinematic or kinetic variables

Author	Index	Variables	Method	Sound value
Morris & Seeherman (1987)	L/R ratio	Ground reaction forces, impulses, timing	Quotient	1
Merkens et al. (1988)	H(orse)INDEX	Ground reaction forces, impulses, timing	Quotient, factors	1
Kastner (1989)	HAAS	Head vertical acceleration	Quotient	0
Buchner et al. (1993)	HAQ	Hip vertical acceleration	Quotient	1.28
Kübber et al. (1994)	WAAS	Withers vertical acceleration	Quotient	0
Peham et al. (1996)	Symmetry	Vertical head movement	Fourier analysis	100%
Buchner et al. (1996b)	Various indices	Head, withers, sacrum, tuber coxae, vertical displacement, maximal acceleration, vertical acceleration amplitude	Quotient	1
Uhlir et al. (1997)	SAAS	Sacral vertical acceleration	Quotient	0
Pourcelot et al. (1997)	Symmetry indices, forelimb, hind limb index	Joint displacement, joint angles	Inter-correlation	1
Weishaupt et al. (2001)	Various indices	Ground reaction forces, impulses	Quotient	0
Audigie et al. (2002)	Energy ratio	Trunk vertical displacement	Fourier analysis	100%
Keegan et al. (2004)	Accelerometric ratios	Poll and pelvis acceleration	Fourier analysis	1

interpretation of the slow motion video images by veterinarian and horse owner. The same criteria as during a standard orthopedic examination are assessed, but with a higher temporal resolution and with as many replays as necessary.

Quantitative assessments need more sophisticated methods and can measure all kinematic or kinetic details described in the previous sections. For clinical applications, however, the need for a rapid turnaround time usually restricts the analysis to localization of the lame limb and quantification of the lameness degree. Several methods and variables are available to define symmetry indices for lameness quantification (Table 9.3). These indices have to meet several criteria to be of practical, diagnostic value. Firstly, they must be sufficiently sensitive to lameness that even small disturbances in the locomotion pattern are reflected by distinct changes in the symmetry index. Secondly, an index value should be indicative of a certain degree of lameness, and the interindividual variation in this variable should be smaller than the differences between lameness degrees. Thirdly, the variable should be easy to measure and interpret. These criteria can be fulfilled to a variable extent by variables derived from both kinetic and kinematic analyses. However, the third criterion is still especially difficult to achieve and is the subject of further technical development.

Kinematic lameness indicators

The typical asymmetric pattern of head, withers or croup movements in lame horses enable their use for the calculation of symmetry indices that are similar to the traditional, subjective assessment by the veterinarian. Kastner (1989) first used the vertical accelerations of the head to calculate a symmetry index named HAAS: head acceleration asymmetry. He used the following equation:

$$\text{HAAS} = \frac{\text{LAA} - \text{RAA}}{\text{BAA}}$$

HAAS: Head acceleration asymmetry
LAA: Left vertical head acceleration amplitude
RAA: Right vertical head acceleration amplitude
BAA: Bigger vertical head acceleration amplitude.

The HAAS index is zero in sound horses with symmetric head movements during the left and right forelimb stance phases. The index tends to −1 if the left limb is lame and it tends to +1 if the right limb is lame. This simple equation has also been applied to locations other than the head, giving rise to WAAS (Withers Acceleration ASymmetry) (Kübber et al., 1994) or SAAS (sacral acceleration asymmetry) (Uhlir et al., 1997). Similarly, using slightly different calculation methods, the hip acceleration can be recorded and analyzed (Buchner et al., 1993) or the vertical displacements in both hips can be compared (May & Wyn-Jones, 1987). These symmetry indices perform very well, but still need considerable effort during recording and analyzing.

More sophisticated calculation methods were used by Peham et al. (1996) to reduce the influence of unsteady head movements. After processing the data using a system-matched filter, the symmetry of the vertical head movement pattern was analyzed by determination of the Fourier series. The symmetry of the horse's movements can then be calculated by comparing the values of the Fourier coefficients and presented as symmetry percentage (Table 9.3) (Peham et al., 1995). Similar methodology was used by Keegan et al. (2001) and Audigie et al. (2002), where Audigie et al. (2002) only used a trunk marker to determine fore or hind limb lameness as well as lameness degree.

A different kinematic method was reported by Pourcelot et al. (1997). They applied an intercorrelation method to analyze the contralateral symmetry of both the vertical joint motion and the joint angle changes during one stride. The results of these calculations are presented as kinematic indices for the comparison of each pair of markers or limb joints, or as an averaged fore or hind limb index. In contrast to the HAAS, these symmetry indices have the value 1 in perfectly sound and symmetric horses and tend to zero in severe lameness.

Accelerometer

Acceleration can be calculated by double differentiation of the displacement of a point, or it can be measured directly using an accelerometer. Conversely, acceleration data can be integrated to calculate velocity or displacement. Barrey et al. (1994) used accelerometers fixed to the sternum of horses to record the horizontal and vertical movements of the trunk. In addition to providing performance indices, this method can be used to assess both symmetry between successive half strides and regularity between successive strides by calculating the autocorrelation function of the acceleration signal. This allows the detection of lame horses as those showing symmetry values lower than 95%, with 100% as the result in perfectly symmetrically moving horses (Barrey & Debrosse, 1996).

An accelerometer mounted to the horse's head has been used to detect head motion asymmetries by Weishaupt et al. (1993). They recorded the vertical head acceleration directly and quantified the improvement of the gait in a lame horse due to analgesics and local anesthetics, in a similar manner to Kastner (1989). Church et al., 2009 again proved the significance of the vertical movement of the pelvis to quantify hind limb lameness by using inertial sensors on both tubera coxae and tuber sacrale.

All accelerometric methods have the advantage of needing little instrumentation and of offering results in a short time using automated data analysis software.

Force plates, force shoes, EGA system

Pratt and O'Connor (1978) introduced the force plate in equine locomotion research. The vertical and horizontal force tracings allow a clinically appropriate analysis of limb loading and have often been used to satisfy the urgent need for objective assessments of orthopedic therapies (see next paragraph), for example in carpal lameness or tendinitis (Gingerich et al., 1979; Goodship et al., 1983; Morris & Seeherman, 1987). Merkens et al. (1988) and Merkens and Schamhardt (1988a, b) tried to establish a clinically oriented assessment system based on the bilateral symmetry of fore and hind limbs. Both amplitude and temporal variables were used to define various symmetry indices that were combined into a single H(orse)INDEX (Table 9.3). Furthermore, graphical displays of the vertical and horizontal forces are presented that allow a quick qualitative assessment of the presence of asymmetries by the veterinarian (Fig. 9.14) (Merkens et al., 1988). The major advantage of force plate analysis is that it does not require any instrumentation on the horse, so there are minimal problems for the horse and its owner. Furthermore, the results are very accurate and reliable. A disadvantage is the large number of trials needed to get enough data when using a small force plate, which requires some time and patience for all concerned. This disadvantage was overcome by the instrumented treadmill in Zürich, which allows for continuous assessment of vertical GRFs, which, however, is still an unique measurement device (Weishaupt et al., 2002).

A special application of the force plate as a diagnostic instrument has been described by Aviad (1988), who used the stability of the force versus time signal of horses standing with the lame limb on a force plate to assess the weight bearing stability and improvement due to therapy. Similarly, Clayton et al. (2003) have used the force plate to detect postural sway in standing horses as an indicator of neurological disease.

Besides force plate studies, two other kinetic devices have been used for the analysis of equine lameness: force shoes and the EGA system. Force shoes measure GRFs in special measuring devices integrated into a horseshoe. Different types of force shoes using piezoelectric transducers (Ratzlaff et al., 1990) or strain gauges (Roepstorff & Drevemo, 1993; Kai et al., 2000) have been designed. Problems in the design of force shoes include the delicate nature of the instrumentation and the considerable weight of the shoes (Hugelshofer, 1982), which impedes their use in a clinical situation. However, the technology is improving, and a clinically useful force shoe may eventually be developed.

Auer and Butler (1980) first described the Kaegi system as a tool for assessing limb loading patterns in lame horses. The system, later improved and described as the EGA system (Huskamp et al., 1990; Tietje, 1992), measures vertical forces in a number of sensors, which are integrated into a special floor. This system needs no instrumentation on the horse and offers data describing the loading of each limb as well as temporal stride variables. Despite the simplicity of use, the high cost of the EGA system prevented the widespread adoption of its use.

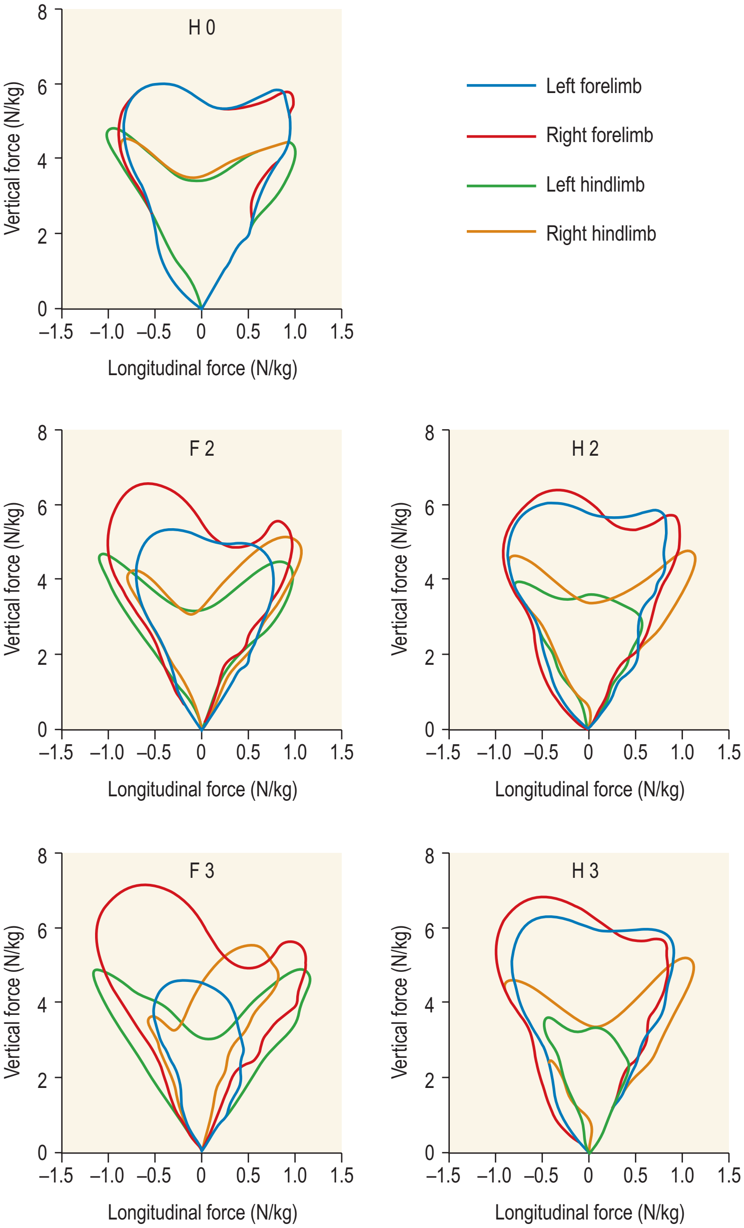

Fig 9.14 Vertical-longitudinal force curves (vectordynamograms) of all limbs of one horse during sound control session (H0), moderate left forelimb lameness (F2), severe left forelimb lameness (F3), mild left hind limb lameness (H2) and moderate left hind limb lameness (H3).

Reprinted with permission from: Merkens H.W., Schamhardt H.C., 1988b. Evaluation of equine locomotion during different degrees of experimentally induced lameness. II. Distribution of ground reaction force patterns or the concurrently loaded limbs. Equine Vet J (Suppl.) 6, 107–112.

Artificial neural networks

A nice computational method to assess the results of locomotion analysis, and to detect asymmetry or lameness, is the use of artificial neural networks (ANN). ANNs are computer programs that use similar methods to the human brain to recognize characteristic patterns in the kinematic or kinetic variables. Similar to human experience, neural networks need to be trained with input data and the corresponding output message. For example, the ANN might be given input data describing the joint angle values or symmetry indices of the head and sacrum, together with the corresponding output message that there is a grade 2 lameness in the left forelimb. After several training cycles, the networks can use different, new input data to arrive at a conclusion describing the corresponding, unknown output information.

There have been three studies in which kinematic data from groups of lame horses were used as input data for an ANN: Schobesberger and Peham (2002) used data of 175 horses with a variety of different orthopedic diseases, Van Loon et al. (1995) used the symmetry indices of the lameness study of Buchner et al. (1995a, 1996a, b), and Keegan et al. (2003) based the ANN on the wavelet transformation of head movement in 12 horses. All authors were able to detect the lame limb and to assess the lameness degree with probabilities between 75 and 85%. However, they concluded that the quality and the reliability depended on using a sufficiently high number of training data. Schobesberger and Peham (2002) estimated the necessary amount of input data for a correct diagnosis in 90% of the cases to be about 6600 input values, and to reach for 95% probability of a correct diagnosis required 13 200 input values. The fact the ANNs require such a large amount of kinematic input data to be adequately trained is likely to restrict their clinical use for lameness diagnosis in the near future.

Biomechanical studies of diagnostic or therapeutic aids in equine orthopedics

A number of kinetic or kinematic techniques have been used to evaluate the effects of diagnostic or therapeutic procedures in equine orthopedics. Some of these procedures are frequently used, but their effects are often small and difficult to quantify. Knowledge regarding the effects of these procedures has been based primarily on experience or logical assumptions, but not on objectively determined results. Especially due to the need for an objective validation of therapies for an evidence based medicine approach, the quantification of equine locomotion became an important topic. Detailed biomechanical studies are available for diagnostic procedures like the effects of flexion tests and diagnostic nerve blocks. Similarly several therapeutic aids have been tested: casts and bandages, medical therapies, extracorporal shock wave therapy and the effects of desmotomy of the accessory ligament of the deep digital flexor tendon. An important field for biomechanical evaluations are studies about the value of various orthopedic shoeing techniques; these studies are described elsewhere and will not be considered here.

Diagnostic aids

Flexion tests

A flexion test is a standard procedure during equine lameness examinations. The objective is to test if pain in a certain region and a worsening of a lameness can be provoked by prolonged flexion of the regional joints. Typical examples of flexion tests are digital flexion, carpal flexion and hock flexion (spavin) tests. Two factors have a significant influence on the outcome of a flexion test: the force applied and the duration of force application. Keg et al. (1997a) analyzed the forces used by a group of clinicians using a force transducer, the 'flex-o-meter' (Fig. 9.15). They found considerable interindividual variation between different clinicians of about 20% of the mean force. Furthermore, there was a significant sex difference in mean force: female examiners used a mean force of 114 N compared with 144 N in male examiners. The intraindividual variation, which is the variation within repeated flexion tests by the same person, was smaller, only about 12%. Therefore, to achieve a high repeatability, it is necessary to be consistent in performing the flexion tests. The same person should perform flexion tests in both limbs of the same horse to allow for a correct interpretation, and it is not possible to equate the results found by different examiners.

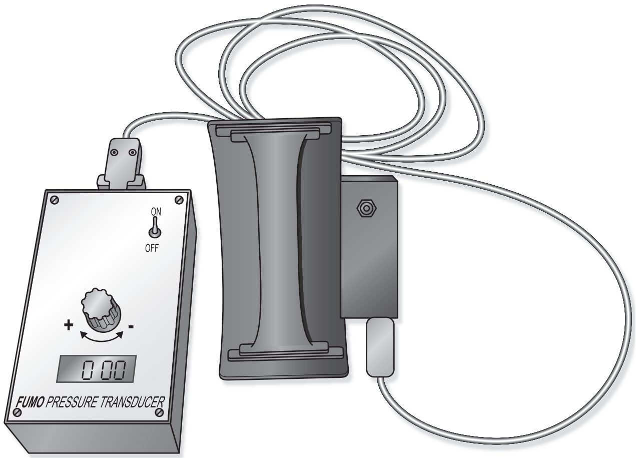

Fig 9.15 Flex-o-meter. (A) Polyvinylchloride plate with rubber tube as inner lining; (B) electronic manometer; (C) charge amplifier.

The second variable, the duration of the forced joint flexion, is also very important. Two studies analyzed the influence of changing flexion force and duration on the outcome of the test in sound horses (Keg et al., 1997b; Verschooten & Verbeeck, 1997). Both studies found dramatic increases in the number of positive flexion tests by increasing the time of flexion to 3 or 5 min. This factor was more important than the force, in which an increase of 25% resulted in only one additional horse out of eight becoming lame (Keg et al., 1997b). Increasing the force from 100–150 N caused only about 6% more positive results in the flexion tests (Verschooten & Verbeeck, 1997). Both studies stressed the importance of standardizing the flexion tests in regard to force and duration, and both concluded that 60 s is an adequate duration for the flexion test. For the applied force, Keg et al. (1997b) suggested 150 N, while Verschooten and Verbeeck (1997) preferred only 100 N. More important, however, is the principle of using the same person to apply all the flexion tests within one horse to achieve the necessary consistency in the applied force.

Diagnostic anesthesia

The effects of diagnostic nerve blocks on the gait of lame horses has often been described (Girtler et al., 1987; Merkens & Schamhardt, 1988a, b; Keg et al., 1992, 1994, 1996a; Keegan et al., 1997) and can easily be quantified. More ambiguous results are reported concerning the effect of diagnostic anesthesias on the gait of sound horses. This information is important for differentiating sound horses from those with slight bilateral lameness. Bilaterally lame horses do not show any asymmetries in their gait patterns, but diagnostic nerve blocks of one affected limb cause a visible lameness of the contralateral limb. This is the only way to prove a bilateral orthopedic problem. This diagnostic procedure, however, is based on the assumption that diagnostic blocks in sound horses do not affect their locomotor pattern, or at least, have a different effect than in bilaterally lame horses. Several investigators tested this assumption using different methods. All the studies of diagnostic anesthesia in sound horses found slight gait changes, but they differed in quality and quantity. Kübber et al. (1994) and Drevemo et al. (1999) found some kinematic changes that were indicative of a slight increase in weight bearing on the anaesthetized limb. Kübber et al. (1994) reported increased asymmetry in the symmetry variables of the head and withers after the nerve block in 9 out of 12 sound horses, while Drevemo et al. (1999) found an increased range in the joint angle pattern of the fetlock joint. The changes were very small and some were very close to the border of statistical significance. Looking at the loading of the limbs using a force plate, however, Keg et al. (1996b) could not find differences in the vertical load before and after local nerve blocks. Only one variable, the time of change from a decelerative to an accelerative horizontal force changed significantly. This indicates a change in the proprioceptive information and a consequent slight change in the locomotion pattern of the horses. This change in proprioception was also proposed by Kübber et al. (1994) and Drevemo et al. (1999) and leads to the conclusion that sound horses do indeed show small changes in their gait pattern after a local nerve block. However, these changes are very small and there might be a gray zone in which it is impossible to differentiate between the responses to desensitization of the limbs in horses with a slight or subclinical, bilateral lameness from the reactions of sound horses.

Therapeutic aids

Bandages

Bandages on the limbs of horses are a widely used tool and serve several different functions. They have important medical uses in wound management or immobilization, and therapeutic uses for applying pressure, cold, heat, water or various medical agents (Stashak, 1987). Another important use of bandages is to protect against injuries of the distal limbs due to interfering, overreaching, hitting a fence or any other cause of skin trauma (Dyson, 1994). The most controversial use of bandages is to prevent tendon strains or joint injuries associated with loading during locomotion. The distal limbs are often bandaged to prevent or support tendinitis or arthritis of the fetlock joint. There are some studies, however, which disprove this protective function or even indicate possible adverse effects of bandages for this purpose. The effects of bandages on tendon strain can be evaluated directly using invasive methods, such as strain gauge implants into the tendons, or indirectly, using non-invasive, kinematic methods. Keegan et al. (1992) implanted strain gauges into the suspensory ligament of 9 horses. They compared ligamentous strain while standing and walking with two types of casts and four types of supportive bandaging materials as well as different bandaging techniques. The results clearly showed that significant support can only be expected for the full cast and the dorsal fetlock splint. There was no effect of any bandage on suspensory ligament strain.

Kobluk et al. (1990) applied the close relationship between fetlock joint angle and suspensory ligament strain to evaluate the supporting capacities of bandages. They measured the kinematics of galloping horses that had been wrapped with different types of support bandages. Some horses showed slightly decreased fetlock hyperextension with bandages, but others showed no decrease or even had increased fetlock joint angles. In general, there was no proof for a protective effect of supporting bandages on fetlock joint angle or tendon strain during loading of the limbs. There might be a physical restriction of the amount of flexion during the swing phase, but this is unlikely to prevent injuries associated with limb loading.

On the other hand, bandages cause pressure on the limb, with the amount of pressure being dependent on the type of bandage and the speed of locomotion. Morlock et al. (1994) quantified the pressures on the metacarpal skin using a small pressure-sensitive mat. They measured local peak pressures up to 14.4 N/cm^2 at the gallop and maximal total forces up to 235 N under the bandage. They concluded that even when no kinematic effect can be seen, the pressure under the bandage might impede blood flow in the distal limb, which could be counterproductive in terms of protection and performance of the horse. Furthermore, if bandages were applied tightly enough to support the tendons during locomotion, the forces applied to the limb at different locations under the bandage, for example the metacarpal skin, are likely to cause problems that would outweigh any positive effects at the tendons or fetlock joint.

Analgesia, NSAIDs, ESWT

The effectiveness of various pharmaceuticals for the therapy of lameness has been quantified in terms of changes in the lameness degree or loading of the limbs. Mostly the peak vertical force was used to follow the effects of an anti-inflammatory therapy, like phenylbutazone, flunixin, etodolac, cox-2 inhibitors (firocoxib) or combinations with intrasynovial corticocoids and orthopedic shoeings (Back et al., 2009; Hu et al., 2005; Erkert et al., 2005; Schoonover et al., 2005; Symonds et al., 2006). Similarly, the immediate analgesic effect of extracorpral shock wave therapy (ESWT) was tested and found to be negligible in horses suffering from navicular disease using the simple parameter peak vertical force (Brown et al., 2005).

Desmotomy

A study of the therapeutic effects of desmotomy of the accessory ligament of the deep digital flexor tendon (also known as the distal check ligament, DCL) took a step further and used inverse dynamic analysis to assess the consequences of this procedure for the digital joints and tendons (Buchner et al., 1996c; Becker et al., 1998a). Desmotomy of the DCL is usually performed in young, growing horses suffering from flexural deformity of the distal interphalangeal joint (McIlwraith & Fessler, 1978). Recently, desmotomy of the DCL has also been proposed as a possible therapy for DCL desmitis, similar to desmotomy of the accessory ligament of the superficial digital flexor tendon to treat SDF tendinitis (Becker et al., 1998a). In a long-term study all clinical, ultrasonographical, histological and biomechanical aspects of the desmotomy were assessed to evaluate the advantages or disadvantages of the desmotomy for treating chronic desmitis of the DCL. A combination of kinetic, kinematic and radiologic techniques was used to study the function of the DCL for normal locomotion and to follow the changes in joint moments, tendon forces and limb kinematics at intervals of 10 days and 6 months after DCL desmotomy in sound horses.

Ten days after desmotomy the horses had no visible lameness or changes in limb loading, but alterations in the locomotion pattern were clearly indicative of the loss of biomechanical function of the DCL (Buchner et al., 1996c). During the whole stance phase a caudad shift of the point of force application at the hoof (center of pressure) reduced the moment arm of the GRF and, consequently, the net joint moment at the coffin joint. Despite the loss of DCL function, the joint motion pattern at the beginning and in the middle of the stance phase was not changed. An increase in function of the SDFT compensated for the loss of the DCL, so the fetlock joint angle was unchanged during maximal vertical loading at midstance. At the end of the stance phase, it was primarily the deep digital flexor tendon (DDFT), rather than the SDFT, that took over the function of the deficient DCL (Fig. 9.16). However, the DDFT could not fully compensate the DCL function. Consequently, some kinematic changes occurred in the later part of the stance phase: the fetlock joint remained hyperextended for a longer time before flexing rapidly at the end of the stance phase, whereas the carpal joint started to flex earlier in the stride cycle. The increased loading of SDFT and DDFT was found to be within the normal range of loading at the walk and the trot. Therefore, it was concluded that

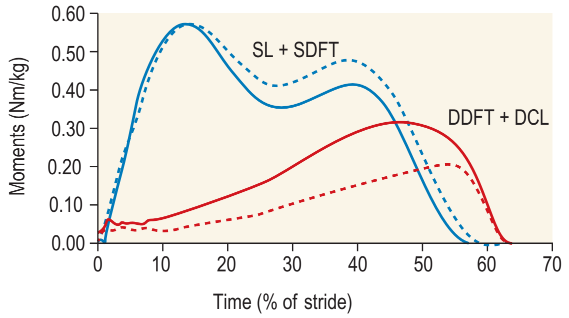

Fig 9.16 Tendon moments at the fetlock joint of suspensory ligament and superficial digital flexor tendon (SL + SDFT), deep digital flexor tendon and its distal check ligament (DDFT + DCL) averaged over six horses at the walk before and after desmotomy of the DCL. Solid lines, before desmotomy; dashed lines, after desmotomy.

Reprinted from Buchner, H.H.F., Savelberg, H.H.C.M., Becker, C.K., 1996. Load redistribution after desmotomy of the accessory ligament of the deep digital flexor tendon in adult horses. Veterinary Quarterly 18, S2, S70–74, with permission from Taylor & Francis Ltd, http://www.informaworld.com.

there is no risk of damage to the compensating tendons after DCL desmotomy, provided locomotion is controlled during the recovery period.

These experimental findings nicely confirmed most of the details that had been predicted by a model analysis of van den Bogert et al. (1989). By using a computer model to simulate the loss of the DCL, the increase in the DDFT force, as well as the change in the position of the point of force application, were predicted correctly, but the increase in the force of the suspensory ligament (SL) was overestimated. Obviously, the SDFT could compensate for the DCL desmotomy by maintaining the normal midstance angle of the fetlock joint so that SL loading was unchanged.

Six months after the desmotomy, the function of the DCL was partly restored by scar tissue formation, which restored 80% of the original tensile strength of the DCL, while its length had increased by 1 cm (Becker et al., 1998b). This healing process restored its biomechanical function to a certain extent and reduced the typical locomotor changes seen 10 days after the desmotomy. However, most of the locomotor changes persisted, especially the caudad shift of the point of force application, and it was assumed that healing would continue for a longer period of time.

In conclusion this study documented the biomechanical changes due to DCL desmotomy and quantified the consequences for the net joint moments and the loading of the tendons. Even 6 months after desmotomy, healing was still in progress and DCL function was not fully restored. These experimental and model studies of DCL function show the potency of non-invasive methods for assessing the biomechanical effects of therapeutic procedures on the internal forces in limb joints and tendons. Similar studies have been performed to assess the effects of various types of orthopedic shoes and to enable an objective assessment of the benefit of these therapeutic measures for the health of the horse.

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CHAPTER 10

The neck and back

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Function

The goal of this chapter is to present a synthesis of the current knowledge on *in vivo* neck and back function and dysfunction at walk, trot, gallop. Descriptions of equine vertebral column movements are often limited to the relative displacements of different axial regions of the horse (mainly neck versus back). These displacements induced and controlled by long muscle chains have been measured using kinematics and accelerometrics, of which in general surface EMG measures muscular activity and needle EMG muscular functionality. An anatomical overview of the vertebral column precedes the locomotor data review on its function and dysfunction (Clayton et al., 2005).

Anatomy

The spinal column of the horse extends from the occipital condyles to the tail and consists of approximately 50 separate short bones, the vertebrae. The spinal column supports the body axis and thus the maintenance of posture. The vertebrae are connected by short and long ligaments, and two types of articulations, and therefore, the spinal column also plays an important role in locomotion. The typical vertebral formula for the horse is seven cervical, 18 thoracic, six lumbar, five sacral, and 15–21 caudal vertebrae (Fig. 10.1), each with its own specific characteristics. The basic form of vertebrae (this does not account for the first cervical vertebra) consists of a ventrally placed vertebral body and a dorsally placed vertebral arch, which encloses the vertebral foramen. The body is composed of an outer cortex of compact bone, which surrounds trabecular bone. The cranial aspect of the body is usually convex, the caudal aspect concave. Both are covered with hyaline cartilage and can as such be regarded as the non-ossified part of the epiphysis of the vertebral body. The basal part of the arch is notched on both the cranial and caudal margin; the two notches of successive vertebrae form one intervertebral foramen that transmits the spinal nerves and vessels (Fig. 10.2). The spinous process, which is located, on top of the arch, varies in its shape, length and inclination. On the left and right junctions of the body and the arch the transverse processes can be found. Mamillary processes, if present, are located between the cranial articular process and the transverse process; accessory processes are located between the caudal articular process and the transverse process. The head and neck unit plays an important role in balancing and in locomotion. Changing the position of the head and neck changes the center of gravity, which provides means for changing the speed of the gaits and even movement on the same position. The thoracolumbar part of the vertebral column is relatively stiff; it has to oppose the forces exerted by the relatively heavy abdominal organs and it has to transmit the propulsive forces brought about by the hind limbs.

Bones

The first cervical vertebra, the atlas, consists of two arches (dorsal and ventral), two lateral wings (enlarged transverse processes) and no vertebral body. On its cranial end it carries a dorsal tubercle (remnant of the spinous process) on its caudal end a ventral one. The wings are an important palpable landmark, to which the head and neck muscles responsible for rotary movements of the head, attach. During development of the vertebrae in early embryonic life (a part of) the body of the first vertebra fuses with the body of the second, providing the latter with a cranial protrusion, the dens. The dens, resting on the floor of the vertebral foramen of the atlas, provides the axis of rotation for the atlas and the head. The body of the axis is long and carries a ventral crest that ends on the caudal ventral tubercle. The high spinous process of the axis gives rise to two articular facets at its caudal extremity; these meet the cranial facets on the third cervical vertebra. The cervical vertebrae become progressively shorter towards caudal. The third, fourth and fifth cervical vertebrae are long and strong and carry a sharp robust ventral crest on their body that terminates in the ventral tubercle. The spinous processes are weakly developed. The transverse processes are split into a cranioventral and a dorsocaudal tubercle, connected by a crest. The sixth cervical vertebrae is shorter, but carries an impressive ventral crest. The ventral tubercle of the transverse process is replaced by a ventral plate (lamina ventralis). The seventh cervical vertebra has the shortest body of the cervical vertebrae, still a weakly developed spinous process and no ventral plate. On its caudal aspect the body carries not only the articular process for the cervicothoracic joint but also the fovea costalis for articulation with the first rib.

The 18 (range 17–19) thoracic vertebrae have short bodies, low articular processes, closely fitting vertebral arches and long spinous processes. The latter increase rapidly in size with T2–T9 forming the basis of the withers. Normally, the tip of T5 or T6 forms the highest point of the withers. Thereafter a gradual decline in height of the spinous processes can be seen. The spinous processes of the first 14 thoracic vertebrae have a backward inclination, the 15th one has an

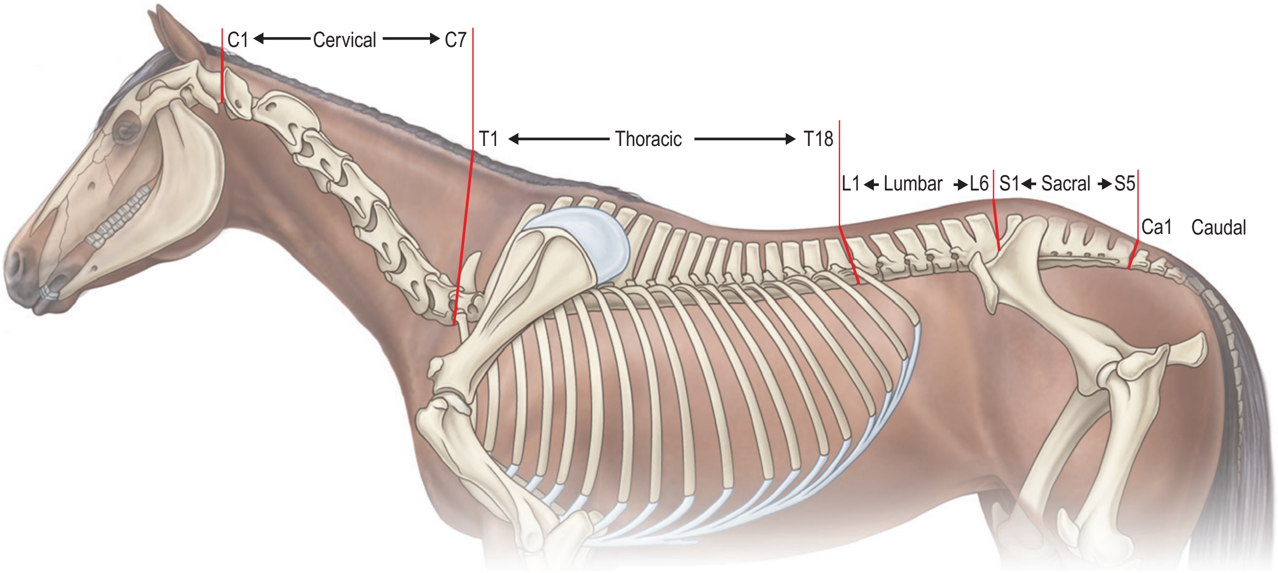

Fig 10.1 The vertebral formula for the horse is seven cervical, 18 thoracic, six lumbar, five sacral, and 15–21 caudal vertebrae.
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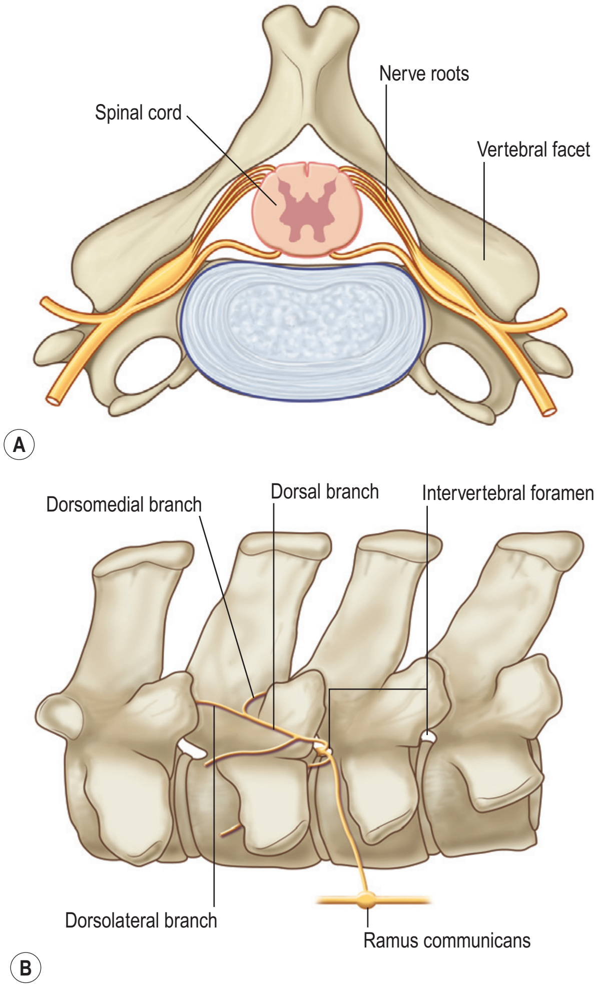

Fig 10.2 The basal part of the arch is notched on both the cranial and caudal margin; the two notches of successive vertebrae form one intervertebral foramen that transmits the spinal nerves and vessels: (A) a transverse view, (B) a sagittal view.

upright spinous process, and the processes of the remaining thoracic vertebrae and of the loin or lumbar vertebrae have a forward inclination. Serial features are an appearance of an additional mamillary process as a projection from the transverse process and its gradual migration to join the cranial articular process and a change toward the end of the number of the thoracic vertebrae in the character of the articular facets from the cervical to the lumbar pattern (Fig. 10.1). There are sternal (10) and asternal (8) ribs, the neck of the ribs become gradually shorter caudally. Costal facets are present on both extremities of the vertebral body for articulation with the rib heads and on the stubby transverse processes for the rib tubercles. The articular facets of the heads and tubercle become confluent in the caudal thoracic vertebrae which increases the mobility of the last few pairs of ribs. The head of a rib has a cranial and a caudal facet, separated by a groove for the attachment of the intra-articular ligament of the head of the rib.

The average number of lumbar vertebrae is six (range five to seven). Their vertebral bodies are longer than those of the thoracic vertebrae, the spinous processes shorter, and the transverse processes are long, flattened and positioned in a cranioventral direction. The transverse processes of the last two lumbar vertebrae and those of the last lumbar and first sacral vertebrae articulate with each other. Transverse processes cranial to L5 can also form articulations. Fusion of the transverse processes can occur without clinical implications.

The sacrum is a completely rigid structure, constructed of five sacral vertebrae and their ossified intervertebral discs. The fusion is complete at the age of 4–5 years. The fusion increases the effectiveness of the forward thrust in locomotion from the hind limb to the vertebral column. The fused transverse processes of the sacral vertebrae are enlarged by the sacral wings, which project laterally and originate from the first sacral vertebra. The sacral wings form a rigid joint with the ilial wings through the oval area (facies auricularis), which is covered with cartilage. The dorsal margin of the sacral wing (tuberositas sacralis) is roughened for the attachment of the sacroiliac ligament.

The number of tail (coccygeal) vertebrae is very variable (15–21). Unlike in other species such as the cat, the biomechanical role of the tail in horses is limited.

Vertebral joints

The atlanto-occipital joint consists of two separate ellipsoid joints between the occipital condyles and the concave articular surfaces of the atlas. In old horses there can be a ventral communication between the two joint cavities. The shape of the articular surface restricts movement between the atlas and the skull to mainly flexion and extension; though some lateral bending is also allowed by this type of joint. The atlanto-axial joint is a pivot joint between the dens of the axis and the ventral part of the vertebral foramen of the atlas. Furthermore, there are caudal articular facets on the body of the atlas and cranial ones on the axis. The joint construction allows rotational movements along the longitudinal axis of the dens. The subsequent cervical vertebrae articulate with two different joint types. First, there is the joint between the extremities of the bodies, formed by the intervertebral discs and second there are joints between the articular facets on the arches of the vertebrae. The intervertebral discs allow movement in every plane, the facet joints restrict the movement to one main plane, depending on their position. In the cervical vertebrae, the facet joints are more or less horizontally oriented allowing mainly lateroflexion, in the lumbar area the facet joints are sagittally orientated, allowing mainly extension–flexion movements. In the thoracic vertebrae there is a gradual change in position of the facet joints.

Intervertebral discs

The intervertebral discs between the vertebral bodies are composed of a pulpy nucleus and a fibrous ring (anulus fibrosus), although especially in the adult horse the distinction between these two parts is difficult (Yovich et al., 1985). The thickness of the discs decreases throughout the thoracic and lumbar region to reach their minimum thickness in the lumbar region. The pulpier nucleus is maintained under pressure and spreads the compressive forces over a wider surface. As a result the surrounding fibrous ring and the ventral and dorsal longitudinal ligaments are also brought under tension. Flexion of the vertebral arch brings about compression of the ventral side of the intervertebral disc and an upward (dorsal) movement of the disc.

Ligaments

The spine is passively stabilized by ligamentous structures. Ligaments prevent too much excursion of the vertebrae. The ligaments can be divided into the nuchal ligament, long and, short ligaments. The specific ligaments of the head and neck region stabilize the joints between the skull and C1 and between C1 and C2. The lateral ligaments are situated between the left and right paracondylar process of the skull and the left and right wings of the atlas. The dorsal and ventral atlanto–occipital membranes reinforce the joint capsule and arise dorsally and ventrally from the foramen magnum. The well-developed elastic dorsal atlanto-axial ligament is located between the dorsal tubercle of the atlas and the spinous process of the axis. The less developed ventral atlanto–axial ligament can be found between the ventral tubercle of the atlas and the ventral part of the body of the axis.

The structure and function of the nuchal ligament has been described by (Gellman & Bertram, 2002a, b). It supports the weight of the head, when the head is held high. The nuchal ligament is composed of two paired parts, the funiculus and the laminae. The funiculus originating from the external occipital protuberance receives the nuchal laminae at the level of the third cervical vertebra, and inserts on the spinous process of the fourth thoracic vertebra. The two parallel parts of the funiculus broaden in the region of the withers from where it continues as the supraspinous ligament to the caudal spinous processes of the lumbar vertebrae, and possibly the sacrum, until the first coccygeal vertebrae. The laminae (two sheets of tendinous tissue) originate from the spinous processes of the axis, the successive cervical vertebrae and insert on the first thoracic vertebrae. Between the nuchal ligament and the second or third thoracic vertebra a bursa (bursa subligamentosa supraspinalis or supraspinous bursa) is present. Additional bursae can be found between the nuchal ligament and the atlas or axis and are called bursa subligamentosa nuchalis cranialis and caudalis respectively. The fibrous supraspinous ligament is composed of two parallel parts like the funiculus of the nuchal ligament. In the lumbar region, the two parts can slope down from the top of the spinous processes. Its inner structure is built up of successive fascicles that span 3–4 vertebrae. In the thoracolumbar region the supraspinous ligament is partly fused with the thoracolumbar fascia to which the large extensor muscles of the back are attached. In the sacral region it unites with the gluteal fascia and the sacroiliac ligament. The supraspinous ligament plays an important role in biomechans of the back. It stretches with flexion of the vertebral column and relaxes upon extension; it thus opposes the spreading of the spinous processes (Fig. 10.3).

The dorsal longitudinal ligament can be found along the floor of the vertebral canal, from the dens of the axis to the sacrum and is attached to each intervertebral disc. The considerably shorter ventral longitudinal ligament is located on the ventral aspect of the vertebral bodies from the 8th thoracic vertebra to the sacrum, and is also attached to each intervertebral disc.

The short ligaments comprise the ligamenta flava, the intertransverse ligaments and the interspinous ligaments. The ligamenta flava are elastic (yellow) sheets that fill the interarcuate spaces. The intertransverse ligaments stretch out between the transverse processes of the lumbar vertebrae and are tensed during lateroflexion and rotation. The interspinous ligaments between the spinous processes are elastic in the cranial part of the spine. They prevent the vertebrae from sliding dorsally, and limit ventral flexion of the spine.

Muscles and nerves

The forelimb is attached to the trunk through muscles, the so-called synsarcosis. The involved extrinsic muscles are the trapezius, rhomboid, pectoral (superficial and deep), and the ventral serrate muscle (Payne et al., 2004). The latter consists of a cervical part (longer fibers, less tendinous) (Fig. 10.4) and a thoracic part (short fibers, much tendinous tissue). The ventral serratus muscle is innervated by a brachial plexus nerve, the long thoracic nerve. The following four muscles are also extrinsic muscles and therefore might be considered to be part of the synsarcosis as well: the subclavius, the latissimus dorsi, the omotransverse and the brachiocephalic muscle. The synsarcosis muscles are all involved in stabilizing the position of the scapula relative to the trunk, but during movement they also assist in protraction or retraction of forelimb. The synsarcosis provides flexibility to absorb the impact forces upon landing on the ground. The trapezius muscle, consisting of a cervical and thoracic part, assists both in pro- and retraction (cervical, pulls the scapula to dorsocranial and thoracic part respectively). Both parts are motor innervated by the accessory nerve, the sensory innervation is transduced via the dorsal rami of the cervical and thoracic nerves. The rhomboid muscle lifts the scapula and turns the scapula to cranial. Dorsal branches of the cervical nerves and a special branch from the brachial plexus (dorsal nerve of the scapula) innervate the muscle (Fig. 10.5). The muscle covers the dorsoscapular ligament, which is unique in the horse. A second head of the rhomboid muscle (m. rhomboideus cervicis) (Fig. 10.6 (3)) runs cranially to the second cervical vertebra. The latissimus dorsi, which is a flexor of the shoulder joint, becomes a powerful retractor with aid of the ground reaction forces. The brachiocephalic muscle (cleidobrachialis, cleidocephalicus) is a protractor, but can also bend the neck and head or move it to one side upon action. It is closely related to the omotransversarius from which it is hard to separate. The cleidocephalicus and omotransversarius muscle are innervated by the accessory nerve, the cleidobrachial part by the axillary nerve. Sensory information is relayed by the ventral rami of the cervical nerves (Dyce et al., 2010) (Fig. 10.7).

The following muscles coordinate the movements of the head, especially by the atlanto-occipital and atlantoaxial joints, like

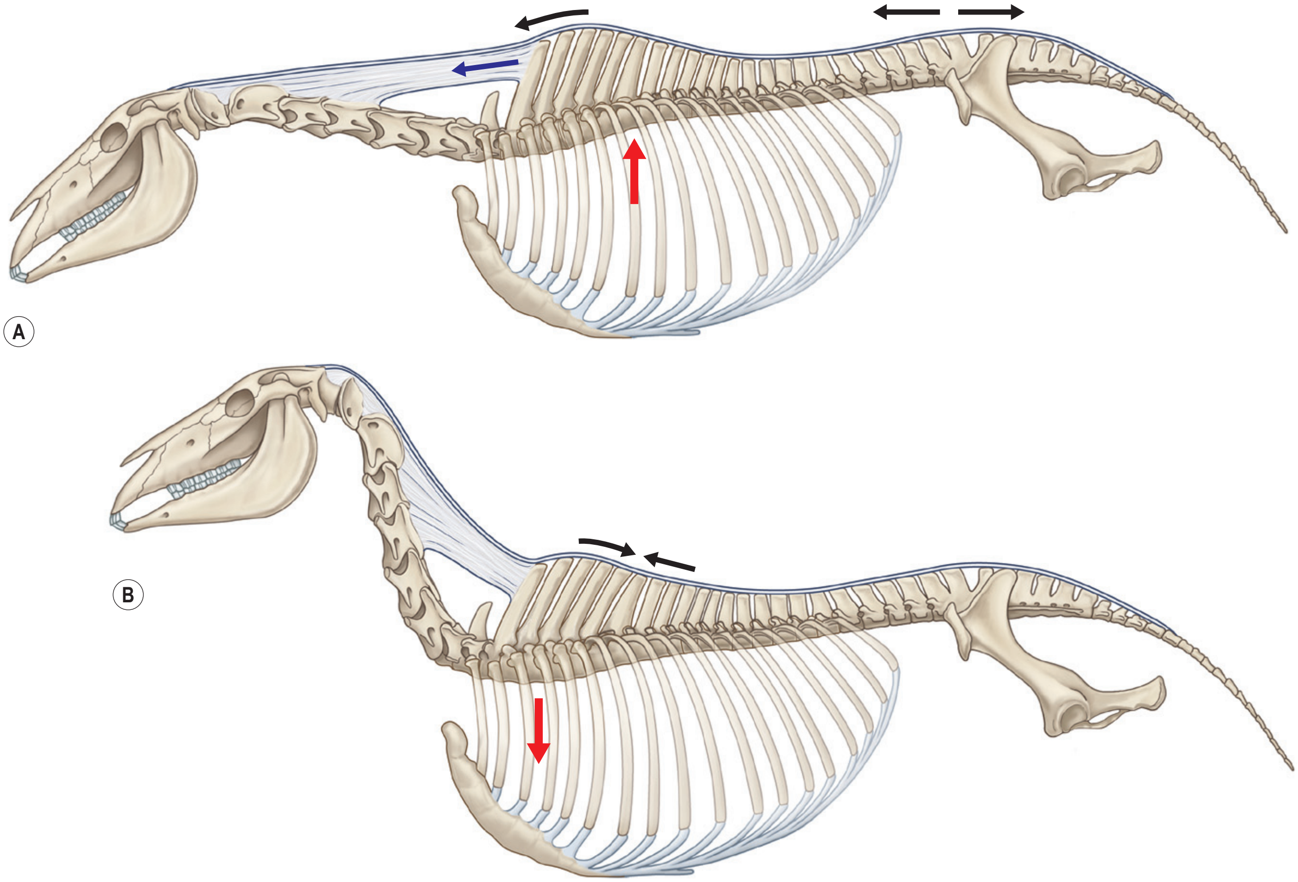

Fig 10.3 The nuchal ligament supports the weight of the head, when the head is held high. It is composed of two paired parts, the funiculus and the laminae.
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shaking, tilting, flexing and turning the head. The m. rectus capitis dorsalis major is located between the spine of the axis and the occiput–nuchal crest, lateral to the nuchal ligament; it contains a deep and superficial part. The muscle extends the atlanto–occipital joint and is innervated by the dorsal branch of the first cervical nerve. Beneath it lies the minor rectus capitus dorsalis muscle, which covers the dorsal atlanto–occipital membrane and shares the function and innervation with the major muscle. The lateral rectus capitis muscle is a small muscular band, which extends from the ventral arch of the atlas to the paracondylar process of the skull. It flexes the atlanto–occipital joint and tilts the head and is innervated by the ventral branch of the first cervical nerve. The ventral rectus capitis muscle between the ventral arch of the atlas and the base of the skull near the tympanic bulla also flexes the atlanto–occipital joint and has the same innervation as the lateral rectus muscle. The m. obliquus capitis cranialis extends obliquely craniolaterally over the atlanto–occipital joint, covered by the splenius and a part of the brachiocephalic muscle. It extends the atlanto–occipital joint and bends the head to the contracting side. It is innervated by the dorsal branch of the first cervical nerve. The m. obliquus capitis caudalis (Fig. 10.6 (12)) is positioned more caudally between the spinous process of the axis and the wing of the atlas; it receives its innervation through the dorsal branch of the second cervical vertebra. Unilateral action provokes rotation of the atlas and thus the head on the dens of the axis. Bilaterally it acts as a fixator of the head.

A neck muscle, not belonging to the large extensor systems, is the splenius muscle, which is a large muscle, located at the dorsolateral part of the neck, under the cranial (cervical) parts of the rhomboid muscle. It originates from the cranial border of the thoracolumbar fascia, the spinal processes of the first three thoracic vertebrae and the median neck raphe. The cephalic parts inserts the nuchal crest and mastoid process with the longissimus capitis. The cervical part inserts on the caudal part of the alar wing and the transverse processes of third and fifth cervical vertebrae. The muscle is a neck extensor and upon unilateral action it moves the neck to the side. It is thought to play an important role in maintaining balance during galloping. The muscle is innervated by the dorsal branches of the cervical nerves. The long muscle of the head (m. longus capitis) (Fig. 10.6 (9)) is a strong muscle, which can be regarded as a cranial continuation of the long muscle of the neck. It has long muscles fibers, and is located on both sides next to the ventral part of the second to fourth cervical vertebra. It unites with the contralateral muscle and ends between the guttural pouches on the base of the skull. It flexes the atlanto–occipital joint, draws the head sideways, or the neck downward and is innervated by the ventral branches of the first four cervical nerves. The segmented long muscle of the neck (m. longus cervicis) extends from the atlas to T6. It runs craniomedially to insert on the bodies of the more cranial cervical vertebrae near the midline. The muscle flexes the neck and is innervated by ventral branches of both the intercostal as the cervical nerves dependent on the part of the muscle. Of the scalenus muscle, only the ventral (Fig. 10.6 (11)) and middle part are present. It takes its origin from the first rib, and is divided by the brachial plexus. It inserts on the transverse processes of the third to seventh cervical vertebrae (middle part) and the seventh cervical vertebra (ventral part). The ventral branches of the fifth to eighth cervical nerve and the first two thoracic nerves innervate both parts. It flexes the neck,

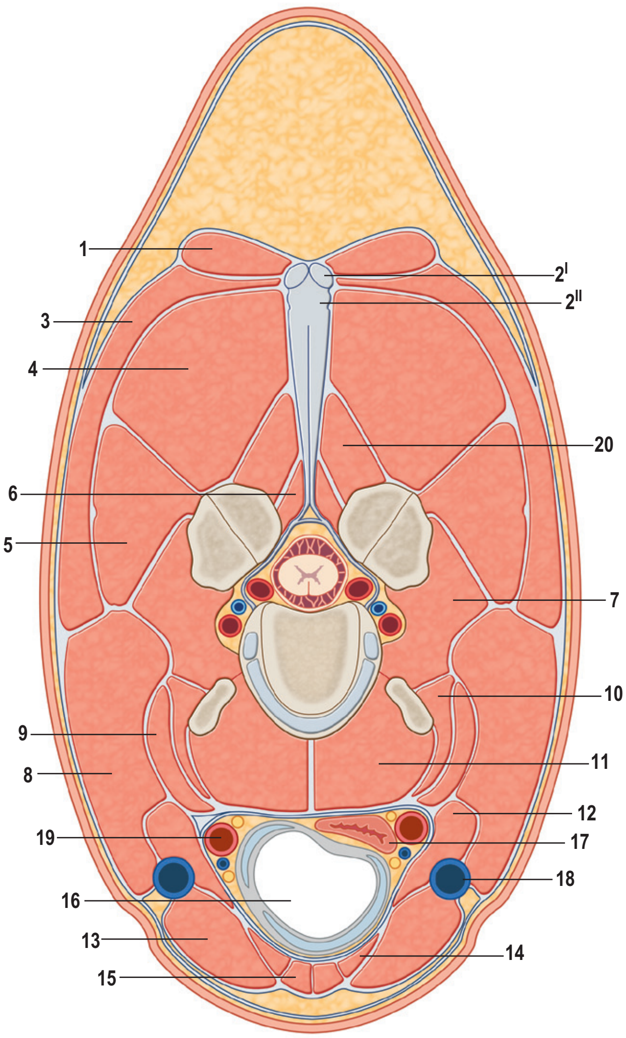

Fig 10.4 Transverse section of the neck at the level of the fourth vertebra. 1, m. rhomboideus, cervical part; 2, nuchal ligament; 2′, funicular part; 2″, laminar part; 3, m. splenius; 4, m. semispinalis capitis; 5, m. longissimus capitis; 6, m. spinalis cervicis; 7, m. intertransversarius; 8, m. brachiocephalicus; 9, m. longissimus cervicis; 10, m. longus capitis; 11, m. longus colli; 12, m. omohyoideus; 13, m. sternocephalicus; 14, m. sternothyroideus; 15, m. sternohyoideus; 16, trachea; 17, oesophagus; 18, external jugular vein; 19, common carotid artery; 20. m. multifidi.

draws it downwards and bends it sideways; it also supports inspiration. The sternocephalic muscle (Fig. 10.6 (1)) has a fusiform body and a long cranial insertion tendon. Dependent on uni- or bilateral action it flexes the head or provides lateroflexion. The muscle has motor innervation from a large branch of the accessory nerve, the sensory information is relayed by the ventral branch of the second cervical spinal nerve.

The epaxial musculature of the neck and back can, apart from the above mentioned muscles, be divided into three main systems, the iliocostal, the longissimus and the transversospinal system, that are located more or less next to each other in the thoracolumbar region, where extensive fusion takes place. The most median muscle (transversospinal system) group is deep to the other two groups, the most lateral one (iliocostal system) is very small in the cervical region. They lie parallel on both sides of the spinous process, and if they are well-developed the supraspinous ligament can be regarded as the bottom of the groove between the muscles. All three systems are divided into a lumbar, thoracic, cervical and capital part on the basis of their topographical position and local presence. Unilateral contraction evokes lateroflexion of the spine. The lumbar part of the iliocostalis and longissimus system share the same origin at the iliac crest, and are in this area strongly fused together, and covered with a shiny aponeurosis. The thoracolumbar part of the longissimus is composed of series of overlapping fascicles, that are cranioventrally orientated and span several vertebral segments. The iliocostalis muscle runs from the intermuscular fascia near the iliac crest (hence the name), but also fascicles arise from the transverse processes of the lumbar vertebrae and the ribs to attach to more cranial segments with glistening small tendons on the caudal edges of ribs 1–15 and the transverse process of the last cervical vertebra. In the neck this muscle is weakly developed (Fig. 10.6 (5)). The longissimus system is topographically divided into a lumbar, thoracic, cervical, atlantic (Fig. 10.6 (7)) and capital part (Fig. 10.6 (6)). Its segmental origin is still reflected in the numerous individual attachments of its muscle bundles. The origin is at the ilium and sacrum, which have their insertion on the spinous and transverse processes of the lumbar and thoracic vertebrae. The thoracodorsal part is covered with a fascia. The cervical longissimus muscle is the cranial continuation of the thoracic part. It has a triangular shape and consists of four separate bundles that insert on the transverse processes of the caudal cervical vertebrae. The atlantal longissimus muscle (Fig. 10.6 (7)) extends from the last four cervical and first two thoracic vertebrae to the wing of the atlas. It partly fuses with the cranial part of the omotransversarius muscle. The capital longissimus muscle (Fig. 10.6 (6)) is a separate muscle, located medial to the cervical part and the splenius muscle, originating at the first thoracic vertebrae and extending to the mastoid process of the skull. At the level of the wings of the atlas, it is strongly fused with the splenius muscle. The corresponding dorsal branches of the spinal nerves innervate these muscle parts. The muscle extends the back, is active during the swing phase, and is also responsible for raising the body during rearing and kicking with both the hind limbs. When unilaterally contracted, it flexes the vertebral column laterally or is responsible for rotation of the head.

The transversospinalis system is the most medial and deepest of the neck and back extensors. Separate bundles connect the spinous and transverse processes with subsequent vertebrae in the lumbar, thoracic and cervical regions. Within the transversospinalis system two separate groups of muscles can be distinguished. The first one is located directly over the skeleton occupying the space between the spinous processes, the vertebral arches and the transverse processes, and is named the spinal system. If the muscle bundles extend between the spinal and the transverse processes of adjacent vertebrae they belong to the transversospinal system. It is common to name both systems together as the transversospinalis system. The fiber orientation is caudoventrolateral to craniodorsomedial. The spinalis thoracis and cervicis muscle passes between the spinous processes of adjacent vertebrae; it forms a common muscle belly, which bridges several segments. The muscle is present between the last lumbar vertebra and the third cervical vertebra; its fibers are craniodorsally orientated. The muscle is innervated by the dorsal branches of the topographically corresponding nerves. The semispinalis capitis muscle is a strong muscle that is located in the triangle between the skull, the transverse processes of the cervical vertebrae and the nuchal ligament, and is covered by the longissimus and splenius muscles. It is composed of two parts, dorsomedially the biventer cervicis (Fig. 10.6 (4)) and ventrolaterally the complexus (Fig. 10.6 (8)) muscle. The biventer cervicis has its origin from the cranial thoracic vertebrae and its insertion on the skull. The muscle can be easily recognized because of the connective tissue inscriptions on the muscle belly, which show the multi-segmented origin of the muscle. The semispinalis capitis muscle raises the head when contracted bilaterally and flexes the head and neck to the lateral side when acting unilaterally and is innervated by the dorsal branches of the cervical nerves. The superficial cervical epaxial muscles have been described by Gellman et al. (2002c).

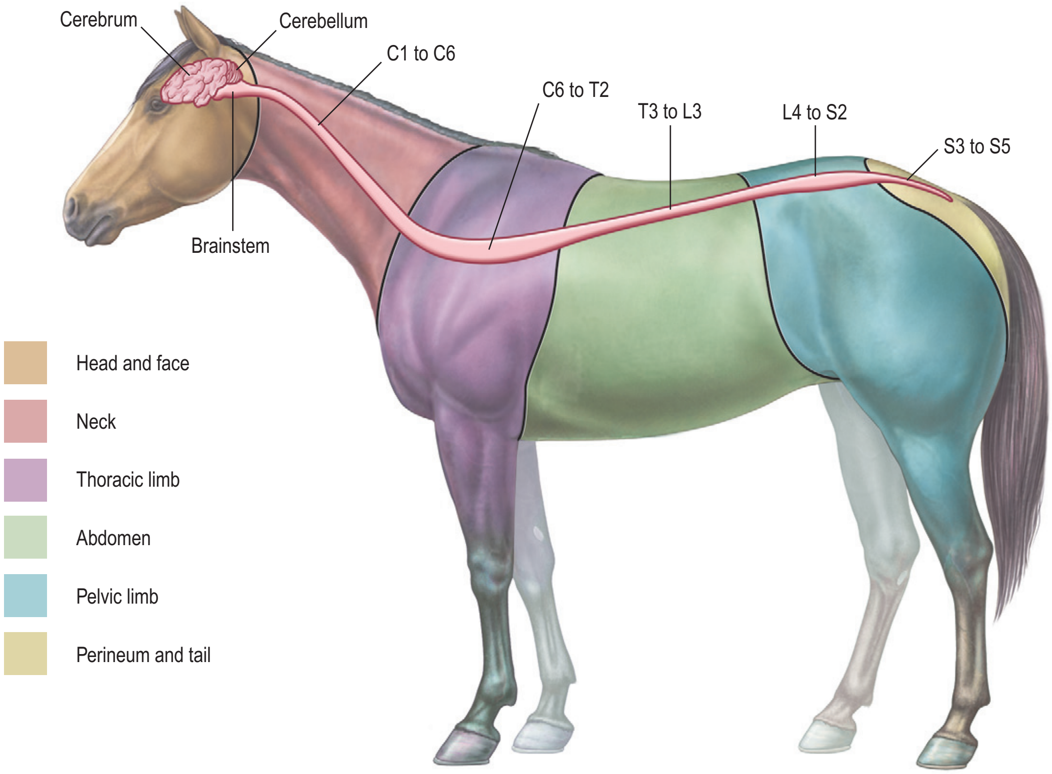

Fig 10.5 A sagittal view with the different functional parts of the neurological system within the vertebral column: face and head, neck (C1–C5), thoracic limb (C6–T2), abdominen (T3–L3), pelvic limb (L4–S2), tail and perineum (S3–S5).

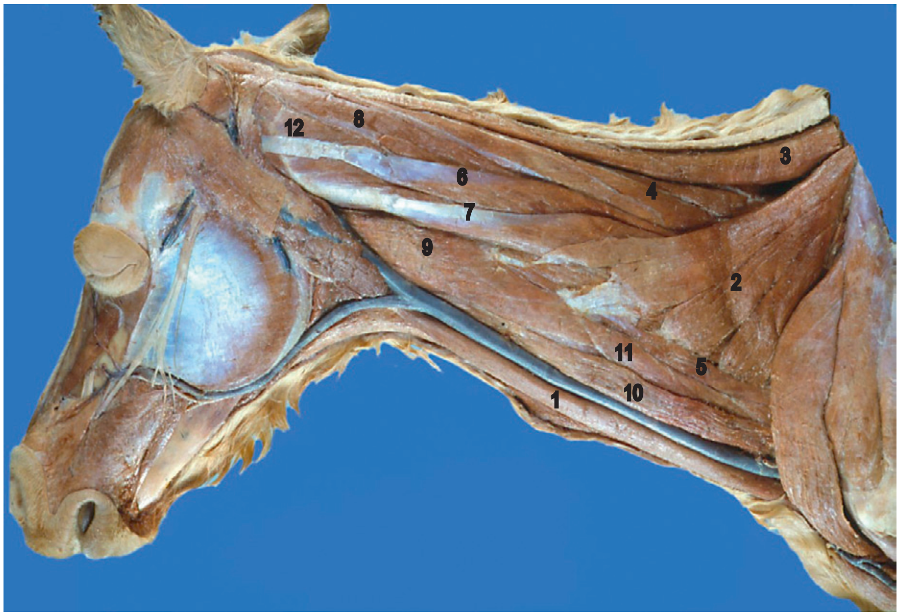

Fig 10.6 A sagittal view to the cervical part of the muscles around the vertebral column: 1, m. sternocephalicus; 2, m. serratus ventralis cervicis; 3, m. rhomboideus cervicis; 4, m. semispinalis capitis, biventer cervicis head; 5, m. iliocostali; 6, m. longissimus, capital part; 7, m. longissimus, atlantal part; 8, m. semispinalis capitis, complexus head; 9, m. longus capitis; 10, m. scalenus, ventral part; 11, m. scalenus, middle part; 12, m. obliquus capitis caudalis.

Recently, the multifidous musculature has been the subject of study in the horse, because it atrophies in people with lower back pain (Stubbs et al., 2011). The muscle is composed of numerous short bundles, which extend from the articular or mamillary processes of the lumbar vertebrae, and from the transverse processes of the thoracic and cervical vertebrae to the spinous processes of the preceding vertebrae. The bundles can span up to five segments in the thoracic region. Cranially it unites with the cranial oblique muscle of the head, caudally with the musculature of the tail. In the neck five bundles are present at each vertebral level that are

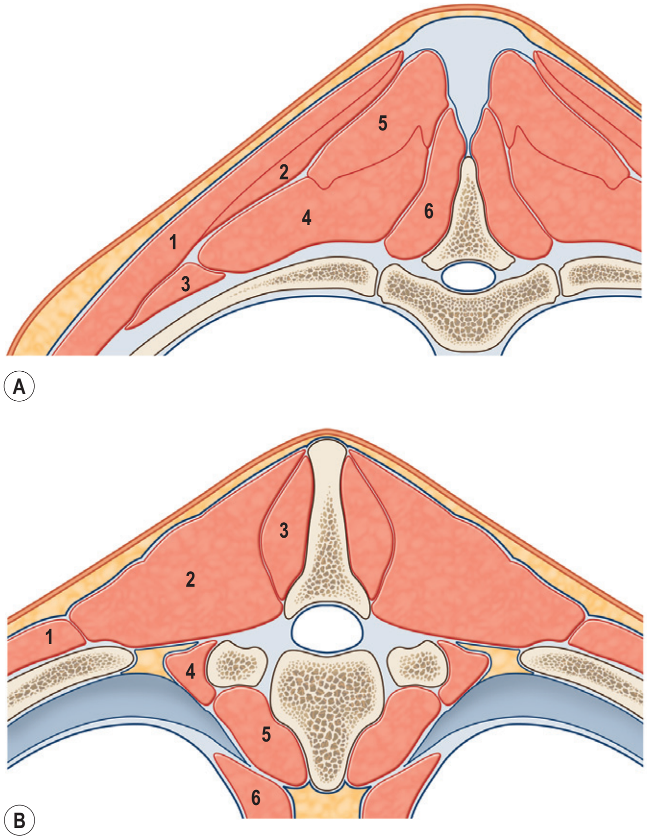

Fig 10.7 A transverse section of (A) the thoracic (1, m. latissimus dorsi; 2, m. rhomboideus thoracis; 3, m. iliocostalis; 4, m. longissimus dorsi; 5, m. spinalis; 6, m. multifidi) and (B) the lumbar part (1, m. iliocostalis; 2, m. longissimus dorsi; 3, m. multifidus; 4, m. psoas major; 5, m. psoas minor; 6, crus of diaphragm) of the muscles around the vertebral column.

innervated by the dorsal branches of the corresponding cervical nerves. The attachment of the hind limb is much more stable, compared to the front limb, to optimize the transmission of the thrust generated by the hind limbs to the back. The hind limb is connected to the pelvis through the hip joint, the pelvis itself is connected with the rigid iliosacral joint to the spine. Extrinsic muscles are responsible for pro- and retraction of the limb: the gluteal muscles (superficial, medial, deep and piriform), the sartorius, the rectus femoris, the biceps femoris, the semitendinosus and the semimembranosus muscles.

The flexed arch of the spine is, for a large part, maintained by the abdominal musculature, especially the rectus abdominis muscle. The hypaxial musculature also stabilizes the vertebral column, the quadratus lumborum muscle, the iliopsoas muscle and the psoas minor muscle.

The quadratus lumborum muscle is a segmented muscle positioned directly ventral to the bodies, the transverse processes and the intervertebral discs from the last thoracic vertebrae to the sacral wings. It serves to stabilize the vertebral column: the ventral branches of the lumbar nerves and the last intercostal nerves innervate it. The psoas major muscle is located lateral to quadratus lumborum, between the bodies and transverse processes of the last two thoracic vertebrae and ribs and the lumbar vertebrae. The iliacus muscle fuses at its insertion with the major psoas muscle to form the iliopsoas muscle. It originates from the medial side of the ilium and is divided in a larger lateral part and a smaller medial part. The common insertion is on the lesser trochanter and can flex the pelvic joint and externally rotate the femur. The muscle is innervated by the ventral branches of the lumbar nerves and the femoral nerve. The psoas minor muscle, which is located between the last two or three thoracic vertebrae, and the first four or five lumbar vertebrae, lies ventrally on the psoas major muscle. Due to its insertion on the ilium it stabilizes the vertebral column and rotates the iliosacral joint. The muscle can be easily recognized from its shiny insertion tendon. It shares its innervation with the quadratus lumborum muscle.

Biomechanics

Several *in vitro* studies have been performed on the biomechanics of the neck and back (Jeffcott & Dalin, 1980; Townsend et al., 1983; Townsend & Leach 1984; Denoix, 1987; Clayton & Townsend, 1989a,b; Sleutjens et al., 2010), but our knowledge of these areas is still incomplete. *In vitro* studies were mainly performed to evaluate the nature and maximal amount of regional or intervertebral movements of flexion and extension, axial rotation and lateral bending (Gellman & Bertram, 2002a,b). With the different protocols used, wide displacements were studied (Denoix, 1999a), but mobility of the vertebral column rarely reaches its maximal limits during locomotion and sporting performance, although back pain due to pressure, tension and/or shearing on vertebral structures (Denoix, 1999b) can alter locomotion of sport and racehorses (Jeffcott et al., 1982; Denoix, 1998; Jeffcott, 1980). These studies on cadavers found that the lumbar part of the spinal column was very rigid, especially with respect to lateroflexion, with increasing mobility in forward direction. The same applied to axial rotation. It should be emphasized, however, that, although this work is of great value as it gives insight into the potential for movement of various parts of the equine spine, it does not represent reality, as there was obviously no influence of any of the active structures.

Of special interest for the biomechanical function of the vertebral column is head and neck movement influence the movement of the back. If the head is lowered, the nuchal ligament will exert a pull on the withers and flex the spinal column. Vice versa, lifting of the head will extend the back (Fig. 10.3). Understanding of this concept is of great importance in the athletic training of sport horses. The question of how the function of the back can best be described dates back to Antiquity. Galenus (130–200 AD) developed the concept of the ‘vaulted roof’ in which the back and the upper part of the rib cage form a roof over the abdominal and thoracic cavities. A collapse of this roof would be prevented by the spinous processes. However, the fact that the spinous processes do not make contact in the normal situation makes this representation improbable. The next concept was developed by Bergmann in 1847 and further elaborated by Zschokke (1892). This concept implies the representation of the back by a bridge that is resting on four piers (the limbs). The upper ledger represents the supraspinal ligament and withstands tensional forces, the lower ledger, the vertebral bodies, is loaded under compression. The smaller girders between both ledgers represent the spinous processes and the ligaments in between these. Although this concept was generally adhered to until World War II, it contains a basic error in that such a bridge will not be loaded by tension dorsally and by compression ventrally, but just the other way round. It was the zoologist Slijper who, in 1946, after a meticulous study of the anatomical form of the vertebrae and especially of the inclination of the spinous processes in various species, came up with the model that is still holding today. His so-called bow-and-string concept not only takes into account the vertebral column and the limbs, but also the sternum and musculature of the ventral abdomen. In this concept the vertebral column is a bow that is held under intrinsic tension by the abdominal wall (Fig. 10.3).

Now the bony vertebral column is loaded under compression and the supraspinal ligament under tension (which is the only force it can resist). Various factors determine the ultimate loading of the system. Contraction of the abdominal musculature, especially of the rectus abdominis muscle, will tense the bow (i.e. flex the back). The same effect will be achieved indirectly by retraction of the forelimbs or protraction of the hind limbs. The fusion of the fibrous sheet of the gluteus medius muscle and the longissimus dorsi muscle as alluded to earlier may be of importance for the latter mechanism. The string will be tensed (i.e. the back extended) by protraction of the forelimbs and retraction of the hind limbs, but also by the considerable weight of the abdominal organs. The latter effect is nicely illustrated by the appearance of many old brood mares with their often very hollow backs. Although often misunderstood, activity of the epaxial musculature will have an extending effect on the back as well, that makes the back hollower. Given the fact that the vast majority of the musculature is located on top of the thoracolumbar vertebral column, contraction of this musculature will automatically lead to extension of the back.

Coordination and locomotion

Considering the complete equine vertebral column, the movements of the neck and trunk and structural and functional description of the behavior of the axial muscles during different gaits and sport exercises has been published previously (Denoix, 1987; Denoix & Pailloux, 1996; Denoix, 1999a,b). At present, few *in vivo* studies have been published. A kinematic method to evaluate back flexibility on standing horses was presented (Licka & Peham, 1998). Neck and back motion and coordination are very different according to the gait and movement that are being performed and there is a need for better knowledge of the nature and amplitude of *in vivo* equine vertebral mobility. Neck and back flexibility and active mobility are essential to the accomplishment of sport exercises and are the subject of constant observation and concern for trainers and riders (Colborne et al., 2001; Cassiat et al., 2004).

The behavior of the osteoarticular components of the equine thoracolumbar vertebral column mainly based on *in vitro* investigations has been performed (Denoix, 1999a). Three major movements take place in the equine intervertebral joints (Jeffcott, 1980; Townsend et al., 1983; Clayton & Townsend, 1989a; Denoix, 1999a):

- Flexion (ventral bending inducing a dorsal convexity) and extension (dorsal bending inducing a ventral convexity) movements, occurring in the median plane, around a transverse axis
- Lateral bending (lateroflexion) to the left and right sides, developed in the horizontal plane, around a dorsoventral axis
- Left or right axial rotation (left or right deviation of a vertebral body with respect to the following one) around a longitudinal axis.

Translational movements of minor amplitude take place in a vertical transverse plane:

- Vertical shearing (dorsoventral translation) is associated with flexion and extension movements
- Transverse shearing (left to right displacement) is associated with lateroflexion and rotation.

Longitudinal compression and tension occur in some parts of the intervertebral joints for every major movement of the vertebral column.

Walk

Kinematic and accelerometric studies of head and trunk movement at walk and trot on treadmills have been performed (Barrey et al., 1994; Buchner et al., 1996). At the walk, the vertical displacement, velocity and acceleration of the head, withers and tuber sacrale showed a sinusoidal pattern with two similar oscillations during each stride. The height of the withers and tuber sacrale was minimal at the beginning of the stance phase and maximal at about mid-stance of both thoracic and pelvic limbs (Buchner et al., 1996). The acceleration signal recorded over the sternum showed also two similar dorsoventral deviations corresponding to each half-stride (Barrey et al., 1994).

A complementary analysis of the walk on a treadmill using three-dimensional accelerometers fixed to the front of a saddle (Galloux et al., 1994) showed that, at the walk, the amplitude of movement was higher in the vertical axis than in the transverse or longitudinal axes; rotation around the transverse axis (pitching motion) was higher than rotation around the longitudinal axis (rolling) and vertical axis (twisting or yaw). Furthermore, the twisting movement was greater in the walk than in the other gaits.

Head movement adaptations associated with a supporting forelimb lameness induced by pressure on the hoof sole resembled those of the trot: the amplitude of the dorsoventral oscillation decreased during the stance phase of the lame limb and increased during the contralateral limb stance phase (Buchner et al., 1996). Similarly, the maximum acceleration amplitude over the sternum was reduced during the stance phase of the lame forelimb (Barrey et al., 1994). For induced hind limb lameness, elevation of the tuber sacrale was slightly reduced during the lame stance phase while head and withers movements were not significantly altered (Buchner et al., 1996).

Surface electromyographic (EMG) activity of neck and trunk muscles was performed while horses walked on a treadmill or on hard surfaces, using skin-mounted surface electrodes (Fig. 10.8).

It was found that the left and right splenius muscles act simultaneously before the landing of each forelimb (or during the second half of the opposite forelimb stance phase) to elevate the head and neck and facilitate forelimb protraction by the elongated brachiocephalicus muscle. The sternocephalicus muscles had reciprocal activity to splenius muscles and act before and during the first half of each forelimb stance phase, the longissimus dorsi muscles act during the intermediate part of each hind limb stance phase to facilitate propulsion (Peham et al., 2001a,b; Licka et al., 2009), and the rectus abdominis muscles do not show any significant EMG activity during the walk (Tokuriki et al., 1997; Robert et al., 1998), and this is correlated to the limited vertical acceleration of the abdominal visceral mass due to the lack of a suspension phase in this gait.

A previous study performed with intramuscular fine-wire electrodes on four horses with and without a rider reported that the

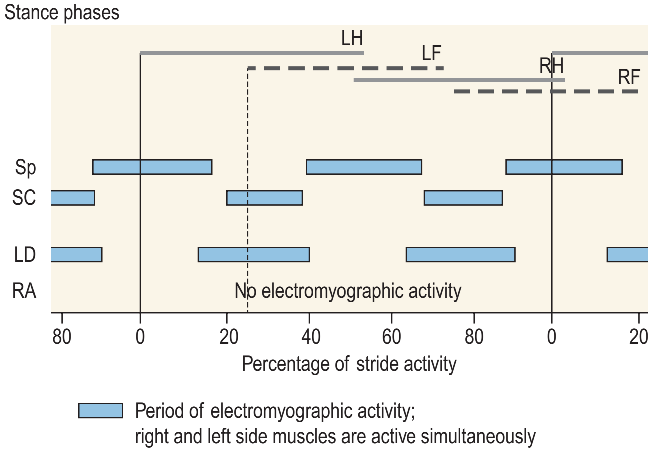

Fig 10.8 Electromyographic activity of neck and trunk muscles at walk (1.8 m/s) on a hard surface. Limbs: LF, left forelimb; RF, right forelimb; LH, left hind limb; RH, right hind limb. Muscles: Sp, splenius; SC, sternocephalicus; LD, longissimus dorsi; RA, rectus abdominis.

Courtesy of Céline Robert, Maison-Alfort, France.

multifidus lumborum muscle was active in the intermediate part of the stance phase of the ipsilateral hind limb and the obliquus externus abdominis muscle had intermittent activity (Tokuriki et al., 1991). On the standing horse, in the neck region, the splenius muscle showed some activity, while the sternocephalicus and brachiocephalicus muscles were silent (Tokuriki & Aoki, 1991). Clinical observation shows that it is probably during walking that the mobility of the thoracolumbar vertebral column is most diversified, with association of rotation and lateroflexion combined with limited movements of flexion and extension.

Trot

Kinematic and electromyographic data of neck and trunk motion and coordination have been established on sound horses with a three-dimensional kinematic analysis system allowing simultaneous recording of the left and right sides of the horse (Audigié et al., 1999; Robert et al., 1998; Pourcelot, 1999). Lame horses have also been investigated using kinematic analysis (Buchner et al., 1996; Audigié et al., 1999).

The vertical displacement versus time of the head, withers and tuber sacrale at trot shows a sinusoidal pattern (Buchner et al., 1996) with two symmetrical oscillations during a stride. The general orientation of the neck and trunk and their alignment vary during the stride (Fig. 10.9). With respect to the tuber sacrale position, the withers elevate during the first and intermediate parts of each diagonal stance phase (upward rotation of the trunk) and descend during the last part of the stance phase as well as during the suspension phase (downward rotation of the trunk). Additionally, the croup presents wider dorsoventral movements (lowering and elevation) than the withers.

In sound trotting horses, the head position is highest in the first half of each diagonal stance phase (Vorstenbosch et al., 1997). During the major part of the stance phase (Fig. 10.9), the neck rotates downward and becomes closer to the horizontal, with the head reaching its lowest point before the end of this phase. During the suspension and beginning of the following stance phase the neck becomes more oblique (Fig. 10.9), and the head is elevated again (upward rotation of the neck).

In early stance both the neck and trunk undergo an upward rotation; during the middle part of the stance phase the angle between the neck and trunk flexes (Fig. 10.9) and during the last part of the stance phase, the neck and trunk rotate downward to become closer to the horizontal. During the suspension phase, extension between the trunk and neck occurs (Fig. 10.9).

A three-dimensional *in vivo* kinematic study of flexion and extension movements of the thoracolumbar spine was performed at the trot in 13 sound horses using five skin markers placed on the median plane of the back over the 6th and 13th thoracic spinal processes as well as at the thoracolumbar, lumbosacral and sacrocaudal junctions (Pourcelot et al., 1998; Audigié et al., 1999). This study showed that maximal thoracic extension occurs near midstance (Fig. 10.10). This passive movement is produced by the visceral mass inertia. The maximal thoracolumbar extension occurs in the second half of each stance phase, followed by the maximal lumbosacral extension at the end of the stance phase (Audigié et al., 1999).

The maximal thoracic flexion takes place during the swing phase and is concomitant with an elevation of the neck (Figs 10.10, 10.11). It is followed by the maximal thoracolumbar flexion. Finally, the maximal flexion of the lumbosacral junction occurs at the end of the swing phase at the time of maximal protraction of the hind limb (Audigié et al., 1999).

The influence of the neck orientation on the thoracic spine dorsoventral mobility has been investigated in cadaver specimens (Denoix, 1987). The results showed that elevation of the neck facilitates thoracic flexion (Fig. 10.11).

An accelerometric device fixed over the sternum area by an elastic girth (Barrey et al., 1994) showed that, for horses trotting on a treadmill, the dorsoventral acceleration curves had a deviation corresponding to each half-stride. The height of the dorsoventral acceleration signal was linearly correlated with speed. Longitudinal accelerations were less repetitive than dorsoventral ones; their magnitude increased with the increasing speed of the gait. Analysis of the trot on a treadmill using three-dimensional accelerometers fixed to the saddle (Galloux et al., 1994) showed that the linear movements along the three axes (longitudinal, transverse and vertical) were similar in amplitude. Rotation around the transverse axis (pitching motion) was smaller in comparison with the other two gaits (walk and canter).

The surface electromyographic activity of neck and trunk muscles at trot has been investigated on hard track surfaces, with or without riders, as well as on a treadmill (Tokuriki & Aoki, 1991; Tokuriki et al., 1991, 1997; Robert et al., 1998, 1999, 2001, 2002; Licka et al., 2004).

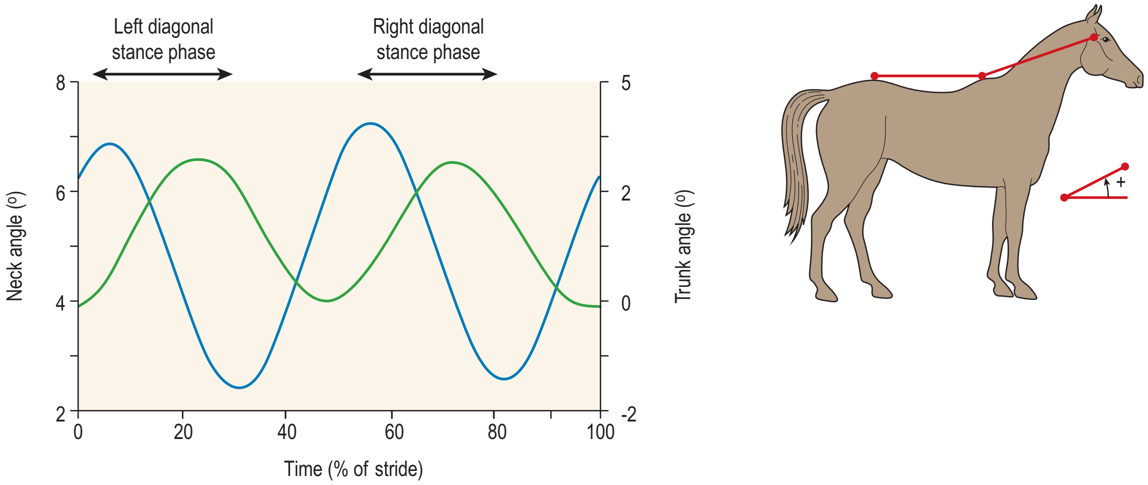

Fig 10.9 Neck and trunk orientation in sound horses guided by hand on hard track at trot (3.1 m/s). Markers are placed over the zygomatic arch, withers (6th thoracic spinal process) and tuber sacrale. The straight line between the first two markers represents the neck orientation; the line between the last two markers represents the trunk orientation. The figure shows the angle variations occurring between these lines and the horizontal plane during one stride. A positive angle indicates an upward angulation of the cranial marker relative to the caudal one as shown in the image on the right. Blue line: neck angle (°) with respect to the horizontal plane; green line: trunk angle (°) with respect to the horizontal plane; diagonal stance phase: full fore hoof–ground contact.

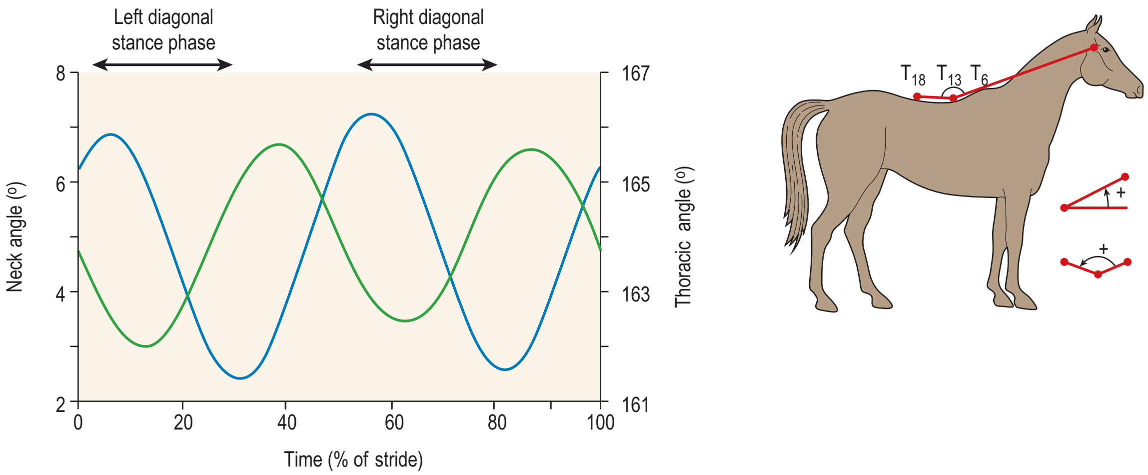

Fig 10.10 Coordination between the neck orientation and thoracic spine dorsoventral movements in sound horses guided by hand on a hard track at trot (3.1 m/s). Markers are placed over the zygomatic arch, withers (6th thoracic spinal process), 13th and 18th thoracic spinal processes. The straight line between the first two markers represents the neck orientation. The thoracic angle is drawn between the last three markers. The figure shows the angle variations occurring between the neck orientation and the horizontal plane as well as the thoracic angle variations during one stride. For the neck, an increasing angle indicates an upward rotation; the thoracic angle increases during flexion of the back and decreases during extension. Blue line: neck angle (°) with respect to the horizontal plane; green line: thoracic angle (°); diagonal stance phase: full fore hoof–ground contact.

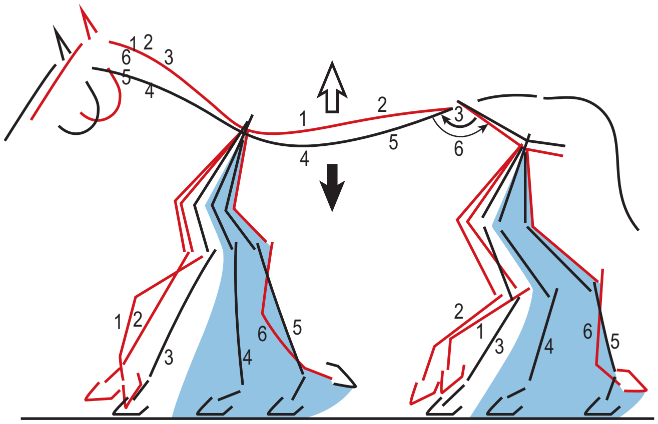

Fig 10.11 Schematic representation of the trunk movements and neck positions during half a stride with reference to the vertebral column dorsoventral peaks of mobility. 1, Maximal thoracic flexion; 2, maximal thoracolumbar flexion; 3, maximal lumbosacral flexion; 4, maximal thoracic extension; 5, maximal thoracolumbar extension; 6, maximal lumbosacral extension. The same numbers indicate the respective positions of the neck and limbs (left diagonal).

Neck muscle activity and neck orientation

Comparison of neck muscle activity and neck orientation demonstrates that the splenius muscle acts before and during the first part of the stance phase of each forelimb (Figs 10.12, 10.13) to limit lowering of the neck (antigravitational activity). As mentioned by Tokuriki and Aoki (1991), muscle activity tends to be higher during the stance phase of the contralateral forelimb than for the ipsilateral one (Fig. 10.12). The sternocephalicus muscles have a reciprocal activity during the suspension phase to control neck elevation (Figs 10.12, 10.13). The brachiocephalicus muscle activity is high during the later part of the ipsilateral forelimb stance phase and during the suspension phase (Fig. 10.13) to achieve protraction of the ipsilateral forelimb; this muscle is inactive during most of the stance phase of the ipsilateral forelimb in order to avoid limiting forelimb propulsion.

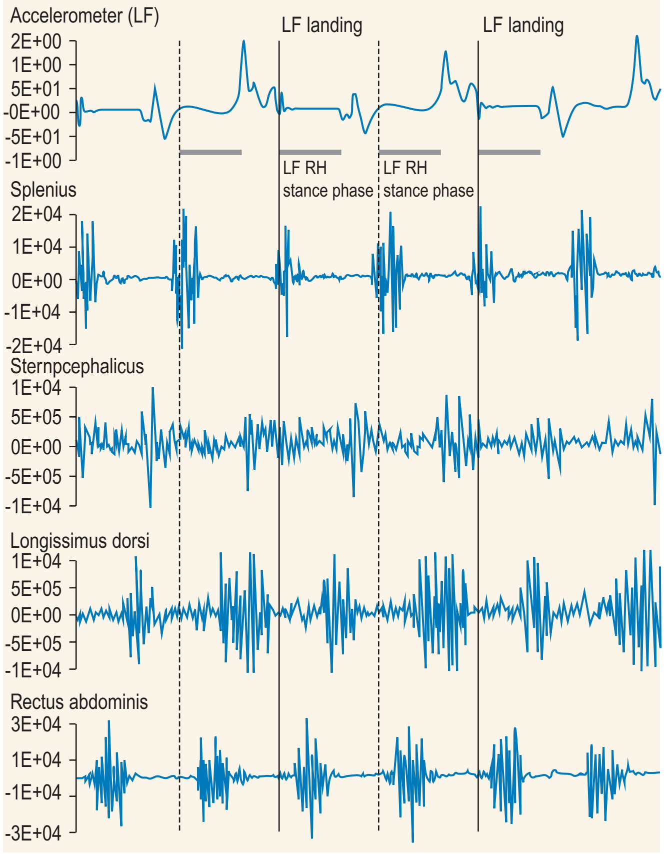

Fig 10.12 Electromyographic activity of two neck and two trunk muscles (left side) at trot on a treadmill (4 m/s) during three consecutive strides. An accelerometer was placed on the left forelimb. LF, left forelimb; RF, right forelimb; LH, left hind limb; RH, right hind limb.

Courtesy of Céline Robert, Maisons-Alfort, France.

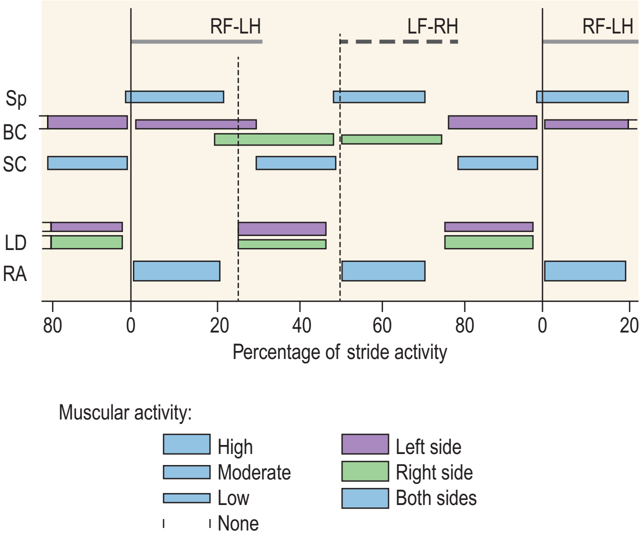

Fig 10.13 Electromyographic activity of neck and trunk muscles at trot (4 m/s) on a treadmill (mean periods for five horses). Limbs: LF, left forelimb; RF, right forelimb; LH, left hind limb; RH, right hind limb. Muscles: Sp, splenius; BC, brachiocephalicus; SC, sternocephalicus; LD, longissimus dorsi; RA, rectus abdominis.

Courtesy of Céline Robert, Maisons-Alfort, France.

Effect of neck orientation on neck muscle activity

Lowering of the neck using the reins induces a reduction of splenius muscle activity during the first half of the stance phase of each diagonal (Fig. 10.14). These data can be explained by the lower amplitude of the neck displacement as well as by increased tension in passive anatomical structures that support the head and neck, such as the nuchal ligament.

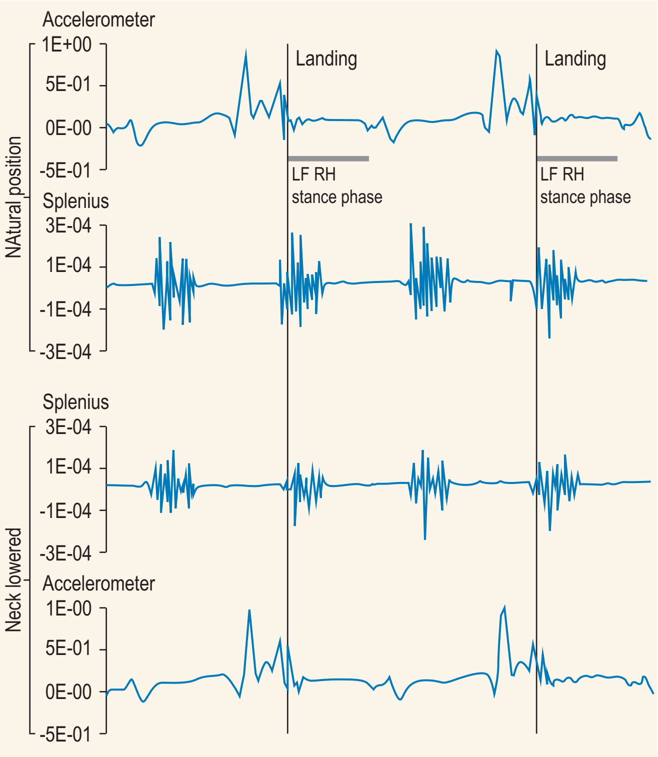

Fig 10.14 Influence of the neck position on the electromyographic activity of the left splenius at trot (4 m/s) with reference to the left front limb.

Courtesy of Céline Robert, Maisons-Alfort, France.

Trunk muscle activity and thoracolumbar movements

Comparison of trunk muscle activity and thoracolumbar movements shows that the rectus abdominis muscle acts during the stance phase (Figs 10.12, 10.13) to limit the passive thoracolumbar extension induced by the visceral mass acceleration. The longissimus dorsi muscles act at the end of each stance phase and during the suspension phase (Figs 10.12, 10.13) to induce lumbosacral extension and facilitate hind limb propulsion as well as to stabilize the thoracolumbar spine as it flexes.

A previous study (Tokuriki et al., 1991) showed that the multifidus lumborum and longissimus lumborum were active before and after lift-off of each hind limb, with the activity being higher for the ipsilateral hind limb. According to this study the obliquus externus abdominis and rectus abdominis had roughly reciprocal activity to these epiaxial muscles. In another study (Tokuriki et al., 1997), the longissimus lumborum was thought to play a role in limiting lateral bending of the trunk during symmetrical gaits.

Dorsoventral movements of flexion and extension have been quantified in sound horses (Audigié et al., 1999; Pourcelot et al., 1998). The maximal range of vertical displacements occurred near the 13th thoracic vertebra and, with respect to the tuber sacrale, reached an average value of 1.5 ± 0.2 cm. In clinical cases with intervertebral osteoarthrosis a significant reduction of this range of motion was observed (Audigié et al., 1999).

Canter

Kinematic analysis was performed in nine high-level vaulting horses cantering at 4–5 m/s on a circle. As no markers could be placed on the back, markers indicative of neck and trunk movements were placed over the zygomatic arch, shoulder joint and tuber coxae (Fig. 10.15). The head and neck were positioned with side reins and the horses were filmed under competitive conditions at a left lead canter from outside of the circle. The neck and trunk angle curves showed that the cranial part of the neck and trunk becomes lower during the intermediate part of the support phase (downward rotation) and elevates (upward rotation) during the leading forelimb stance phase and the suspension phase (Fig. 10.15). The orientation changes of the neck angle occur before those of the trunk. An analysis of the canter using three-dimensional accelerometers fixed to the saddle (Galloux et al., 1994) showed higher amplitudes of motion than for the other gaits (walk and trot), especially along the longitudinal and vertical axes. Rotation around the transverse axis (pitching motion) and around the longitudinal axis (rolling) were greater than in the other gaits, while twisting around the vertical axis was lower. EMG activity of trunk and neck muscles was recorded with surface electrodes at the canter (Figs 10.16, 10.17). Recording of neck muscle activity showed that the splenius muscles were active once in the stride cycle, during the trailing diagonal stance phase (Fig. 10.16). These muscles limit neck lowering and cause the neck to extend during the leading forelimb stance phase and the suspension phase. The sternocephalicus muscles had a reciprocal activity and were active from the end of the leading forelimb stance phase to the first part of the trailing hind limb stance phase (Fig. 10.16). The brachiocephalicus muscle moving the trailing forelimb was mainly active during the stance phase of the leading forelimb. The brachiocephalicus muscle on the side of the leading forelimb was mainly active during the suspension phase. This left to right dissociation is correlated to the asymmetry of the gait and to the respective chronology of each forelimb protraction.

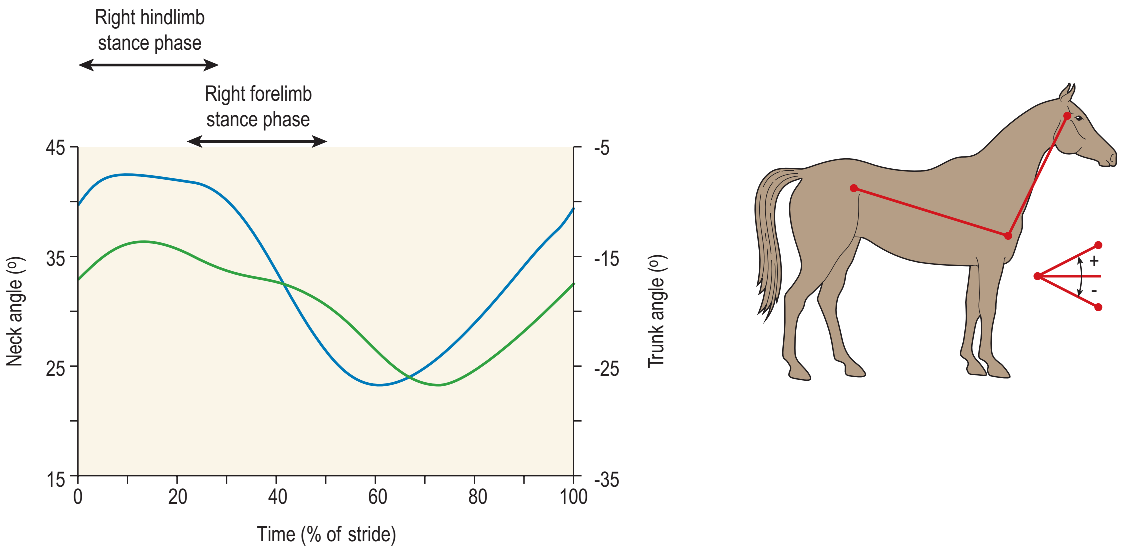

Fig 10.15 Neck and trunk orientation in a sound horse being lunged with side reins at left lead canter (4.5 m/s) on soft ground (sand) in competitive conditions (vaulting gymnastics). Markers are placed over the zygomatic arch, point of shoulder and tuber coxae. The straight line between the first two markers represents the neck orientation; the line between the last two markers represents the trunk orientation. The figure shows the angle variations occurring between these lines and the horizontal plane during one stride. An increasing angle indicates an upward rotation; a decreasing angle indicates a downward rotation (blue line). Neck angle (°) with respect to the horizontal plane; (green line) trunk angle (°) with respect to the horizontal plane.

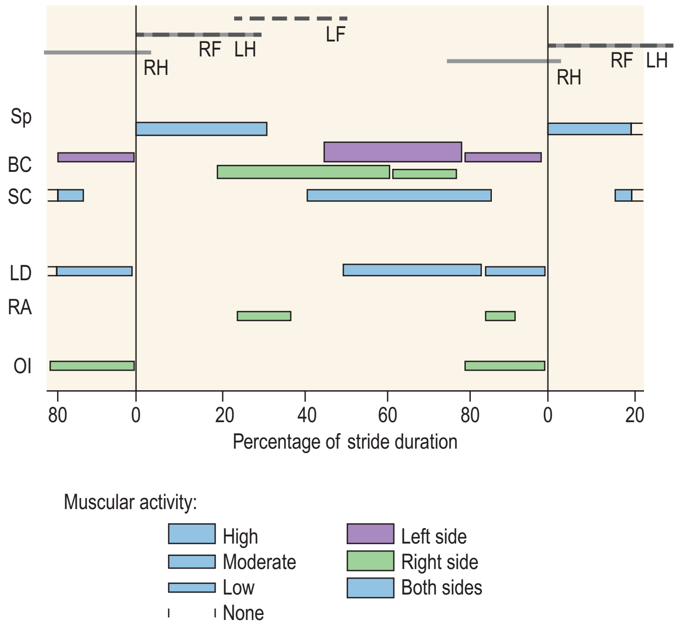

Fig 10.16 Electromyographic activity of neck and trunk muscles at ridden left lead canter (6 m/s) on hard ground (mean values on three horses). Limbs: LF, left forelimb; RF, right forelimb; LH, left hind limb; RH, right hind limb. Muscles: Sp, splenius; BC, brachiocephalicus; SC, sternocephalicus; LD, longissimus dorsi; RA, rectus abdominis; OI, obliquus internus abdominis.

Courtesy of Céline Robert, Maisons-Alfort, France.

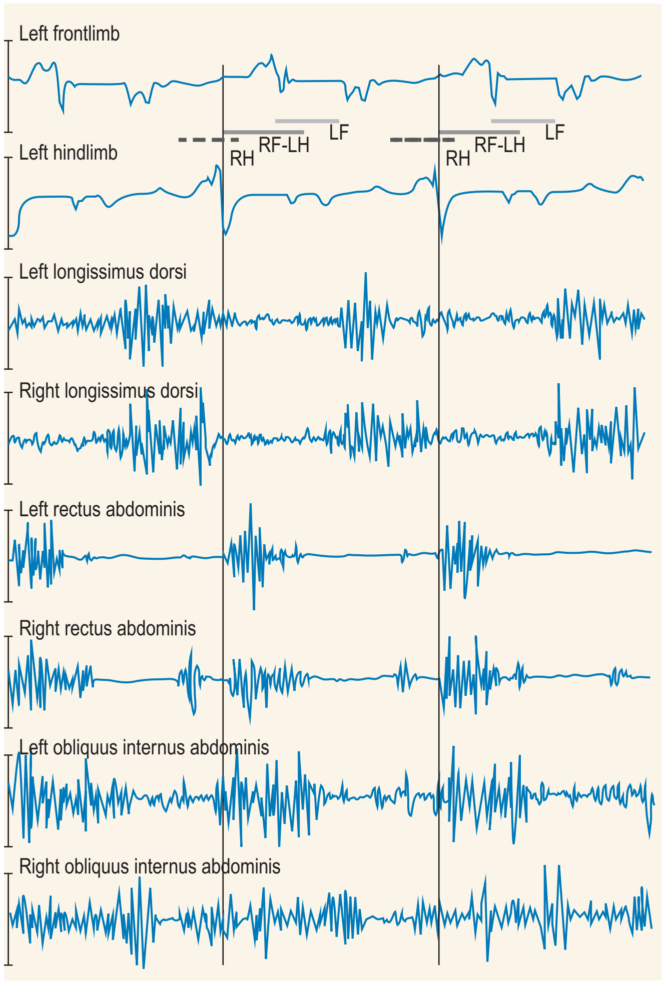

Fig 10.17 Hoof accelerometer signals and electromyographic activity of trunk muscles at ridden left lead canter (6 m/s) for three consecutive strides. LF, left forelimb; RF, right forelimb; LH, left hind limb; RH, right hind limb.

The longissimus dorsi muscles were active once per stride at the end of the leading forelimb stance phase, during the suspension phase and during the trailing hind limb stance phase (Figs 10.16, 10.17). The function of these muscles was to prepare the landing of both hind limbs and to extend the trunk before forelimb landing. The rectus abdominis muscles had reciprocal activity during the support phase of the diagonal limbs; they act to support the visceral mass and to initiate thoracolumbar flexion during the leading forelimb stance phase (Fig. 10.18) and the suspension phase. Bursts of activity were observed simultaneously in the longissimus and rectus abdominis muscles on the side opposite to the leading forelimb during the stance phase of the trailing hind limb.

The obliquus internus abdominis muscle corresponding to the leading forelimb was active during most of the intermediate part of the support phase (Figs 10.16, 10.17), contributing to visceral support and trunk lateroflexion. The opposite obliquus internus abdominis muscle had a burst of activity at the end of the support phase and beginning of the swing phase.

During the canter, the use of intramuscular wire electrodes has shown that the multifidus lumborum and longissimus lumborum are active during the swing phase of the trailing hind limb. The rectus abdominis and obliquus externus abdominis have reciprocal activity (Tokuriki et al., 1991).

Walk vs trot vs canter

The horses worked at a walk, trot and canter on a treadmill and movement of the back and limbs was measured with a complex series of high-speed cameras. The studies have demonstrated far less movement of the back at trot than in the other two gaits. At the walk, the range of motion for flexion–extension is fairly constant for vertebrae behind T10 (approximately 7°), lateral bending is greatest in the more cranial thoracic vertebrae and in the pelvic segments (values >5.6°), but less in the lumbar region between T17 and L5 (<4°). Axial rotation increases gradually from 4° at T6 to 13° at the tuber coxae. At the trot the range of flexion–extension for all vertebrae does not exceed 2.8–4.9°, lateral bending is even less (1.9–3.6°). Axial rotation at this gait is in the order of 3°. At the canter flexion–extension movement is substantially larger (maximal range 15.8 ± 1.3°). Lateral bending is maximally 5.2 ± 0.7° and axial rotation 7.8 ± 1.2°. An important relationship was demonstrated on the movement of the lumbar back and pelvis. Functionally, this part of the back essentially rotates (twists) as a single unit is readily observed when the walk is viewed from behind. Subsequently, there is transition from the lumbar back to the thoracic back that leads to a progressive (smoother) rotation of the chest vertebrae. During diagonal support phases (e.g. left forelimb, right hind limb) in the trot and canter, the forelimb pushes the chest vertebrae in one direction while the hind limb rotates the pelvis and lumbar back in the opposite direction. This twisting occurs at about the same time as the maximal extension of the back. The strings of the back (abdominal muscles) restrain these movements. The above-mentioned movements of the back were found to be very symmetrical. The relationship between the movement of the limbs to the movement of the back is paramount to the symmetrical bending of the back. The shape of the movement partly depends on the gait. Flexion–extension movement has a double sinusoidal motion pattern at the walk and trot, but a single sinusoidal pattern at the canter. Lateroflexion has the form of a single peak and trough at all gaits, as has axial rotation. This has to do with the symmetry of the gait and the effect of hind limb placement on spinal kinematics.

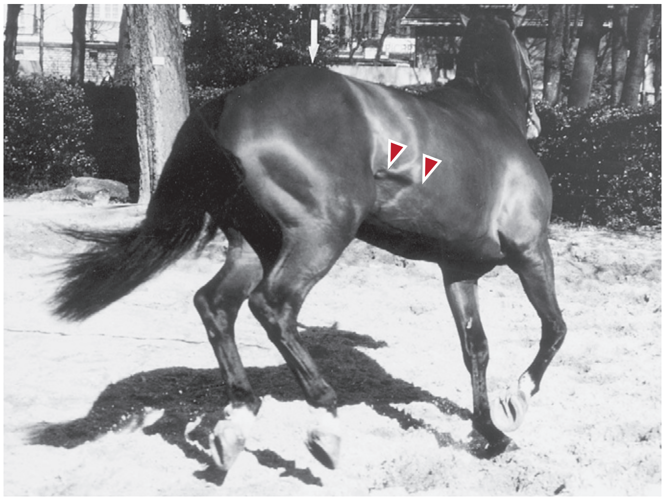

Fig 10.18 Leading forelimb stance phase during left lead canter while lunging on a circle. See the rectus abdominis contraction (red arrowheads) inducing lumbosacral flexion (white arrow).

Variability within the same horse is limited for flexion–extension and axial rotation (6–8%), but considerably more for lateroflexion (8–18%). The variability between horses is larger, as could be expected, and the same applies here: lateroflexion may vary as much as 16–25% between individual horses, which is considerably more than the variation in the rotation around the other two axes (10–16%).

Neck dysfunction

Since the publication of Ricardi and Dyson (1993) there has been a growing interest in the head and neck region as a potential source of pathological locomotor disturbances and the availability of EMG (Giovagnoli et al., 1998; Tokuriki et al., 1999; Van Wessum et al., 1999; Wijnberg et al., 2004) and MEP techniques (Nollet et al., 2003a,b, 2004) has proven to be a great asset in investigating this region. These studies proved that a neuropathy in combination with myelopathy and facet joint arthrosis can, like in humans, also result in neck pain, clinical signs of incoordination or front leg lameness, stringhalt and disability in horses (Schnebel et al., 1989; Moore et al., 1992; Dunbar et al., 2008; Levine et al., 2008). Moreover, different head and neck positions (HNP) have become under debate in the equine community, especially in the disciplines of dressage and show jumping, as they might have an effect on normal, physiological function too (Jeffcott et al., 2006; McGreevy et al., 2010; Sleutjens et al., 2012; Wijnberg et al., 2010).

The general aim of training the equine athlete is to achieve a well-balanced horse in harmony with its rider that is able to show its individual gait qualities (Weishaupt et al., 2006; Heuschmann, 2007). The head and neck position is believed to be an important aid in achieving this goal, as it influences fore and hind limb kinetics and kinematics, as well as thoracolumbar movement (Denoix & Audigie, 2001; Rhodin et al., 2005; Gómez-Alvarez et al., 2006; Weishaupt et al., 2006; Rhodin et al., 2009; Waldern et al., 2009).

The use of specific head and neck positions in training is not uncontested. The recent discussion in the international dressage world focuses on the extremely flexed head and neck position 'hyperflexion' or 'Rollkur', or 'low, deep and round' (Jeffcott et al., 2006; Heuschmann, 2007; Van Bostel et al., 2009; Wijnberg et al., 2010), which is believed by some trainers to be a useful tool to improve the gymnastic ability that is asked from today's high performance dressage horses and is rejected by others on the basis of presumed negative effects on equine welfare (McGreevy et al., 2010).

Some recent studies on locomotion demonstrated that, although a flexed head and neck position induced an increase in range of motion in the lumbar back in the unridden horse and would imply a more animated use of the hind limbs, a longer stride length at walk and a more equal weight distribution between fore and hind limbs (Gómez-Alvarez et al., 2006), this effect could not be reproduced while horses were ridden (Rhodin et al., 2009). An extremely elevated neck, however, caused an increase in extension of the thoracic and lumbar back in the unridden as well as in the ridden horse (Gómez-Alvarez et al., 2006; Rhodin et al., 2009). Furthermore, an extremely elevated neck was shown to affect the functionality of the locomotor apparatus much more than an extremely low neck by an increase in peak vertical force in the forelimbs, which is, among other factors, a potential risk factor for the development of injuries (Biau et al., 2002; Weishaupt et al., 2006; Waldern et al., 2009).

Dysfunction of the vertebral column can originate from pathology of bone, cartilage, joints, ligaments, tendons, muscles or nerves and therefore the clinical signs can be rather diverse. Several clinical signs can occur and vary from lameness, to less specific signs such as paresis, muscle atrophy, decreased range of motion, expressions of pain such as resistance to perform or to position (Sleutjens et al., 2012). Pathology in the nervous system can also result in clinical signs of upper motor neuron disease such as dysmetria, hypermetria, hypometria and deficits in proprioception. A thorough and detailed lameness exam and neurological exam are necessary to localize the area of interest that can be subjected to additional diagnostic methods such as local blocks, radiology, ultrasound, scintigraphy and last, but not least, EMG needle examination. A study using fone-wire EMG to localize a problem (Wijnberg et al., 2004) showed that lesions in the segment L3–S3 were overdiagnosed and lesions in the C1–T2 region were underdiagnosed without (semi) quantitative EMG examination and Motor Unit Action Potential (MUP) Analysis. In addition, this study showed that if generalized muscle atrophy was present, it was more often associated with a generalized neuropathy than a myopathy. If the problem was defined as lameness of unknown origin, most often the diagnosis was a neurogenic problem in the segment of C1-T2. Remarkably signs of hypermetria or the hind limb or hind limbs appeared to be the result of a cervical lesion rather than a pelvic lesion.

Quantitative analysis of motor units recorded with needle EMG allows detection of a disturbance of the functionality of the neuromuscular system and appeared to be able to diagnose myopathy or neuropathy in an early stage of the disease (Wijnberg et al., 2000, 2003a,b). The absence of raised activity of muscle enzymes appeared not to exclude myopathies, and is explained by the fact that not all myopathies will coincide with leakage of muscle enzymes, at that time point or indeed at any time. This makes this technique interesting since in contrast to diagnostic imaging techniques it provides information about the functionality of the region examined (Wijnberg et al., 2004). Since normative values have recently become available on two paraspinal neck muscles, this technique can contribute further insights into neck pathology and its relevance (Wijnberg et al., 2002, 2011).

Effect of different head and neck positions on physiology and performance during exercise

A range of positions of the head and neck (HNP) have been evaluated and reported during exercise (Gómez-Alvarez et al., 2006; Sloet et al., 2006; Van Breda, 2006; Weishaupt et al., 2006; Rhodin et al., 2009; Waldern et al., 2009; Wijnberg et al., 2010). However, these studies contain some subjective elements and neck positions that have not yet been fully objectively quantified. Furthermore, little is known about the biomechanical consequences of these head and neck positions on the loading of the cervical vertebrae.

Therefore, a study designed in order to test whether five *in vivo* head and neck positions commonly used during training and competition in sport horses, could be objectively quantified in the sagittal plane from straightforward angles and distances using a home-video camera and standard anatomical landmarks (Elgersma et al., 2010). The second objective was to test whether the loading on the cervical vertebrae could be calculated from an anatomical model, developed from measured cervical vertebral dimensions, calculated centers of rotations, determined intervertebral angle limitations, and earlier reported nuchal ligament properties, and subsequently whether the model could be used to estimate the relative differences in loading between the objectively quantified HNPs (Sleutjens et al., 2010).

Goals were to determine the effect of dorsoventral flexion and extension on intervertebral foramina dimensions in the equine cervical spine (Sleutjens et al., 2010, 2012), to evaluate the effect of different HNPs on single fiber (SF) and quantitative electromyographic (EMG) examination directly after moderate exercise (Wijnberg et al., 2010), to evaluate the effect of different head and neck positions on intrathoracic airway resistance and corresponding arterial blood gas values during a regular training exercise (Sleutjens et al., 2009) and to investigate the effect of head and neck position (HNP) on behavior and cortisol levels in blood and salivar in Warmblood riding horses (Dierendonck et al., 2010). This study used 7 healthy, base-level trained Dutch Warmblood riding horses (sex: five mares, two geldings, age: 10.3 ± 3.6 years (mean ± SD), height at the withers: 161.2 ± 1.4 cm, weight: 531 ± 47.3 kg), with no history of respiratory disease, cardiovascular disease, musculoskeletal or neuromuscular disorders. Radiographic and ultrasound examination of their spinal column showed no abnormalities.

Videos were taken at the walk on a straight line in five different head and neck positions, which were accomplished using side rains (Fig. 10.19). The five head and neck positions, of which HNP1, HNP2, HNP4, and HNP5 were identical to those used in an earlier experiment (Weishaupt et al., 2006; Gomez Álvarez et al., 2006; Rhodin et al., 2009; Waldern et al., 2009), were defined as follows (Fig. 10.20):

- HNP1: Free, unrestrained, neutral position.
- HNP2: Neck raised; bridge of the nose around the vertical.

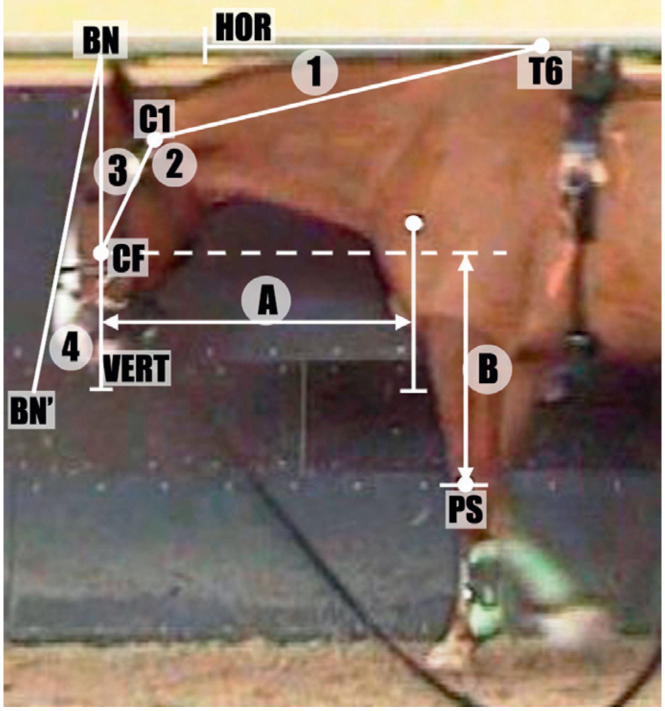

Fig 10.19 From the captured video-frame at LF midstance, the coordinates of the reflective markers were defined, from which the five head and neck positions (HNPs) were objectively defined using the angles between C1–T6-Hor ('angle no. 1'), CF-C1–T6 ('angle no. 2'), C1–CF-Vert ('angle no. 3'), BN'–BN-Vert ('angle no. 4') and the horizontal distance between CF and TS ('distance A') and the vertical distance between CF and PS ('distance B').

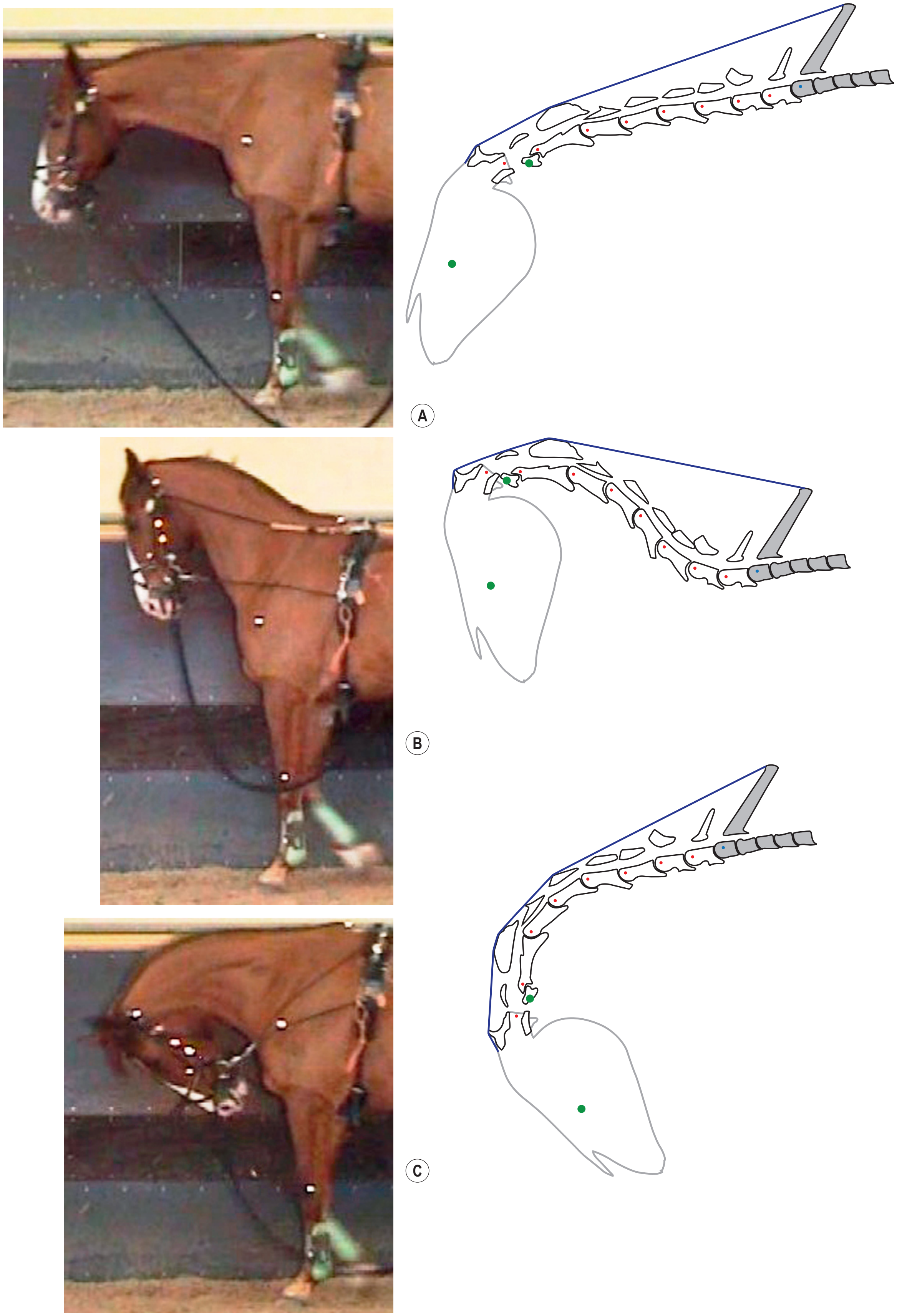

Fig 10.20 Different HNPs evaluated in this study shown at the moment of LF midstance in an anatomical simulation model.

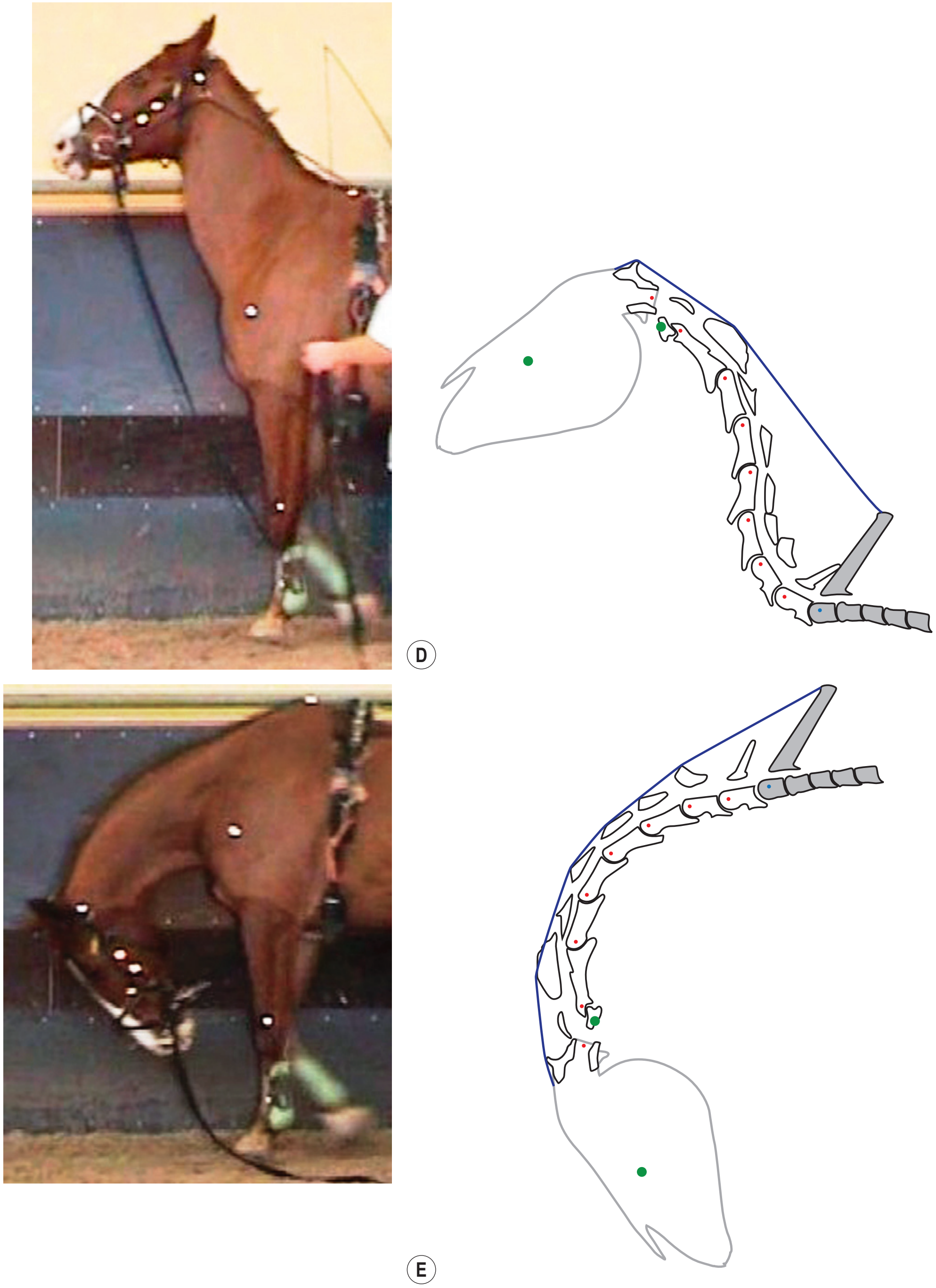

Fig 10.20 *Continued*

- HNP4: Neck lowered and considerably flexed; nose pointing toward the chest.
- HNP5: Neck raised and considerably extended; bridge of the nose in front of the vertical.
- HNP7: Neck lowered and flexed; nose pointing towards the carpus.

In addition, they were evaluated by an international dressage team to check for realistic and correct interpretation, and thus considered as being currently representative and commonly used in training and competition. HNP7 was included because two interpretations of the hyperflexion, 'Rollkur' or 'low, deep and round' training position were found to exist among riders (HNP4 and HNP7). To accustom the horses to the experimental set-up, they were trained in the different head and neck positions on the lunge for at least 3 weeks.

Spherical reflective markers were glued to the skin over the dorsal spinous process of Th6, the wing of the atlas (C1), the rostral part of the facial crest (CF), the suprascapular tubercle (TS) and the lateral styloid process of the radius (PS). Two additional markers were placed on the horse's bridle, while the bridge of the nose (BN, BN') could be identified in every video frame. The known distance between these two bridle markers was used as a calibration reference for the video-frame analysis. A home-video camera was set on the line A-C perpendicular to the long side of the riding arena, where the horses were evaluated.

Video analysis was done using custom software program to determine the marker coordinates. Head and neck positions were described using four angles and two distances. For each HNP the following angles and distances were measured (Fig. 10.19):

- (C1–T6-Hor): the angle between the wing of the atlas (C1), the dorsal spinous process (T6) with the horizontal: angle no. 1. This angle has a negative value when the atlas is lower than T6.
- (CF-C1–T6): the angle between the rostral part of the facial crest (CF), the wing of the atlas (C1) and the dorsal spinous process of (T6): angle no. 2.
- (C1–CF-Vert): the angle between the wing of atlas (C1), the rostral part of the facial crest (CF) with the vertical: angle no. 3. This angle is negative when the facial crest is caudal to the atlas.
- (BN′–BN-Vert): bridge of nose with the vertical: angle no. 4. This angle is negative value when the bridge of the nose is behind the vertical.
- (CF–TS): the horizontal distance between the rostral part of the facial crest (CF) and the supraglenoid tubercle (TS): distance A.
- (CF–PS): the vertical distance between the rostral part of the facial crest (CF) and the lateral styloid process (PS): distance B. For each HNP, 5 video captures were taken per horse on the left and right sides with the camera perpendicular to the line of motion. Measurements were made with the left front limb (LF) at midstance with the left metacarpal bone vertical (Figs 10.19, 10.20). The four angles (angle no. 1, 2, 3 and 4) and the two distances (A and B) were measured and the mean and the SEM of the group of seven horses were calculated.

For every HNP digital L/M radiographs were made of the cervical vertebrae C2–C7 of one horse (horse no. 1), while it was standing square with the head and neck in the sagittal plane to determine the *in vivo* longitudinal angles between the cervical vertebrae (C2–C7). Cervical angles were given a negative value when the body of the cranial vertebra sloped in regards to the body of its successive caudal vertebra.

From an additional Warmblood horse (horse no. 8), which was euthanized for other reasons than musculoskeletal or neuromuscular disorders, the *ex vivo* longitudinal angles between the cervical vertebrae (C2–C7) were measured in five different positions (neutral, extension 20° and 40°, flexion 20° and 40°), which according to Sleutjens et al. (2009) represents respectively the *in vivo* HNP angles: HNP 1, HNP 2 and 5, and HNP 4 and 7.

The (*ex vivo*) CT images (horse no. 8) were overlaid on the (*in vivo*) digital radiographical images (horse no. 1) using imaging processing software to facilitate accurate and representative cervical intervertebral angle measurements to feed the model. All data were transferred into commercially available modeling software. The model was based on the inertial properties data of Buchner et al. (1997), Gelmann et al. (2002) and Gelmann and Bertram (2002a,b).

The first step in building the model was to measure the cervical vertebral dimensions from the *ex vivo* specimen (horse no. 8). For this, digital images were produced of the vertebrae C1–Th2 using a CT scan (Sleutjens et al., 2009) and a rectangle was projected over the vertebral body with the cranial head and the caudal tail as longitudinal, sagittal reference length. Thus, using free available software the dimensions of the vertebrae were determined. The following values were found: C1, 4.4 cm; C2, 13.4 cm; C3, 11.0 cm; C4, 11.1 cm; C5, 10.6 cm; C6, 9.8 cm; C7, 8.3 cm; T1, 5.9 cm; T2, 5.9 cm; T3, 5.6 cm; T4, 5.3 cm; T5, 5.1 cm; T6, 5.1 cm. Cervical CT images of six cadaver equine cervical spines were taken in the neutral position, extension (20° and 40°) and flexion (20° and 40°). Images were reconstructed in the oblique plane perpendicular to the long axis of each intervertebral foramen from the C2/C3 to C7/T1 level. Foramina height and length were measured in each position and compared to the neutral position (Sleutjens et al., 2010).

The horses were acclimatized to the experimental neck positions during a training period of at least 3 weeks, until they accepted the induced neck positions. Acceptance was defined as walking in the required position with no pressure on the bit. A standardized exercise test was performed namely: trot$_1$ for 10 min at a heart rate (HR) of 101 ± 8 bpm, canter for 4 min at a HR of 128 ±10 bpm, trot$_2$ for 5 min at a HR of 104 ± 7 bpm and walk for 5 min at a HR of 73 ± 8 bpm.

Mean consecutive difference (MCD) of single fiber potentials and motor unit action potential (MUP) variables (amplitude, duration, area, turns and phases) were recorded in each position directly after exercise at rest in a fixed HNP using commercial EMG equipment. Muscle enzyme activity was measured before and 4, 6 and 24 h after exercise (Wijnberg et al., 2010).

Intrathoracic pressure was indirectly measured during exercise using a portable intra-oesophageal pressure (Pes) measuring device. Arterial blood samples were taken immediately after every test interval from a catheter placed into the transverse facial artery. Arterial oxygen pressure (PartO_2), oxygen saturation (SartO_2) and carbon dioxide pressure (PartCO_2) values were corrected for core temperature (Sleutjens et al., 2009). Continuous telemetric ECG recordings were made using the Televet system in order to determine or exclude cardiac arrhythmias that potentially could occur as a result of hypoxia.

The horses performed an exercise test in each (HNP), which consisted of warming-up at trot (15 min), canter (4 min), trot$_2$ (10 min), walk (5 min) and cooling down. External influences were prevented and the horses were videoed. Afterwards, predefined behavioral elements were scored by the same person in The Observer® program. Blood and salivary samples were collected at 8.00 am, prior to and directly at the end of the exercise test, 30 and 60 min after the exercise test and at 8.00 pm, in order to determine basal cortisol levels and the effect of exercise in the different HNPs. Several behavioral expressions were recorded such as:

- Head toss: The horse attempts to move or moves the head in a quick forward-upward motion.
- Head shake: The horse attempts to shake or shakes its head in a quick left to right motion.
- Head pull: The horse lets its head hang in the reins and pulls the reins forward.
- Shying: The horse shies away from an object or side of the arena.
- Blowing: Non-pulsated sound produced by forceful expulsion of air through the nostrils.
- Snorting: Sound of forceful exhalation through the nostrils with an audible flutter pulsation, while the horse attempts to lower the head (Dierendonck et al., 2010).

Elgersma et al. (2010) showed that mean angles were significantly different between the 5 HNPs for C1–T6 with the horizontal ((C1–Th6-Hor): angle no. 1) and for CF–C1 ((C1–CF-Vert): angle no. 3) and bridge nose ((BN′–BN-Vert): angle 4) with the vertical ($p < 0.05$). For angle 2 ((CF-C1–Th6)) all HNP, except for HNP2 and 4, were significantly different ($p < 0.05$). The horizontal distance from CF to TS (distance A) was different only between HNP1 and all others, while the vertical distance from CF to PS (distance B) was significantly different between all 5 HNPs ($p < 0.05$).

Sleutjens et al. (2010) showed that an extension of 20° causes a decrease in intervertebral foramina dimensions at segment C5/C6–C7/T1. A decrease in intervertebral foramina dimensions is caused by 40° extension at segment C4/C5–C7/T1. Flexion causes no significant change in foramina dimensions, except for the length at segment C6/C7 at 20° flexion.

Wijnberg et al (2010) showed that mean MCD in all HNPs were significantly higher than in HNP1 ($p < 0.05$) of which HNP4 was highest ($p < 0.05$) with 39 compared to 30 in HNP2. HNP5 and 7 with 25 MCD were lower than the MCD in HNP 2 and 4 ($p < 0.05$). Odds ratio for potential pathological MCD and conduction block was 13 : 6 in HNP4 compared to HNP1 ($p < 0.05$), but there are no reference values for horse patients yet. Number of turns and duration followed the same pattern as MCD indicating temporal dispersion of the MUP and a non-synchroneous arrival of the individual muscle fiber action potentials that contribute to the MUP. Only LDH activity increased at all time points in HNP4 at time points 4 ($p < 0.05$), 6 ($p < 0.05$) and 24 ($p < 0.05$) and in HNP5 and HNP7 at 4 ($p < 0.05$) (Wijnberg et al., 2010).

Sleutjens et al. (2009, 2012) proved that using HNP1 as reference, inspiratory intrathoracic pressure (IP) became more negative during trot$_1$ (each HNP) ($p < 0.05$), canter and trot$_2$ (HNP4) ($p < 0.05$) and walk (HNP4, HNP5) ($p < 0.05$). Intrathoracic pressure difference (IPΔ) increased during trot$_1$ and walk (each HNP) ($p < 0.05$) and canter and trot$_2$ (HNP4) ($p < 0.05$). PartO_2 increased during canter (HNP4) ($p < 0.05$). PartCO_2 (mmHg) and SartO_2 (%) did not change significantly.

Van Dierendonck et al. (2010) demonstrated that head tossing and head shaking were increased during exercise in HNP2 ($p < 0.05$) and head pulling in HNP2 ($p < 0.05$). During detaching of the side rains, head shaking was increased in all HNPs ($p < 0.05$), but most in HNP2, holding the head low was increased in HNP5 ($p < 0.05$). During cooling down, holding the head low was increased in HNP5 ($p < 0.05$), HNP2 ($p < 0.05$) and HNP4 ($p < 0.05$). During exercise, helper encouragement was increased in HNP2, HNP4 and HNP7 ($p < 0.05$), helper slow down was increased in HNP2 and HNP5 ($p < 0.05$), shying was decreased in HNP7 ($p < 0.05$), blowing was increased in HNP2 and HNP4 ($p < 0.05$), snorting was increased in HNP7 ($p < 0.05$) and swishing of the tail was increased in HNP2 ($p < 0.05$). During attaching and detaching of the side rains, tail swishing was increased in respectively HNP2 ($p < 0.05$) and HNP2, 7 ($p < 0.05$, $p < 0.05$).

Discussion of measurements from the neck

This study objectively quantified and measured differences between five *in vivo* head and neck positions commonly used during training and competition in sport horses. Mean angles of C1–T6 with the horizontal (C1–T6-Hor) and of CF–C1 with the vertical (C1–CF-Vert) in combination with the horizontal distance from CF and TS (CF–TS) and the vertical distance from CF to PS (CF–PS) were shown to differ between HNPs.

The *in vivo* 'hyperextended' HNP5 (*ex vivo*, 40° extension) had the largest, most positive (C1–T6-Hor), (C1–CF-Vert) and (BN′–BN-Vert) angles and the longest vertical (CF–PS) distance; in HNP2 (*ex vivo*, 20° extension) the (C1–CF-Vert) angle was close to zero, the *in vivo* 'neutral' HNP1 had the largest (CF-C1–T6) angle and the longest horizontal (CF–TS) distance; HNP4 (*ex vivo*, 20° flexion) the smallest (C1–CF-Vert) and (BN′–BN-Vert) angle; the *in vivo* 'hyperflexed' HNP7 (*ex vivo*, 40° flexion) was the HNP with the smallest, most negative (C1–T6-Hor) angle and the shortest vertical (CF–PS) distance ($p < 0.05$).

In conclusion from the angles of C1–T6 with the horizontal and of CF–C1 with the vertical in combination with the vertical distance from CF to PS, we were able to objectively quantify the head and neck position in a particular horse during training and competition from home-video images. This enables routine (standard video) monitoring, including timing, of the applied HNPs during training and competition in the practical field situation. The *ex vivo* findings suggest that an increase in extension of the equine cervical spine could cause compression of the cervical nerve root at the level C4/C5–C7/T1. This information contributes to a more complete understanding of different training techniques with respect to the head and neck position (Sleutjens et al., 2010) but it also raises questions with regard to the findings in the study on neuromuscular function measured using stimulated single fiber EMG. Based on these findings it cannot be ruled out that especially HNP4, leads to a rather large diminished MCD compared to the control position, and that factors other than compression might play a role in this induced delay. For example, traction on the nerve in this flexed position. MCD and MUP variables indicated that head positions affect neuromuscular functionality. The meaning of this elevation of MCD, in a range that in humans is considered to be pathological, remains unclear as long as there is no information from patients with known nerve damage. Therefore, it would be interesting to measure patients with cervical vertebral pathology (Wijnberg et al., 2010). Especially HNP4 leads to a higher elevation in muscle enzyme activity that caused the horses to develop a dynamic obstruction of the respiratory tract, evidenced by an increase in intrathoracic pressure difference and a more negative pressure during inspiration. However, the authors did not find a change in arterial oxygen or carbon dioxide pressure, respectively. In contrast, they found a significant increase in arterial oxygen pressure in HNP4 during canter. This may be explained by the fact that the horses were by no means working at maximal capacity, leading to a lot of reserve capacity that prohibits a measurable decline or increase in arterial oxygen or carbon dioxide pressure, respectively. Further research is needed to elucidate the origin of this effect on arterial blood gases and to evaluate the effect of an extremely flexed head and neck position (HNP4) in patients with upper/lower airway disease (Sleutjens et al., 2009, 2012). HNP2 and HNP5 cause more resistance behaviors during exercise and attachment of the side rains. After detaching the side reins (HNP5) and during cooling down after HNP5, 2 and 4, the horses displayed a lower head and neck position, possibly to compensate pain in the exhausted neck muscles. Cortisol levels are needed to further complete the knowledge of the effect of HNP on the mental state of the equine athlete (Van Dierendonck et al., 2010).

Back dysfunction

Introduction

Dysfunction of the back is an important reason for poor performance in the horse. Clinical history and examination are important features in the diagnosis of back problems. However, the interpretation of these findings is subjective and varies due to experience, tradition and personal bias. Therefore, ancillary aids such as radiography, scintigraphy, ultrasonography, thermography and local anesthesia are commonly used in the diagnosis of back problems.

The relationship between these ancillary aids and pain or dysfunction is debatable as many fully functioning riding horses can display pathological changes that apparently do not diminish their athletic performance. There is a clear need to document the functional and dysfunctional back objectively to assist our clinical examination and to determin of the health status of the equine back (Haussler et al., 2001, 2006a,b; De Heus et al., 2010).

Back pathology, with pain and reduced motion, has been identified as an important cause of poor performance (Jeffcott, 1975, 1980; Denoix, 1998). A general geometric approach to the biomechanics of the back in relation to vertebral pathology has been presented (Rooney, 1982). Kissing spines, vertebral spondylosis (Jeffcott, 1980; Haussler et al., 1999) and osteoarthrosis of the dorsal synovial intervertebral joints between the articular processes (Denoix, 1998; Girodroux et al., 2009) are the most significant vertebral lesions responsible for back discomfort and clinical manifestations in horses.

Thus, to comprehensively understand the different, complex movements of the back horses in daily use, horses in regular training, horses with complaints of poor performance with the back as the cause, and of horses with obvious back pain were objectively evaluated for their function and dysfunction.

Kinematic examination of normal horses

In the study of a group of normally functioning riding horses (Johnston et al., 2004), the clinical examination of the back consisted of visual inspection, palpation and observation of movement when in hand, on a lunge, and ridden. Individual limbs were flexed to register reaction and lameness. Only horses that were clinically sound and did not demonstrate abnormal reaction to palpation, flexion tests nor abnormal movement (behavior) during the riding or lunging tests, were used. The clinical examination in the asymptomatic, normal horse illustrated the importance of the normal appearance of well functioning horses. Still, in the majority of the horses some reaction to palpation was apparent. Furthermore, the location of reaction to palpation seemed to be dependent on the main use of the horses. This could be explained by the differences in training these horses were subjected to, in their respective discipline. Dressage horses and show jumpers in this study were also ridden with different types of saddles, which might influence how the back is loaded. The dressage rider normally sits 'deeper' on the horse, while the rider of a show jumper will sit more in a forward seat. However, this should not lead to a pathological reaction upon palpation, as then there might be something wrong. Horses that were reactive to palpation of the back, did not always show impaired function, dysfunction or lack of performance.

The horses were trained four times on a treadmill (Johnston et al., 2004). The dorsal spinous processes were identified by palpation and spherical, reflective markers were placed over the identified landmarks (Fig. 10.21). For collecting the position data of the markers, a camera system consisting of six cameras was used. The system is based on passive markers and infrared cameras. Data were captured during steady state locomotion during walking and trotting. Movement of the back was described in terms of extension–flexion, lateral bending, lateral excursion and axial rotation. The range and symmetry of movement were calculated. Additionally, characteristics of the horses' back, height at withers, and weight were determined. The characteristics that were derived from marker data were length of the thoracic back (horizontal distance T6–T17), length of the lumbar back (horizontal distance L1–L5), length of whole back (horizontal distance T6–S3), width (i.e. the distance between the tubera coxae), and curvature of the mid-thoracic back.

Walk and trot are symmetric gaits and the movements of the back in these trained animals were also highly symmetric. Normal function and symmetry are apparently highly related both in gait and movement in the back. The only difference in conformation that dressage horses had longer lumbar backs than jumpers. Dressage horses demonstrated more lateral movement than jumpers. Furthermore, dressage horses demonstrated less symmetry in the mid-thoracic region than did the jumpers at the walk. Suppleness is thought to be associated with increased back length and may therefore explain a conformational preference toward the dressage horse. Because the musculature of the back is passive during the walk,

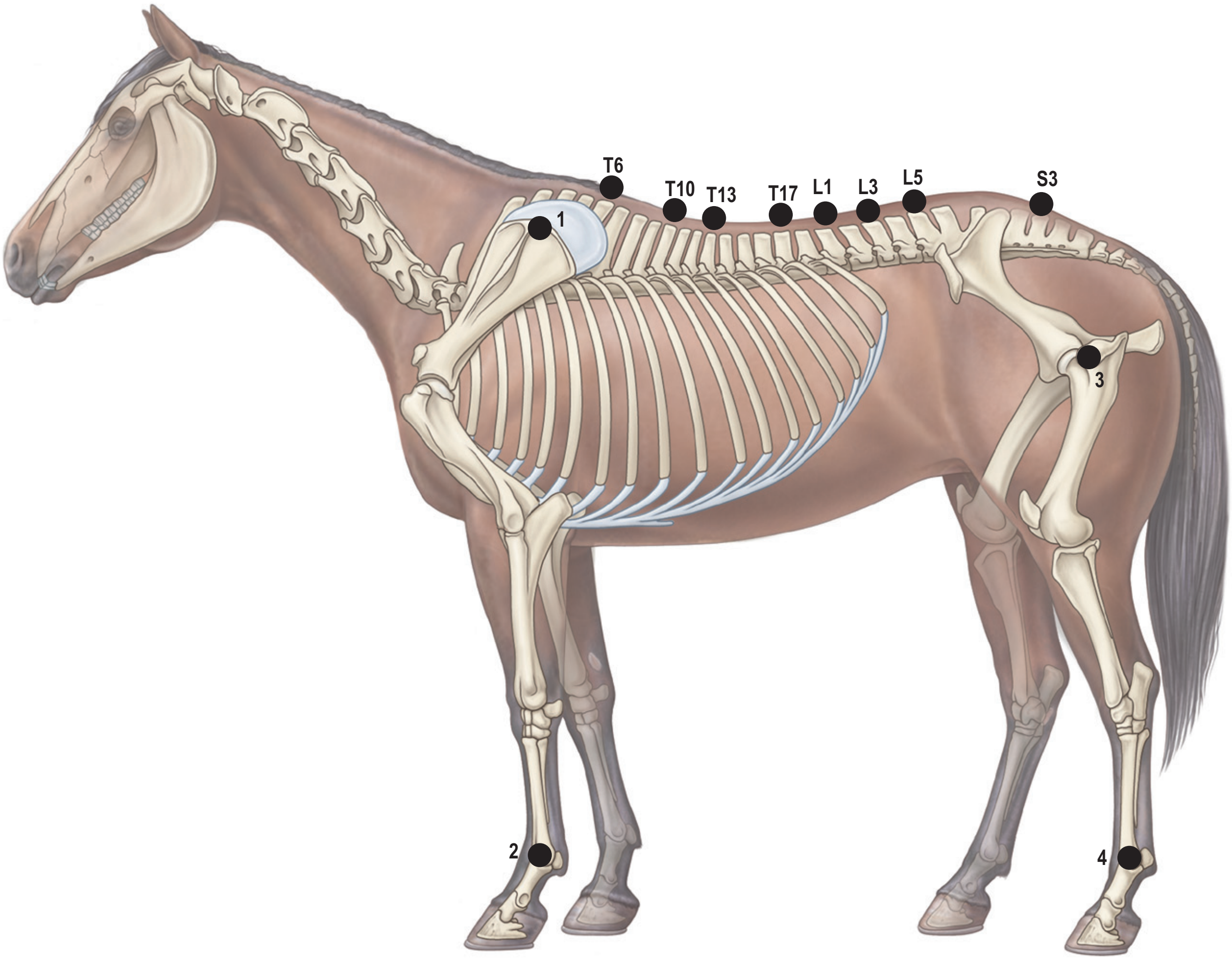

Fig 10.21 Marker placement on back and limbs. Lumbar vertebrae 1, 3 and 5 (L1, L3, L5); sacral vertebra 3 (S3). 1, Proximal spina scapula; 2, lateral collateral ligament of the metacarpophalangeal joint; 3, cranial part of the trochanter major of the femur; 4, lateral collateral ligament of the metatarsophalangeal joint.
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lateral movement may be greater and less symmetric in the dressage horse. Gender was found to be an important factor in the lateral movement of some of the segments of the back while working at the trot. Mares demonstrated greater lateral excursion (displacement of the back to each side) in the cranial back than did geldings, and greater movement symmetry. The functional significance is not known, however mares show increased occurrence of bony changes on the underside of the vertebrae (spondylosis) when compared to geldings and stallions. Perhaps excessive lateral movement is a contributing factor in the degenerative processes between the vertebral structures of this part of the mid-thoracic back that is most susceptible to spondylosis. Age was also a determinant in the movement of the back. Older horses had decreased flexion–extension at the transition between thoracic and lumbar back at the trot. Perhaps wear and tear due to age in this area of high shearing is an important factor in the pathogenesis of certain disorders. These trained riding horses demonstrated highly symmetrical movement of the back, which is in contrast to research horses used in an earlier study (Faber et al., 2000, 2001a,b,c, 2002). Training and perhaps quality of horse may influence movement symmetry and function of the back. Factors such as gender and age, thus are important in the function of the back. The effect of gender is intriguing and requires further investigation, while age is more intuitive as it is likely related to the wear and tear of use. Perhaps the most influential factor (not related to use) for the function of the back is the perceived conformation for the respective disciplines (Johnston et al., 2002). Further investigation on the relationship of back conformation and function to orthopedic health is warranted as to determine the most appropriate conformation and function for the different sporting disciplines.

There were no statistically significant associations between the clinical, kinematic, radiographic and scintigraphic results (Erichsen et al., 2003a,b, 2004). The age, gender, use, weight and height of the horses did not influence, the presence or absence of clinical or radiographic and scintigraphic changes nor the classification of possible outliers in the range of movement and the symmetry of movement. However, there was a statistically significant positive association between the total number of times a horse was graded as a possible outlier in the range of movement and the symmetry of movement and increased isotope uptake (IRU) during a scintigraphic examination (Erichsen et al., 2003a,b, 2004). The number of times a horse was graded as a possible outlier in the range of movement was significantly associated with the presence of coinciding radiographic changes, IRU and lunging abnormalities respectively. Deviation from the normal function of the back is related to clinical, radiological and scintigraphic abnormalities. Consequently, the objective determination of function may indeed suggest subclinical structural and functional abnormalities. Kinematic studies on the treadmill (Licka et al., 2001a,b; Johnston et al., 2004; Johnson & Moore-Colyer, 2009) and overground (Audigie et al., 1999; Gomez Alvarez et al., 2007, 2009) provide a viable means of determining difficult performance problems that are related to the back.

Kinematic examination of horses with back pain

To study back dysfunction a group of riding horses with impaired performance, altered movements during work and clinical back pain were used (Wennerstrand et al., 2004). Horses were Warmblood riding horses between 5 and 15 years old. Only horses that had not been treated for back pain, with the exception of rest and/or convalescence training, during the last 3 months were allowed to participate. Back pain was considered present if the horse showed clear signs of pain/discomfort on palpation of the back and the reaction did not decrease with repeated palpation. Commonly, horses demonstrating back pain reacted to palpation by adverse reactions like bolting or rearing, tail swishing, unruliness, rapid caudal movement of the ears or stiff, jerky movements.

Horses with back pain show an aberrant pattern of the movement of the back, which, with the aid of objective measurement techniques, makes it possible to classify a horse with back dysfunction. It is reasonable to believe that a horse with a sore back will try to move in a way that, if possible, may alleviate the pain. Apparently, this will best be accomplished by a stiffer dorsoventral (flexion-extension) movement in the caudal thoracic back and at the thoracolumbar junction, at both the walk and trot. The abnormal lateral movement seen at the withers and decreased rotation (AR) of the pelvis, results in a side-to-side swaying walk as seen from behind. Presumably, the symptomatic horse has altered the neuromuscular control of the walk and trot to cope with back pain. Acquired pathological limitations could also be an initial source of the problem and therefore crucial factors to the decreased range of movement (ROM) of the back.

Apparently, flexion of the back is reduced to limit the relative displacement of the individual segments of the thoracolumbar back, perhaps due to excessive muscular activity as aggravated by nociception. The normal movement of the back is more controlled by muscle activity at the trot than at the walk, where the movement is more passive with greater amplitude for the lateral and twisting movements. This may be the reason why the ROM for the AR of the pelvis is decreased in a horse with back pain at the walk, but not at the trot.

The reduction in the ROM for the flexion and extension (FE) and AR movements has earlier been observed in another study – a case study of one horse with increased responsiveness to palpation of the lumbar and sacral back (Faber et al., 2003). The shorter stride length observed in the horses with back pain at the walk, coinciding with the decreased FE movement of the back, is well in accordance with the findings of Jeffcott (1980) and Faber et al. (2003). It is also in agreement with the positive relationship between the pro- and retraction of the hind limbs and the FE movement of the back that has been established in clinically sound horses at the walk (Faber et al., 2000) and trot (Faber et al., 2001). In the present study, the expected reduction in stride length in the patients was not seen at the trot though. The explanation for this is not obvious, but it is possible that the muscle activity in the hind limbs was altered and may have influenced the stride length. The slight difference in stride velocity at the trot is not likely to have caused the decrease in the ROM (Robert et al., 2001).

Since all horses showed muscle soreness on palpation of the back, and more than half of them had pathological skeletal reactions, it is reasonable to believe that this was the main reason for the decreased dorsoventral FE movement at both gaits and the changed lateral movement at the walk.

This study supports the use of objective measurements of the back kinematics as a valuable tool to help identify horses with back dysfunction. Before using it more extensively it is necessary to further evaluate the method, including measurements on patients whose diagnoses can be confirmed, and long-term follow-up of back patients after treatment.

Differences between horses with and without back pain

The studies of Wennerstrand et al. (2004) and Johnston et al. (2004) nicely show significant and objective differences between horses with back pain and asymptomatic controls at both the walk and trot. The differences are most striking at the thoracolumbar junction, where the patients, in addition to the changes in the ROM, also were less symmetrical for the FE movement at the walk. These findings indicate that the thoracolumbar junction is one part of the back especially predisposed to impairment (Denoix, 1998; Holm et al., 2006; Peham & Schobesberger, 2006). The most apparent criterion between horses with back pain and horses without problems is their function. Despite many changes in the radiographs and scintigraphy, the horses in the healthy group managed to maintain their normal work. Imaging techniques are important in the isolation of horses with back problems, but do not seem to be predictive, at least at this point in time, in determining if horses will become dysfunctional. Encouraging, however, is a clear separation of patients from normal, as horses with back pain have more outliers than the fully functional horses. In other words, horses with back pain move significantly differently from the fully functional horse as determined from kinematic data. Thus, kinematic studies are valuable in the definition of clinical and perhaps subclinical classification of horses with dysfunction of the back.

The results from the clinical, kinematic, radiographic and scintigraphic examinations are likely to overlap between horses with and those without back pain or back dysfunction. The sensitivity and specificity of these, as well as other tests or examinations, depend on the cut-off points set in order to determine the presence or absence of a change. Cut-off levels of changes set so low, that changes would be present in a majority of asymptomatic horses, would not be helpful in the evaluation of symptomatic horses. Since mild changes were common in these studies (Erichsen et al., 2003a,b, 2004), they are not likely to be good indicators of clinically significant pathology in symptomatic horses. Therefore, mild changes were grouped together with no changes to allow some variation in the lower range of the classification system and to make the criteria less sensitive. The level from which the changes should be considered significant, is also important if changes are early signs of later clinical problems. This can only be determined by performing a longitudinal study.

It may be that the examinations used in this study are not the optimal or final combination for the detection or description of symptomatic or asymptomatic horses in terms of back pain or dysfunction. Data on the ultrasonographic and thermographic or quantitative electromyographic appearance of the back of the asymptomatic horse have not been published extensively and, few, if any, other practically useful tests would contribute significantly in a general evaluation of the equine back.

A major advantage of the protocol used in these studies is the broad and complementary approach of the examinations. The detailed clinical examination is quintessential to identify and classify the signs of reduced or impaired performance. The kinematic examination is functional, objective, and relatively easy to perform. The radiographic and scintigraphic examinations are indicative of specific anatomic lesions within the relative context. In the study of asymptomatic horses, none of the examinations by themselves is sufficiently specific to describe these horses as asymptomatic. Kinematics and radiographic and scintigraphic results support the clinical examination suggesting that these horses are asymptomatic.

The examination of the equine back remains a complicated and interesting challenge but with information gained in this study used for comparison, the combined results from clinical, kinematic and radiographic and scintigraphic examinations of the back in symptomatic horses can be used to decrease the risk of excessive false positive results. In addition, muscle pathology of the back is not reflected by an increase in muscle enzyme activity and therefore needle EMG can often be helpful in detecting underlying muscle fiber loss.

It can be concluded that the equine back is a very complex structure that takes a central position in the entire equine musculoskeletal system and hence can be decisive for performance. A good knowledge of how the back works is therefore essential. The close interrelationship between the limbs and the back (and neck) is often underestimated. In a recent survey a group of orthopedic patients and a control group of animals presented for a prepurchase exam were subjected to a full lameness examination as well as a full back examination, irrespective of their eventual complaints. In that study it appeared that the prevalence of lameness in horses with a diagnosed back problem was much higher than in horses without such a problem (Landman et al., 2004).

The diagnosis of back pain is elusive and complex. Single factors such as conformation, lameness, equipment, and way of riding are likely to contribute to the clinical manifestation. Consequently, function or dysfunction is ultimately the determining factor in the diagnosis. Indiscriminate uses of imaging or palpation do not seem to be accurate determinants of back pain. A complete clinical evaluation is paramount and in this study an objective measure of function may certainly contribute to an accurate diagnosis. Techniques in the diagnosis of back pain, such as local anesthesia, need to be evaluated to appreciate their correct usage and interpretation. It can be anticipated that, notwithstanding the limitations all kinematic gait analysis systems suffer (Van Weeren, 2002), computerized analysis of spinal kinematics will become more popular as an aid in diagnosis and to monitor recovery and/or the success of chosen therapies. Understanding back pain requires a fundamental understanding of the normal function of the back and how normal intervention can affect its function. The biomechanical concept of the action of the back is crucial too for a good understanding of various riding techniques in dressage horses and how certain training methods could affect the musculoskeletal system (Van Weeren, 2005). It should be emphasized, however, that this matter is extremely complex, as there are many factors that may influence performance. Of these, use of the horse, the quality of the rider and the tack are among the most important.

The effect of head and neck position on the movement of the back

Head and neck positions have been standardized by the use of side reins (Fig. 10.22). Flexion–extension movement of the back at walk with the head and neck in the high position was significantly lower as compared to the movement with the head and neck in a free or in a low position at the caudal part of the back (Biau et al., 2002; Weishaupt et al., 2006; Gómez-Alvarez et al., 2006; Rhodin et al., 2009; Waldern et al., 2009). The same tendency was seen with the head and neck in the low position as compared to the free position but probably because of the low number of observations, no significant differences were found. At trot only flexion–extension movement of segment T17 was lower at the high position.

At walk the stride length was shortest with the head in the high position but this was not seen at trot where the stride length was constant. It is, however, known that the movement of the back is related to stride length. Horses with longer strides extend and flex their backs in the caudal saddle region to a greater extent at walk (Johnston et al., 2002). Faber et al. (2000, 2001) found that an increasing stride length of the hind limb was correlated with an increasing flexion–extension range of movement for most of the vertebrae both in the walk and in the trot. This is in accordance with our findings but the stride length was also associated with the head and neck position.

The different results at walk and trot may be due to the different characteristics of the gaits (Roepstorff et al., 2002; Bystrom et al., 2006). At walk the horse moves the head and neck to a greater extent as compared to trot, where the head and neck position is more constant. When the head and neck are fixed, as with side reins, this impedes the natural movement at walk more than at trot. At trot, speed influences movement of the back (Robert et al., 2001), but in this study the speed at trot was constant.

It seems probable that the decreased flexion–extension movement of the back in the high head position is directly caused by the shorter stride length, which in turn is caused by the head and neck position. The lateral bending movement of the lumbar back with the head and neck in the high position was at walk significantly lower as compared to the movement with the head and neck in a free position, which was similar for flexion–extension. On the other

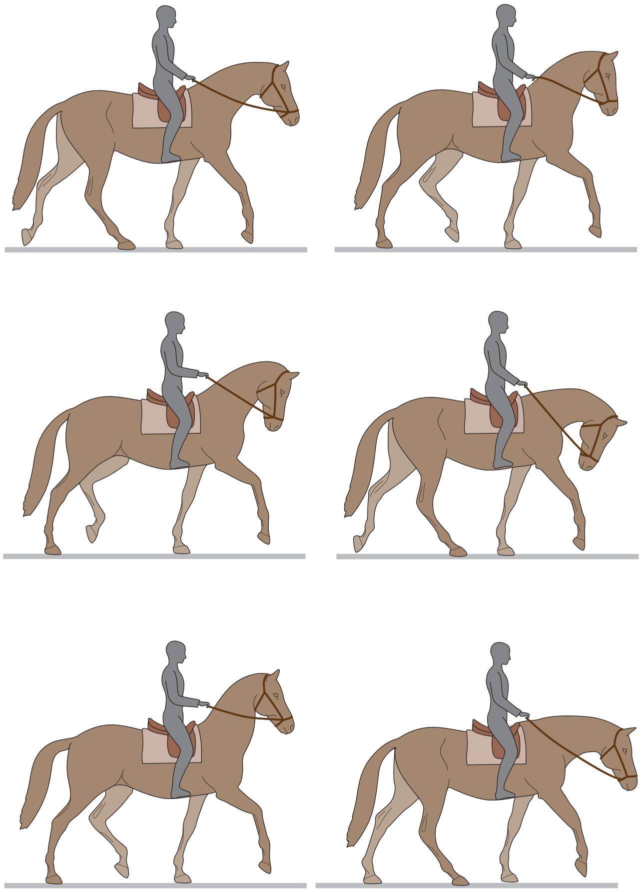

Fig 10.22 The six different head positions measured in the study. From right to left and top to bottom, the positions are designated free, FEI like position, FEI like position but head slightly behind the vertical, deep overrolled or 'Rollkur' position, the extremely high and stressed position, the relaxed low position.

hand the thoracic region of the back had a significantly larger lateral bending movement. The lower movement in the lumbar back may have been due to the shorter stride length and the larger movement in the thoracic region of the back can be compensation or the direct cause of the head and neck position.

The axial rotation was significantly lower with the head in a high position as compared to the free and low position at walk. For axial rotation at the walk, there is a high degree of synchronization between the vertebrae T13 through the pelvis; only T10 moved independently and there is no significant correlation with the stride length. For pro- and retraction of the hind limb there is a positive correlation with the stride length. In this experimental set-up we did not have the possibility to encourage the horses forward and thereby affect the hind limbs. If a constant stride length could be achieved, for example by long reining, together with variable head and neck positions the causal relationship between the head and neck position and the movement of the back could be proven (Fig. 10.22).

The effect of local analgesia in the movement of the back

Diagnostic infiltration of local aesthetic solution is commonly used in cases of equine back pain. The evaluation is subjective and it is not known how local analgesia affects an asymptomatic back. Holm et al. (2006) evaluated the effect of infiltration of local anesthetics on the movement of the asymptomatic equine back, and the usefulness of kinematic studies as an objective and quantitative tool in evaluating local analgesia in clinical practice.

The kinematics of the back in ten clinically sound horses were measured on two occasions at the walk and trot before and after infiltration with mepivacaine (a local anaesthetic) and infiltration with sodium chloride (saline or water and salt solution that is similar to water in the body) around the spaces between T16 and L2. The kinematics were compared between the two occasions before infiltrations and before and after each infiltration. The range of motion for dorsoventral flexion–extension of the back was significantly increased in all measured segments other than T10 at the walk, as was the lateral bending (LB) at T10, L3 and L5 after infiltration of mepivacaine. For lateral excursion (side to side movement of the back) the total movement increased at all measured segments. At the trot, the only affected segment was L3, where the infiltration with mepivacaine decreased the ROM for FE. After infiltration of sodium chloride the ROM for FE increased at T13 and T17 at the walk. Lateral bending and lateral excursion were not affected, while AR increased at the walk. At the trot, LB increased at L3 and L5. The symmetry of movement was not affected by infiltration of either mepivacaine or sodium chloride at the walk and only at L5 for LB at the trot after infiltration of sodium chloride. Local infiltration of aesthetic solution affects the movement of the back in asymptomatic horses, which is important to consider when using it in clinical practice. Thus, the effect of local analgesia of the back could be qualitatively and quantitatively evaluated from kinematics. Diagnostic infiltration of local anesthetic solution affects the function of the back also in the asymptomatic horse, which must be considered when interpreting the use of this clinical aid in assessing clinical cases of back dysfunction.

General conclusions

Research on the function and dysfunction of the neck and back has been of great academic and public interest. The popularity of the research is due to the fundamental understanding of the central roll of the neck and back in the riding horse, but as well as the lack of in-depth insight into the function of the neck and back. Restricting and restraining the position and movement of the head and neck alter the movement of the back. The flexion–extension movement of the caudal back, with the head and neck in the high position at the walk, has the most pronounced reduction; most likely depending on the significantly shorter stride length. There are only small difference between long reins and side reins with regard to the movement of the back at the walk and trot. Consequently, long reining and free movement (with or without side reins) on a treadmill are similar. Considering the intention and normal use of long reining, proper technique is thus essential as the positioning of the head (use of hand) is central in the movement of the horse.

Movement and forces are not necessarily similar in all cases as demonstrated by the use of draw reins. Similarly, more extreme movement does not induce similar and more extreme differences in forces. To induce a shift in weight (though only slight) from the forelimb to the hind limb draw reins with normal reins are required. Extreme bending of the head and neck by use of the draw rein did not lead to the same result. As in long reining proper equipment and technique when using for example draw reins is required to achieve the intended result.

The head and neck positions (HNP) in sport horses, however, are under debate in the equine community, as they would interfere with equine welfare (Jeffcott et al., 2006). These HNPs have, until recently, never been objectively quantified and no information used to be available on their head and neck loading.

To quantify *in vivo* HNPs in horses and develop a model to estimate loading on the cervical vertebrae in these positions, videos were taken of seven Warmbloods at walk on a straight line in five

Table 10.1 **Mean ± SEM *in vivo* measured angles and distances defining different head and neck positions (HNP) commonly used in training and competition evaluated in a group of horses (n = 7)**

Measured values	HNP1	HNP2	HNP4	HNP5	HNP7
Angle 1	−16.2 ± 2.1*	3.6 ± 2.0*	−33.3 ± 1.2*	34.8 ± 2.0*	−41.5 ± 1.7*
Angle 2	131.9 ± 2.0*	87.2 ± 1.9^{a}	84.4 ± 1.3a	119.2 ± 3.8*	103.6 ± 2.6*
Angle 3	25.7 ± 1.7*	0.9 ± 2.5*	−38.9 ± 1.1^{a}	63.9 ± 3.6*	−27.8 ± 1.5*
Angle 4	11.9 ± 1.3*	−12.8 ± 2.5*	−51.7 ± 1.8*	47.2 ± 3.5*	−41.0 ± 2.2*
Distance A	73.5 ± 3.4*	43.9 ± 1.7^{b}	34.5 ± 1.3^{c}	45.4 ± 2.1^{b}	37.2 ± 1.7^{c}
Distance B	60.2 ± 4.9*	89.8 ± 3.0*	46.7 ± 2.1*	144.8 ± 3.9*	18.6 ± 3.3*

*$p < 0.05$; pairs a, b and c are not significantly different.

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positions, representing all HNPs during Warmblood training and competition. Markers were glued at five anatomical landmarks. Two-dimensional angles and distances were determined from video frames for the five HNPs ($p < 0.05$).

Thus, Elgersma et al. (2010) was able to objectively quantify the different head and neck positions by angles and distances, which were significantly different from each other (Table 10.1). Therefore, it was possible to induce repeatable and reproducible the desired head and neck position in different experimental circumstances by using side rains. Sleutjens et al. (2010) found from *ex vivo* data that extension of the cervical spine could have an adverse effect on neuromuscular functionality with the most profound effect on the segment C6–C7. The concommittant *in vivo* study of Wijnberg et al. (2010) on neuromuscular transmission showed that compared to HNP1, each head and neck position had a potentially adverse effect on neuromuscular functionality. The greatest adverse affect was seen in HNP4, though based upon reference values for humans. This effect could be even more profound in patients with cervical pathology. HNP 7, another interpretation of a flexed HNP from the induced neck positions, had the least affect on neuromuscular functionality. This effect might be caused by another factor than a decrease in intervertebral foramina dimensions. Furthermore, especially HNP4 leads to an increased intrathoraric pressure difference and a more negative inspiratory pressure. These effects may be caused by a dynamic upper airway obstruction and are possibly even more profound in patients with upper airway disease. Last but not least, HNP4 caused a shift to sympathetic dominance during walk, based on heart rate variability, possibly indicating (exercise) stress. HNP2 and HNP5 caused more active resistance behavior during exercise and applying of the side rains. Cortisol levels are under examination to further complete the knowledge of the effect of HNP on the mental state of the equine athlete, and the type of stress detected using heart rate variability.

These results justify to conclude that training with an extreme flexed head and neck position (HNP4) has an effect on the healthy, base-level trained Warmblood riding horse during moderate exercise for a longer period (± 30 min) of time and during lunging exercise. However, it remains a challenge to judge for another subject than yourself to which extent this effect is necessarily negative. For example, we could argue that an organism needs to have some degree of stress in order to perform. However, the resistance behavior we observed in HNP2 and HNP5 is not desirable during training/competition. This behavior was not seen in HNP4 and HNP7, our impression is that the horses showed more submissive behavior during these positions which is in agreement with the argument that riders feel that their horse is more under control and more sensitive to the riders input while trained in a flexed head and neck position. The results on the cortisol test are needed to define whether the horse does indeed feel more relaxed in these positions, or just does not have the ability to behave in an adverse manner. This is probably also influenced by the character of the individual and its tendency to submissive behavior. A temporary decreased conduction velocity indicating a decreased neuromuscular transmission is an unwanted, negative effect, although not per se a pathological effect, but the question remains how these values will be when some degree of facet joint arthrosis is present, thereby pressing to some extent on peripheral nerve roots, like is experienced in humans (Yoo et al., 1992; Farmer & Wisneski, 1994; Humphreys et al., 1998; Lu et al., 2000; Muhre et al., 2001; Nuckley et al., 2002; Kitagawa et al., 2004; Ebraheim et al., 2006; Morishita et al., 2006; Tanaka et al., 2006; Abbed & Coumans, 2007; Hubbard et al., 2008; Down et al., 2009). Nevertheless, trainers/riders insisting on using HNP4 in the base-level trained horse for a longer period of time should at least realize the possible consequences. There are still several remaining questions, which need to be answered in order to complete our understanding of the effect of head and neck position on the well-being of the equine athlete. It would for example be interesting to repeat the study in elite dressage horses, to see if there is a difference between horses trained at different levels. Additionally, the training circumstances could be expanded. Although it could possibly pose a greater challenge on standardization and safety, it would be interesting to measure in the ridden horse or the horse working on a treadmill. Furthermore, besides the healthy horse, there are many patients with some sort of upper/lower airway disease or a more or less advanced stadium of cervical arthrosis, which are still used in training/competition on various levels.

The following logical question is which head and neck position would be advisable. HNP1 is the natural position of the horse during exercise. However, it is unreasonable to believe that in the opinion of trainers/riders this position would be sufficient to prepare the horses for competition at any level. As stated above HNP4 is questionable as is HNP5 because of its effect on the back, locomotor apparatus and behavior (Gómez-Alvarez et al., 2006; Rhodin et al., 2009; Weishaupt et al., 2006; Waldern et al., 2009). HNP2 is still the position desired during competition by the national (KNHS) and international (FEI) organizations and preferred above HNP 4 for gymnastic training of a horse on the lunge and for shorter times, although we demonstrated that it affected neuromuscular transmission and increased resistance behavior during exercise. After all, HNP7 looks at a position which could be used during training, since round and deep posture is trained with less effect measured so far. In the end, variation is probably the key word while adapting the training strategy to the level of the individual horse, rider and training goal while being cautious with extreme flexed head and neck positions in the base-level trained Warmblood riding horse. All this information will be of potential help in better understanding the occurrence, and eventually in improving treatment and prevention of locomotor disturbances in sport horses, induced by suboptimal head and neck positions during training and competition. In this way, this approach may contribute to equine welfare and indirectly to promotion of the equine industry (McGreevy et al., 2010).

The back is a complex entity that provides stability and flexibility. Normal movement is highly symmetrical and specific. The thoracic back is an extension of the flexible neck to allow for rotation and lateral bending (Stubbs et al., 2006). As the forelimb is loaded, the back will need to accommodate for the strut like system. The scapula will assumedly impose bending of the forward segments of the thoracic back. On the other hand, the stable lumbar back-pelvis complex transfers the propulsive energy of the hind limb to lift and propel the rest of the body. Intersegmental movement of the lumbar back is slight to provide the needed stability. Consequently, the lumbar back, with the exception of the joint between the last lumbar vertebra and sacrum, acts as a functional unit transferring the movement through the joints of the back and supported by the muscles and ligaments that surround these bony structures. The muscles of the lumbar back (longissimus dorsi) limit flexion while the muscles of the abdomen limit extension of the lumbar and later thoracic back. A more complex system of muscles function about the thoracic back to aid in lateral movement and limit extension, while the large ligament of the neck causes extension or limits flexion of the part of the back. In equine sports, engagement of the hind limbs and manipulation of the head and neck are thus important features in training and competition. Our use of the horse has a central role on the function of the back. Perception of conformation, riding technique, equipment, and training will impinge on the normal function of the back and consequently function of the horse as a whole. The manipulation of the head and neck alters the movement specific regions of the back. The use of reins is frequently used to aid in this manipulation and thus education of the horse. Raising the head and neck extends and limits the amount of movement of the back, while lowering the head and neck tends to flex the back. In the ridden condition, the back becomes extended due to the weight of the rider (De Cocq et al., 2004, 2006) and stride length decreases. Consequently, raising or lowering of the head and neck would exacerbate or mitigate this condition. Training with weights may help to mobilize and strengthen the muscles of the back and limbs to help prepare the horse for loading as engendered by riding. Intriguingly interesting and important to recognize is that movement of the limbs (as induced by increased weight) has also a significant effect on the back. The innate movement pattern, lameness, and shoeing practices can potentially induce changes that may affect the normal function of the back. A direct relationship between shoeing and movement of the back is difficult to appreciate. We know that horses respond to similar farrier techniques similarly in the hoof capsule and bony segments of the distal limb (under the carpus and tarsus), but quite differently when taking into consideration of the movement of the whole body.

Draw reins used with normal reins resulted in lowering the neck and placing the head more vertical or behind the vertical and increased propulsion from the hind limbs. Interestingly, exaggeration of this condition with draw reins only did not exaggerate engagement of the hind limb; on the contrary the hind limbs reduced their driving function. Function of the horse (and back) is thus the complex interaction of rider-horse that is influenced by training, equipment, and tradition; this interaction having the most potential influence on the orthopedic health of the horse (and back). The close proximity of these bony structures as well as other structures of the back is subsequently site for many pathological changes that may or may not limit performance through dysfunction/pain. The bulky muscles limit our ability to appreciate these pathological changes thus limits our ability to identify them as factors in the orthopedic function of the horse. The back offers thus a considerable challenge for the clinician. Presently, the diagnosis of back pain is often through exclusion of sources of reduced performance. Back pain is thus a functional diagnosis and requires considerable experience to understand and properly manage. The interaction between lameness and back dysfunction is apparent in the clinics, though the interrelationship to the successful treatment of lameness and back dysfunction is not as apparent. In many cases horses need only to be treated for the lameness and any symptom from the back is resolved. Not uncommon are lamenesses that are readily isolated but do not respond to therapy until combined therapies for the lameness and back pain are initiated. Finally, some clinical cases are overtly lame and the lameness is first resolved (isolated) to the back. Subsequently, back pain is likely a symptom and a source of other injuries and performance problems, as well as being a primary cause of locomotor disturbance. The information gained to date reveals that clinical and potentially kinematic examinations are fundamental to the diagnosis of back dysfunction. Aids such as radiology, scintigraphy, and diagnostic anesthesia are only helpful when the functional (clinical) diagnosis is established. Knowing the characteristic way of walking can provide a strong indication for back dysfunction as indicated from the kinematic studies. A protocol might become a basis for a clinical examination of horses with performance problems that may be related to the back, and thus documentation for further studies. The correct evaluation of therapies and rehabilitation programs can also be established through this protocol. Potentially, a preferably longitudinal study using a protocol can offer a golden standard of diagnosis determination. However, many details on interrelationship of lameness and back pain, involvement of difficult areas of clinical evaluation such as the lumbar back, and interaction of riding/training/equipment/tradition affect the orthopedic health of the back are needed to successfully apply the information gained in this study. Because of their limited mobility and heavy muscles, the axial regions of the horse are probably the most difficult to investigate with biomechanical techniques and diagnostic procedures. Nevertheless, in the recent years a lot of information has been gained on the biomechanics of the neck and back, especially with kinematic analysis and quantitative (needle) electromyographic studies (Wijnberg et al., 2004, 2008, 2010). However, detailed knowledge of the functional behavior of the different structures of the axial regions is still incomplete. Further research is required to understand the pathogenesis of the different pathological conditions of the back as well as to identify the sources of pain in back problems. These data are essential for application of the different methods of physical therapy on equine athletes. Further investigations are needed to establish a rational basis for the training of sport and racehorses in order to develop their neck and back athletic capabilities as well as to identify physical exercises helpful for the management of back problems.

Studies on the effect of lameness from limbs on the movement of the back found a changed posture and a reduced mobility of the caudal back (Gomez Alvarez et al., 2007, 2008). Perhaps the most difficult anatomical region of the horse to understand, from a veterinary perspective, is indeed the caudal back. The caudal back is the lumbar back and the connection between the back and the pelvis. The caudal back is constructed to support and transmit the hind limb's energy to the forelimb (Van den Bogert et al., 1994; Spadavecchia et al., 2002, 2004). Indeed, considerable pathological changes are found in this part of the back at pathological examination (Jeffcott, 1980; Haussler et al., 1999) that would assumingly affect the function of the horse as a whole. We therefore need to address this area of the horse in a methodical manner to better understand the changes to these structures that may be important to the normal function of the athletic horse.

Perhaps the single most important factor to the orthopedic health of the riding horse is the interaction with the rider. The weight of the rider is known to induce extension of the lumbar back and alter the way of moving. While we do not exactly know what these alterations may result in the health of the horse, it is plausible to suggest that if the horse is not properly prepared for this task than injury will assuredly ensue. In the studies with high level dressage horses walking and trotting on a force measuring treadmill with and without their normal rider we could measure the three-dimensional movement of the rider and horse as well as the pressure from the rider and saddle on the back of the horse, and the forces at all four hooves simultaneously (Fig. 10.23). Follow-up studies in this area would be aimed at the effect of rider position and education on the movement and forces in the high-level dressage horse. The effect of the saddle on the movement of the horse is very poorly understood and is subject to considerable speculation. Recent studies using modeling (Schlacher et al., 2004; Peham & Shobesberger, 2004, 2006) have also contributed considerably to our present understanding, Considering the relationship of the rider and horse, the saddle is supposed to be important in the orthopedic health of the horse (De Cocq et al., 2004, 2006; Back, 2013) (Fig. 10.24).

Having these measurements techniques available there is a great need on the objective evaluation of different therapies and rehabilitation programs on horse with dysfunction and/or pain of the back. Currently, most of our therapies are based on experience and conjecture (Marks et al., 1999; Xie et al., 2005; Haussler et al., 2007; Van de Weerd et al., 2007; Gomez Alvarez et al., 2008; Sullivan et al., 2008). Animal owners are often confused and indeed in some cases horses are being treated with methods that are not efficacious and perhaps injurious. A systematic approach in the evaluation of therapies and rehabilitations programs is required to assure the proper care of horses with back-related problems.

Fig 10.23 Horse ridden on the force measuring treadmill.

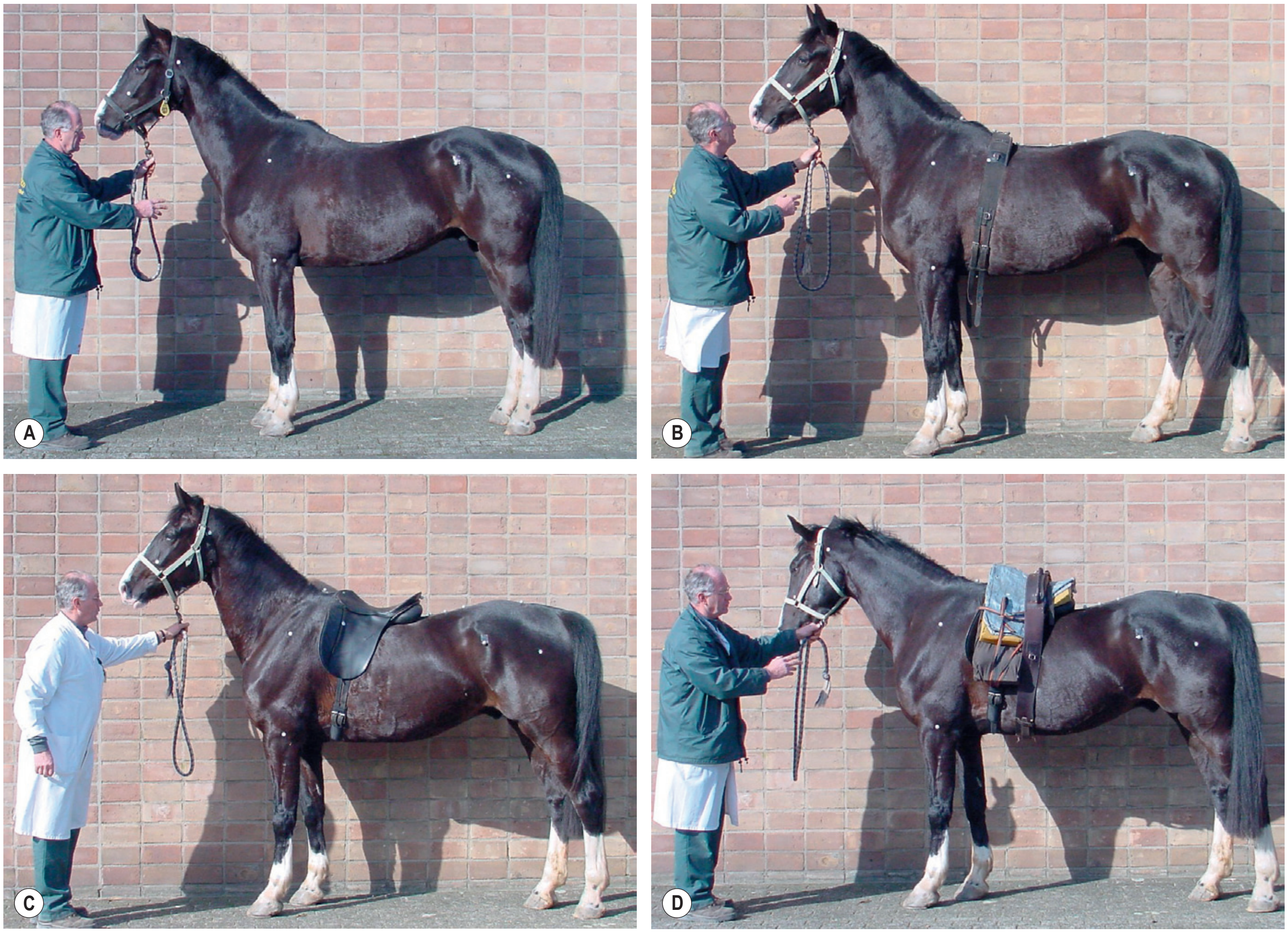

Fig 10.24 Pictures of all four situations: (A) unloaded; (B) with lunging girth; (C) with saddle; (D) with saddle and 75 kg lead.

Reprinted from De Cocq, P., van Weeren, P.R., Back, W., 2004. Effects of girth, saddle and weight on movements of the horse. Equine Vet. J. 36, 758–763, with permission of the Equine Veterinary Journal.

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CHAPTER 11

The effects of conformation

Mikael Holmström, Willem Back

Introduction

For as long as the horse has been used by man, conformation has been regarded as an important indicator of performance and soundness. In accordance with the variety of uses, many different types and breeds of horses have evolved, ranging from heavy draught horses to light, refined racehorses. The result is that a huge number of breeds exist today, each with its own specific conformational characteristics. Nevertheless, conformational traits are not always a guarantee for performance and soundness. The effects of conformation on lameness and athletic potential have mostly been evaluated subjectively and based on anecdotal evidence and experience of the observer (Van Weeren & Crevier-Denoix, 2006). Some people would consider this an 'art form' in which some people have a natural talent for assessing the influence of different conformational characteristics on injury and talent. This chapter will focus on conformational characteristics that, subjectively or objectively evaluated, are considered important for the performance and soundness of the sport horse and the racehorse.

The study of equine conformation

History and tradition

Much has been written about the conformation of the horse during the past 200 years, but very little is based on research. This does not mean that the work is of less interest. It is thought provoking that many of the relationships between conformation and performance described by Bourgelat (1750) and Magne (1866) correspond well with the results from recent research. They stressed the importance of the hindquarter conformation. Horses with hind limbs placed well underneath themselves were found suitable for dressage work, whereas those with hind limbs camped out behind were likely to show good speed. Another early author, Hörman (1837), wrote that a long and forwardly sloping femur facilitates lifting of the hind limb and the horse's ability to step under itself. Ehrengranat (1818) maintained that a sloping shoulder, long radius, short fore cannon and a flat croup are desirable for good movement. According to Schmidt (1928), a small hock angle means that, although the horse will be able to step under itself easily, it will not be able to carry weight on the hind quarters due to decreased strength in the hock. Thus, he regarded a normal hock angle as advantageous for the function of the hind limbs. Most authors of handbooks on conformation evaluation believe that a large hock angle leads to rigid and incorrect hind limb movements as well as an increased strain on the hind limb joints (Wrangel, 1911–1913; Forsell, 1927; Anon, 1940; Bengtsson, 1983). Much of these horsemen's knowledge is still in practice but parts of it seem to have been forgotten in recent years.

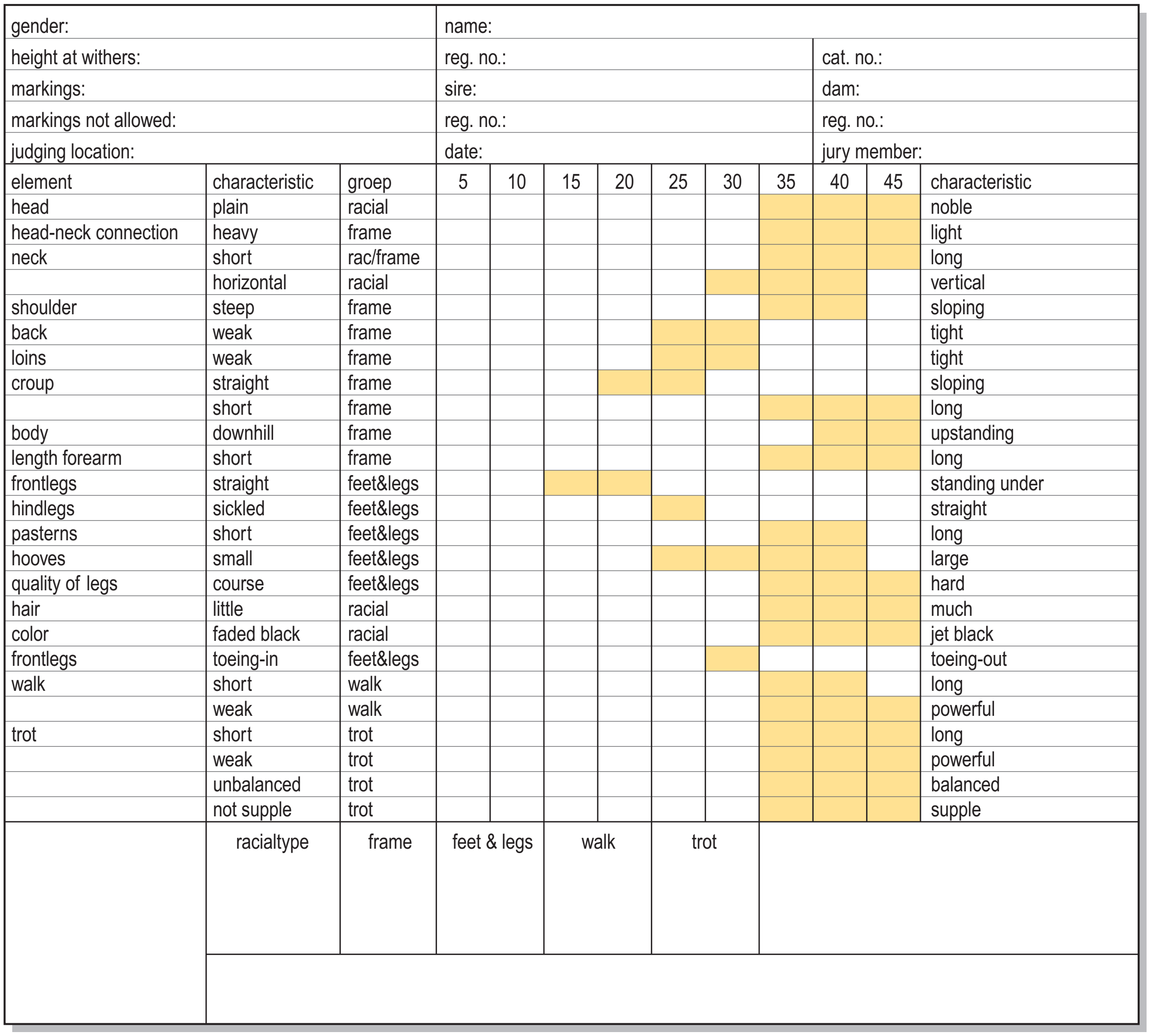
In the practical situation, it often appears that the results from research based on both subjective evaluation and quantitative analysis has confirmed some and rejected other aspects of these old relationships. Some of the 'forgotten' relationships have also been rediscovered. Even though objective methods for conformation evaluation will probably play a more important role in the future, traditional subjective evaluation will always be important. It must be kept in mind that there are aspects of conformation that cannot be measured by objective methods.

Subjective evaluation

Traditional subjective evaluation of conformation is currently performed in many different ways. Almost every country has its own protocol. Furthermore, many breeds have their own specific regulations that instruct the judges how to judge according to the standards of the breed. A problem with traditional evaluation is that subjective evaluations of conformation vary greatly between judges, although some morphological characteristics are assessed more consistently than others (van Vleck & Albrechtsen, 1965; Grundler, 1980; Magnusson, 1985a; Van der Veen, 1996). It is obvious that the reliability of the evaluation is dependent on the skill and experience of the individual judge.

The importance of the traditional conformation evaluation also varies between breeds. In racehorses and Standardbred trotters, racing performance is the main parameter when selecting individuals for breeding. In riding horses intended for dressage and jumping, the selection is mainly based on conformation and performance tests carried out at 3–4 years of age. Since riding horses perform in competition much later in life than racehorses, it is desirable to have a method for prediction of breeding value in young stallions and mares that do not have any performance record. Because the selection of stallions in most countries is stepwise, and performance tests are only applied to those that reach minimum conformation standards, it is very important that conformation evaluation is based on correct criteria.

A step towards a more objective interpretation and analysis of subjectively obtained conformation scores is the so-called linear scoring system, in which trained members of the jury score the conformation of the horse relative to the mean of the population (Van der Veen, 1996). Thus, judging still remains subjective, but it is the interpretation and the analysis of the judges' scores that becomes more objective. In the Netherlands this is done for the Warmblood (KWPN) as well as the Friesian (KFPS) horses at studbook admission (Fig. 11.1).



gender:
name:
height at withers:
reg. no.:
cat. no.:
markings:
sire:
dam:
markings not allowed:
reg. no.:
reg. no.:
judging location:
date:
jury member:

element	characteristic	groep	5	10	15	20	25	30	35	40	45	characteristic
head	plain	racial							▨	▨	▨	noble
head-neck connection	heavy	frame							▨	▨	▨	light
neck	short	rac/frame							▨	▨	▨	long
	horizontal	racial						▨	▨	▨		vertical
shoulder	steep	frame							▨	▨		sloping
back	weak	frame					▨	▨				tight
loins	weak	frame					▨	▨				tight
croup	straight	frame				▨	▨					sloping
	short	frame							▨	▨	▨	long
body	downhill	frame								▨	▨	upstanding
length forearm	short	frame							▨	▨	▨	long
frontlegs	straight	feet&legs			▨	▨						standing under
hindlegs	sickled	feet&legs					▨					straight
pasterns	short	feet&legs							▨	▨		long
hooves	small	feet&legs					▨	▨	▨	▨		large
quality of legs	course	feet&legs							▨	▨	▨	hard
hair	little	racial							▨	▨	▨	much
color	faded black	racial							▨	▨	▨	jet black
frontlegs	toeing-in	feet&legs						▨				toeing-out
walk	short	walk							▨	▨		long
	weak	walk							▨	▨	▨	powerful
trot	short	trot							▨	▨	▨	long
	weak	trot							▨	▨	▨	powerful
	unbalanced	trot							▨	▨	▨	balanced
	not supple	trot							▨	▨	▨	supple
	racialtype	frame	feet & legs		walk		trot					

Fig 11.1 Typical example of a linear scoring form to judge a Friesian sport horse.
Data from http://www.kfps.nl.

Quantitative analysis

Quantitative methods for measuring conformation can be used for an objective evaluation (Rossdale & Butterfield, 2006). Several studies have been carried out, especially on riding horses. The results do often show a great deal of conformity, but in most cases it is impossible to directly compare such parameters as angle measurements from different studies, due to differences in methods of measurement.

Quantitative conformational analysis, as a complement to the traditional evaluation, has been proven to increase the accuracy in the prediction of performance potential in young riding horses (Holmström & Philipsson, 1993). However, applying this knowledge in practice, i.e. in breeding evaluation programs, talent scouting, etc., has been very difficult. Much of the resistance to quantitative analysis is due to the deeply rooted tradition of subjective evaluations in the horse industry, combined with a lack of familiarity with the new methods. In addition, there are some shortcomings in the method itself. Obtaining quantitative measurements has, until recently, been a slow procedure – too slow to be incorporated into stallion tests and other similar events. New computerized methods have now been developed that will speed up the process and make it possible to measure many horses in a short time.

In recent years an objective method, developed in Sweden by Magnusson (1985a) for a study of Standardbred trotters, has been further developed and refined for use in the Thoroughbred racehorse industry in the USA (M Holmstrom and D Lambert, unpublished work, 2004). The method was originally based on reference points marked on the horse with small paper dots glued to the skin (Fig. 11.2), and when first used all measurements were registered 'by hand' from a picture projected on a wall using a simple measuring band and a protractor. Later the whole procedure was computerized and the measurements were obtained from a digital photo on a laptop computer. The measurements were registered by clicking with the mouse on the white markers. The computer then calculates all length and angle measurements (Fig. 11.3). In the most recent version joint angles and length and proportional measurements can be obtained from a picture with just one paper dot on the hip.

Conformation and growth

Conformation evaluation in young growing horses calls for an understanding of the effect of age, i.e. the effect of growth on the conformation. The accuracy of quantitative methods applied to foals and yearlings, with the aim of predicting future performance and soundness, are dependent on age adjustments according to reliable growth curves for each individual measurement. Growth curves for some body measurement such as height at the withers

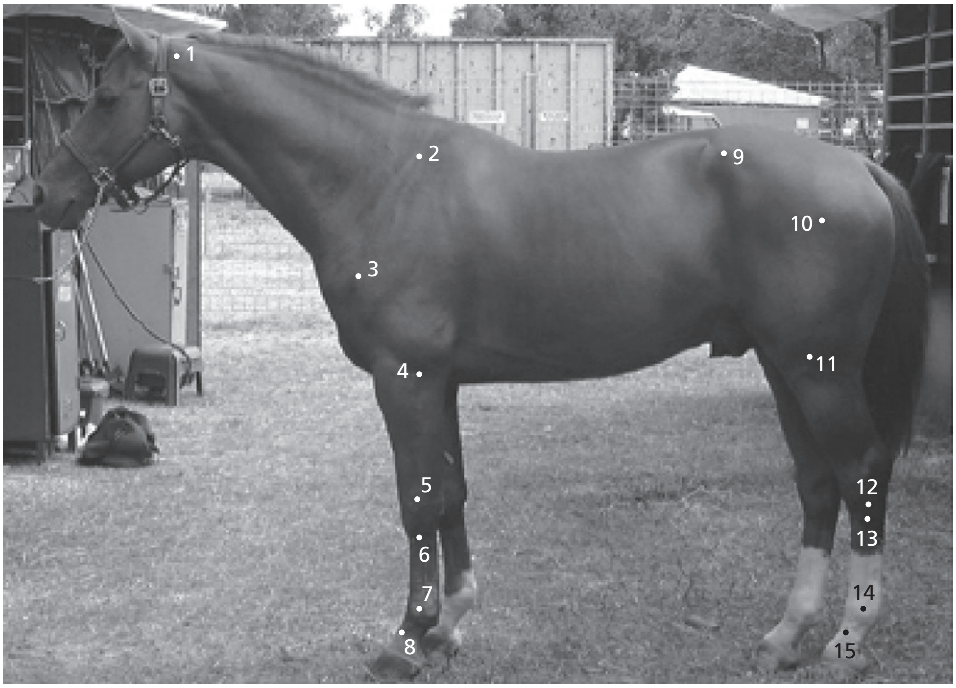


Fig 11.2 Standard position and reference points used in conformation analysis of Thoroughbred racehorses. Head and forelimbs: 1, the cranial end of the wing of the atlas; 2, the proximal end of the spine of the scapula; 3, the posterior part of the greater tubercle of the humerus; 4, the transition between the proximal and middle thirds of the lateral collateral ligament of the elbow joint; 5, the lateral tuberosity of the distal end of the radius; 6, the space between the fourth carpal and the third and fourth metacarpal bones; 7, the proximal attachment of the lateral collateral ligament of the fetlock joint to the distal end of the third metacarpal bone; 8, the proximal attachment of the lateral collateral ligament of the pastern joint to the distal end of the first phalanx. Hind limbs: 9, the proximal end of the lateral angle of the ilium; 10, the center of the anterior part of the greater trochanter of the femur; 11, the proximal attachment of the lateral collateral ligament of the stifle joint to the femur; 12, the attachment of the long lateral ligament of the hock joint to the plantar border of the calcaneus bone; 13, the space between the fourth tarsal and the third and fourth metatarsal bones; 14, the proximal attachment of the lateral collateral ligament of the fetlock joint to the distal end of the third metatarsal bone; 15, the proximal attachment of the lateral collateral ligament of the pastern joint to the distal end of the first phalanx.

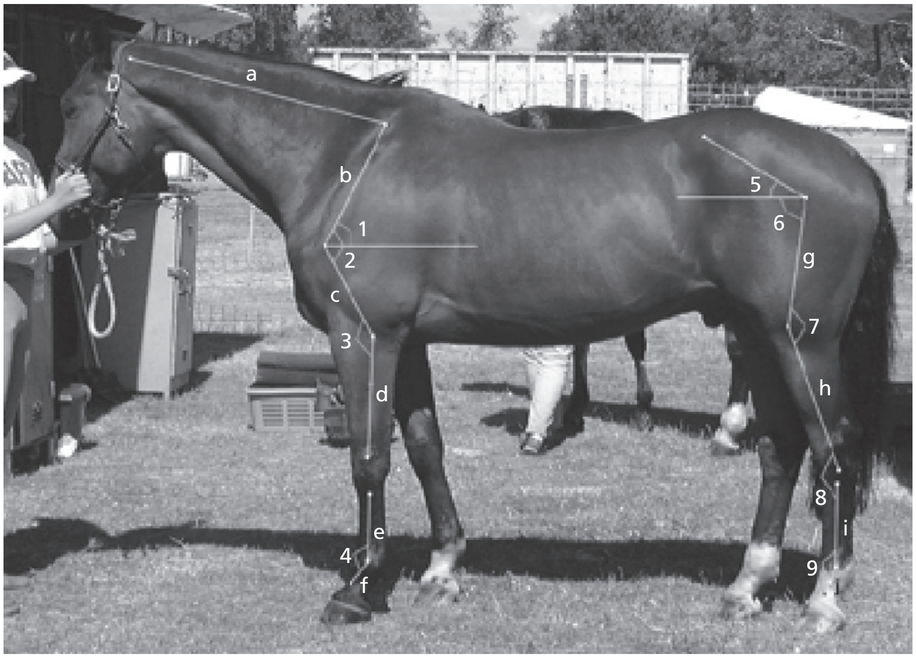


Fig 11.3 Length measurements: a, neck; b, shoulder; c, humerus; d, radius; e, fore cannon; f, fore pastern; g, femur; h, tibia; i, hind cannon; j, hind pastern. Angle measurements: 1, shoulder inclination; 2, shoulder joint; 3, elbow joint; 4, fore fetlock joint; 5, pelvis inclination; 6, femur inclination; 7, stifle joint; 8, hock joint; 9, hind fetlock joint.

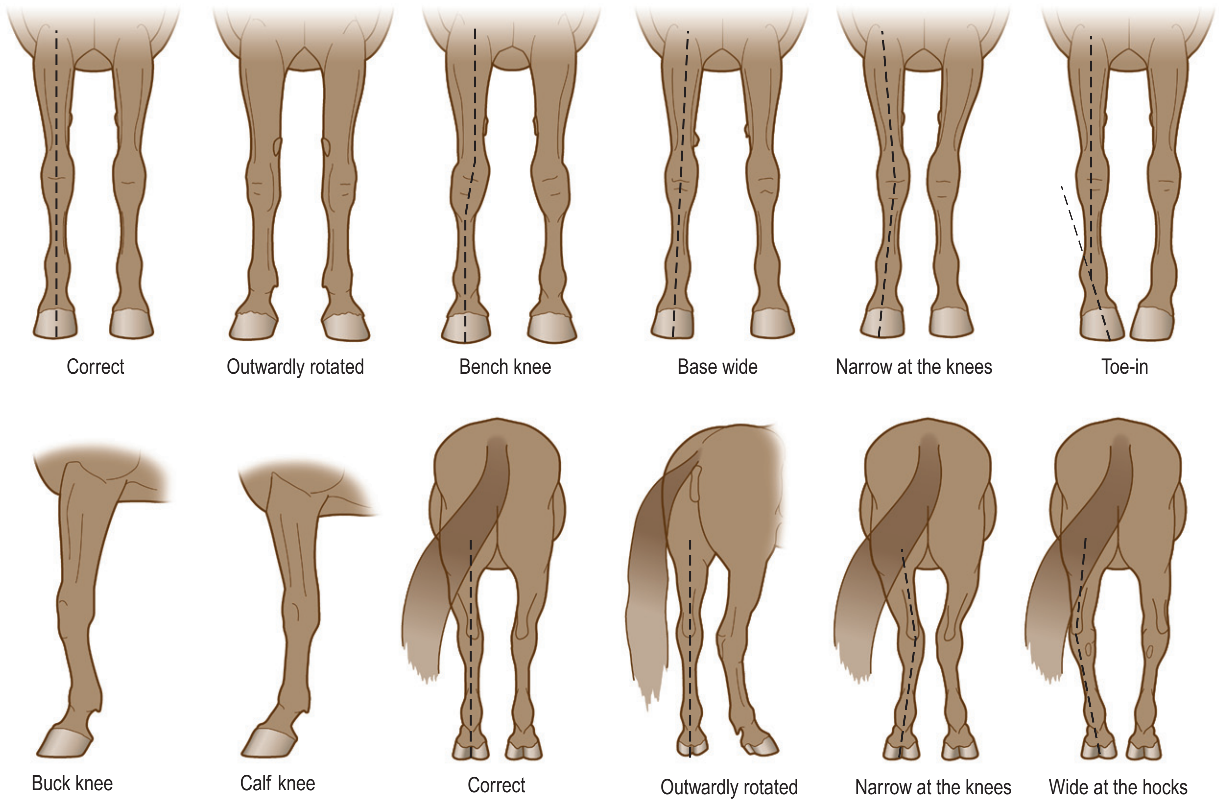


Fig 11.4 Deviations of limb and toe axes in the fore and hind limbs.

are mainly breed specific while many other growth curves are specific for the method used for measuring a trait. Thus, growth graphs obtained by one quantitative method cannot be used together with a different quantitative method.

Conformation, performance and soundness

Searching for talented young sport horses involves evaluation of many different qualities. Temperament, movement and jumping ability are of course the most important in riding horses, but the significance of conformation must not be neglected. Furthermore, dressage riders seek 'good looking' horses, with conformation that facilitates good movements, soundness and, above all, the ability to show a high level of collection. The competition results of Grand Prix horses are certainly dependent on the skill of their riders and trainers, but their conformation and movement must have the basic qualities that create the necessary conditions for successful training of the horse. Resistance from the horse is often interpreted as poor temperament but might just as well be due to pain or lack of ability to carry weight on the hind limbs caused by inappropriate conformation and/or movement. Potential world class Grand Prix dressage horses are difficult to find because many promising young horses with excellent gaits fail to learn passage, piaffe and other collected movements, resulting in years of wasted training. The ability to collect and work in balance is also very important in a jumping horse.

Conformation is also important in the selection of most other performance horses including Thoroughbred racehorses and Standardbreds. However, a successful use of conformation as an indicator of performance requires good knowledge of the relationships between conformation and performance, as well as a reliable method for its evaluation. In most cases a subjective evaluation is not sufficient. Many important variables are almost impossible to judge correctly without objective measurements.

This chapter will focus on objective measurements and subjective conformational characteristics that are important for the function of sport horses and racehorses. For those who have a specific interest in the characteristics of a specific breed, that information can be obtained from the respective breeding organization.

Deviations of limb and toe axis

One important part of the subjective evaluation is to describe deviations of limb and toe axes, if any. The most common deviations are described in Figure 11.4. Deviations from the straight (normal) limb and toe axes have traditionally been considered as a considerable weakness. However, not all deviations from what has been the desired conformation should be judged as abnormal. About 80% of all Warmblood riding horses and Standardbred trotters had outwardly rotated hind limbs (Magnusson, 1985a; Holmström et al., 1990). The frequency of this 'faulty conformation' is so high that it must be regarded as normal. Boldt (1978) maintains in his dressage handbook that outwardly rotated hind limbs facilitate exercises such as half-pass and shoulder-in. In this context, it is important to distinguish between hind limb rotation and toe-out conformation as well as between rotated hind limbs and hind limbs that are narrow at the hocks (cow hocked). Confusion between these characteristics should be avoided, especially as the rotated hind limb conformation should be considered normal. To judge this aspect of conformation, the observer should stand behind the point of the hock rather than behind the tail of the horse. The latter position makes it impossible to see if the rotated hind limb is also narrow at the hocks.

Table 11.1 Frequencies (percent) of subjectively scored deviations of limb and toe axes in different groups of riding horses

Characteristic	Mild				Moderate				Severe				Total			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Forelimbs																
Front view																
Outwardly rotated	3.0	7.1	3.0	3.7	–	3.6	–	0.6	–	–	–	–	3.0	10.7	3.0	4.3
Bench knee	48.4	32.5	53.0	48.4	6.1	21.4	11.0	11.8	–	–	–	–	54.5	53.6	64.0	60.2
Base wide	–	–	–	–	–	–	1.0	0.6	–	–	–	–	–	–	1.0	0.6
Narrow at knees	9.1	21.4	10.0	11.8	–	–	–	–	–	–	–	–	9.1	21.4	10.0	11.8
Toe-in	39.4	25.7	37.0	37.2	9.1	10.7	7.0	8.1	–	–	3.0	1.9	48.5	46.4	47.0	47.2
Side view																
Buck knee	18.2	35.7	6.0	13.8	3.0	10.7	2.0	3.7	6.1	–	–	1.2	27.3	46.4	8.0	18.7
Calf knee	9.1	7.1	21.0	16.2	3.0	–	3.0	2.5	–	–	–	–	12.1	7.1	24.0	18.7
Hind limbs																
Rear view																
Outwardly rotated	84.9	82.1	67.0	73.3	3.0	3.6	7.0	5.6	–	–	–	–	87.9	85.7	74.0	78.9
Narrow at the hocks	–	7.1	10.0	7.4	–	–	–	–	–	–	–	–	–	7.1	10.0	7.4
Wide at the hocks	–	14.3	3.0	4.4	–	–	1.0	0.6	–	–	–	–	–	14.3	4.0	5.0
Toe-out	–	0	1.0	0.6	–	–	–	–	–	–	–	–	–	–	1.0	0.6
Side view																
Camped under	–	7.1	4.0	3.7	–	–	1.0	0.6	–	–	–	–	–	7.0	5.0	4.3

1, elite dressage horses (n = 33); 2, elite show jumpers (n = 28); 3, riding school horses (n = 100); 4, total (n = 161).

Data from Holmström et al. (1990). ©EVJ Ltd.

Bench kneed conformation in the forelimbs together with a toe-in conformation is a very common type of deviation in riding horses, while outwardly rotated forelimbs are seldom seen in adult riding horses (Holmström et al., 1990). According to Magnusson and Thafvelin (1985a) the converse is the case in Standardbred trotters. This difference may partly be explained by the fact that trotters are narrower through the chest than the riding horses, even after adjustment for different height at the withers. Several other authors have also found that bench knee and toe-in conformation seems to be related to weight and width of the breast (Santschi et al., 2006; Firth et al., 1998). Santschi et al. (2006) studied the development of front limb deviations in foals and concluded that calf knee conformation in foals tends to self correct and eventually and it was also found that the incidence of bench knee increased between the age of 1 week and 18 months. Anderson et al. (2004) compared conformation to injury in Thoroughbreds and found that calf knees were somewhat protective agains injuries. Today most clinicians feel that mild carpal valgus is protective and is actually normal during growth.

As in the hind limbs, there is often confusion between outwardly rotated forelimbs and a toe-out conformation. Even though bench knee conformation in a riding horse does not have any documented negative effects on the long-term performance, bench kneed horses have been reported to have a higher frequency of splints on the medial side of the third metacarpal bone (Adams, 1974; Davidson, 1970; Nordin, 1980).

The frequency of toe-in and/or bench knee conformation, as well as of most other deviations, was the same among the elite dressage horses and show jumpers as in a group of riding school horses (Table 11.1). This indicates that mild-to-moderate deviations from the 'normal' limb conformation do not impair either soundness or performance in riding horses. However, it is important to emphasize that, even though mild and moderate deviations can be accepted, severe deviations of any type should be considered as a major weakness. Several authors have claimed that there is an increased stress to the distal parts of the limbs in horses with toe-out and toe-in conformation (Churchill, 1962; Rooney, 1968; Beeman, 1973; Magnusson, 1985c). This can often be noticed as synovial distensions of the fetlock and the coffin joints, as well as swelling of the distal metacarpal growth plate.

According to Adams (1974), calf knee (back at the knee) conformation may predispose to lameness, whereas buck knee (over at the knee) conformation is less serious. This is probably true for Standardbreds as well as Thoroughbred racehorses that overextend the carpal joint considerably during the midstance phase. Steel et al. (2006) reported that carpal lameness occurred in 28% of a group of Standardbred horses and was present in 56% with forelimb lameness. Of the variables studied, poor forelimb conformation and more intense speed training were predisposing factors. Back et al. (1996) proved in Warmbloods that there is a relationship between a calf knee conformation at square stance and carpal hyperextension at trot.

Head, neck and body

Many of the criteria that are used to describe the head, neck and body are very difficult or impossible to analyze objectively. Such criteria are type, the setting of the neck, the shape of the withers, the 'harmony' of the horse, etc. They have to be evaluated subjectively. Other characteristics, such as length of the neck and body or height at the withers, can be objectively measured or subjectively scored (Van der Veen, 1996).

It is obvious that there are significant relationships between head, neck and body characteristics and performance, which are reflected in the difference between, for example, a slow, heavy draught horse and a fast, elegant racehorse. Thus, differences between breeds have, to a large extent, originated from different demands upon the horses. However, within a certain breed it is much more difficult to correctly describe and evaluate the relatively subtle differences, and this difficulty has been associated with a rather large variation between judges (van Vleck & Albrechtsen, 1965; Grundler, 1980; Magnusson, 1985a). Long experience, a deep understanding of the influence of conformation on performance and, when appropriate, inclusion of objective measurements can minimize these discrepancies. Figure 11.5 shows two horses, one with a low set neck and the other with a well set neck.

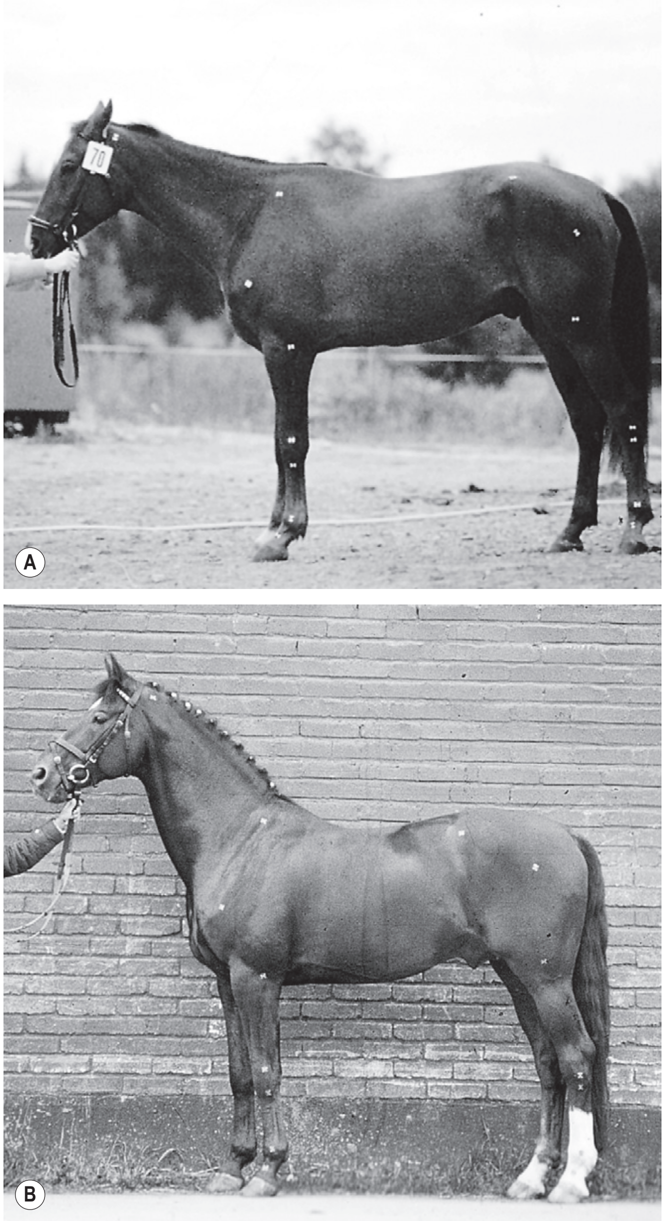


Fig 11.5 Horses with (A) low set neck and (B) well set neck.

In handbooks on evaluation of the conformation of sport horses, some characteristics are described more consistently. A long and well-set neck are considered important for most kinds of performances (Wrangel, 1911–1913; Forsell, 1927; Anon, 1940; Boldt, 1978; Bengtsson, 1983) and a long well-developed withers is said to be important for horses that are working under saddle (Van der Veen, 1996). In a large, cohort study of a Warmblood population, in which linear scoring results collected at studbook admission were related to later performance in dressage and show jumping, it appeared that when horses were genetically selected on height at the withers, neck length was shorter. Longer necks were genetically related to a conformation more suited for dressage performance but had less impact on jumping performance (Ducro et al., 2009a).

In contrast, results from objective studies show that elite show jumpers have significantly longer necks than elite dressage horses and 'normal' horses (Holmström, unpublished data) (Table 11.2). Other studies showed significantly shorter necks in elite dressage horses than in other riding horses but there was no significant correlation between the length of the neck and gaits under saddle in 4-year-old riding horses (Holmström et al., 1990; Holmström & Philipsson, 1993). Available objectively obtained results indicate that a long neck might be an advantage for jumping horses, probably because it makes it easier for the horse to maintain balance over the fence. In dressage horses, the setting of the neck is probably more important than its length (Van der Veen, 1996). It is generally agreed among riders and trainers of riding horses that a low set neck makes it very difficult to work the horse in a proper frame. However, there are no data supporting this statement, mainly because of the difficulties of objectively measuring the setting of the neck.

In Thoroughbred racehorses the length of the neck is part of the overall subjective conformation evaluation of young stock. The general opinion is that sprinters should have shorter necks than stayers but objective analysis of 780 grade 1 and group 1 winners in the USA and Europe showed that on both dirt and turf the sprinters, i.e. distances up to 7 furlongs, had slightly longer necks compared to the rest of the grade 1 and group 1 winners (M Holmstrom, unpublished work, 2009). The differences were small but statistically significant.

The setting of the head to the neck is also of importance (Van der Veen, 1996). A wide throat latch has always been considered important in racehorses, Standardbred trotters and Quarter Horses because it is said to facilitate breathing. In dressage horses, a wide distance between the wing of the atlas (first cervical vertebra) and the posterior ridge of the mandible has been considered important by riders. In a study of differences between elite dressage horses, elite jumping horses and 'normal' horses it was found that both the dressage horses and the jumpers had significantly greater width in this area than other horses (Holmström, unpublished data). A possible explanation is that a small distance might cause problems, most likely a mechanical resistance, at higher levels of collection when the horse is required to perform a maximal flexion at the poll.

Height at the withers has been linked to jumping performance in several studies (Neisser, 1976; Langlois et al., 1978). Müller and Schwark (1979) found that show jumpers were taller at the withers than dressage horses. Even though there is a positive correlation between height at the withers and jumping performance up to a certain limit (around 172 cm), it must be remembered that there is a great variation among elite show jumpers. The range of the height at the withers was between 158 cm and 178 cm in a study of the World Cup finalists in 1997 (Holmström, unpublished data). According to Ducro et al. (2009a) height at the withers was genetically related to dressage ranking but not to jumping ranking.

It is generally agreed that height at the withers is not related to stride length in different gaits (von Wagener, 1934; Krüger, 1957; Dušek et al., 1970; Dušek, 1974). However, Holmström and

Table 11.2 Comparison of adjusted means for length and angle measurements*

Variable	4-year olds	Dressage	Jumping	Injured
Length measurement (cm)				
Neck	70.51^{a}	71.55^{ab}	74.02^{c}	72.87^{bc}
Scapula	40.07^{a}	42.00^{c}	40.51^{a}	41.00^{ab}
Humerus	32.10^{a}	33.07^{b}	32.14^{a}	32.01^{a}
Radius	37.15^{a}	37.64^{b}	37.69^{a}	37.58^{ab}
Fore cannon	20.92^{a}	21.56^{b}	21.37^{b}	21.14^{ab}
Fore pastern	9.12^{a}	9.52^{b}	9.51^{b}	9.16^{a}
Femur	40.24^{a}	41.20^{b}	40.36^{a}	40.09^{a}
Tibia	48.52^{a}	49.14^{ab}	49.74^{b}	49.40^{ab}
Hind cannon	26.83^{a}	27.36^{b}	26.68^{a}	26.55^{a}
Hind pastern	8.74^{a}	9.01^{ab}	9.34^{b}	9.07^{ab}
Angle measurements (°)				
Shoulder inclination	64.5^{a}	66.3^{b}	67.0^{b}	66.5^{b}
Shoulder joint	126.3^{a}	124.5^{b}	126.2^{a}	126.0^{a}
Elbow joint	152.4^{a}	148.5^{b}	151.1^{a}	150.7^{a}
Fore fetlock joint	148.7^{a}	149.9^{ab}	151.3^{b}	148.2^{a}
Pelvis inclination	31.0^{a}	27.5^{b}	28.2^{b}	31.0^{a}
Femur inclination	85.4^{a}	84.7^{b}	84.5^{b}	87.8^{c}
Stifle joint	154.1^{a}	155.6^{b}	154.0^{a}	153.4^{a}
Hock joint	159.4^{a}	160.4^{a}	159.2^{a}	157.0^{b}
Hind feltlock joint	154.6^{a}	153.4^{a}	155.7^{a}	156.1^{a}

*Between elite dressage horses (n = 40), elite show jumpers (n = 51), 4-year-olds tested at quality events (n = 217) and horses with back problems or recurrent lameness problems (n = 52). Differences in sex, and, for the stifle angle, differences in femur inclination, have been taken into consideration.

Values with different superscripts differ significantly from each other.

Philipsson (1993) found positive correlations between height at the withers and subjective scores for the canter in 4-year-old riding horses. However, elite dressage horses have not been found to be larger than other riding horses (Barrey et al., 2002). Ducro et al. (2009a) found that height at the withers was positively genetically correlated to conformation grades for sports performance. The results above indicate that judges might be positively influenced by the size of the horse, while in reality it has just a marginal impact on elite performance in dressage and show jumping.

Table 11.3 Significant conformational differences between horses treated for recurrent lameness and other insured horses

Variable	Lame horses mean (SD)	Sound horses mean (SD)
Height at the withers	165.4 (4.2)	163.5 (3.60)*
Femur inclination	86.7 (1.7)	85.4 (2.3)**
Hind fetlock joint angle	156.6 (6.2)	153.8 (6.4)*

*$p < 0.05$; **$p < 0.01$.

In Standardbred trotters many authors have found a positive correlation between height at the withers and performance (Bantoiu, 1922; Richter, 1953; Magnusson, 1985d), while a negative correlation between height at the withers and soundness was found by Magnusson (1985c). In Thoroughbred racehorses no significant effect of the height at the withers on performance has been found by Holmström (unpublished work, 2004) but the height at the withers is likely to have a similar negative correlation to soundness as in Standardbred trotters. In a study of relationships between conformation and soundness in insured riding horses in Sweden, horses with recurrent lameness problems were significantly taller at the withers than the sound horses (Table 11.3) (Holmström, unpublished data). This was confirmed by a (UK) study among owners of registered dressage horses, in which it was reported that 33% of the horses had been lame at some time during their career, 24% of these within the previous 2 years (Murray et al., 2010). A number of factors were associated with the occurrence of lameness including increased risk for older and bigger horses.

Swedish Warmblood riding horses (Holmström et al., 1990) and Hannovarian stallions (Dušek, 1974) seemed to have a rectangular body shape, i.e. the length of the body is greater than the height at the withers. Oldenburg and East Friesian breeds have also been shown to have this body form (Degen, 1953; Weferling, 1964). At the Royal Dutch Warmblood selections, stallions are selected for 'rectangular' body proportions in contrast to a 'square' body (Van der Veen, 1996). Müller and Schwark (1979), on the other hand, measured 687 horses competing in dressage, show jumping and 3-day events and found them to have a rather short body form. The horses had about the same height at the withers as Swedish Warmbloods but it was not clear how the body length was measured. Neisser (1976) and Schwark et al. (1977) found negative correlations between body length and performance in show jumping.

The average body length of 780 grade 1 and group 1 winners in the USA and Europe analyzed by Holmström (unpublished work, 2009) was 108% of the height at the withers, i.e. the Thoroughbred racehorses had, on average, a long body form. No significant correlation between body length and performance has been found but a short body form is very rare among top class racehorses. No significant differences in body length between grade 1 and group 1 winners on dirt and turf were found. The influence of body length on performance is still somewhat unclear but a majority of the available studies indicate that a somewhat long body form is preferable.

There is not much objective data available on the effect of the length of the body on soundness but Magnusson (1985c) found that Standardbred trotters with a short back had fewer problems with back pain then those with a long back. On the other hand, horses with short backs showed more scalping problems. This confirms the statement that a short back is a strong back but predisposes to interference, such as over-reaching, forging and scalping (Pritchard, 1965; Nordin, 1980; Van der Veen, 1996).

Scope, as defined by Holmström and Lambert, i.e. the relationship between the length of the back and the distance between the forelimbs and hind limbs, has shown to have a significant impact on the performance of Thoroughbred racehorses on dirt tracks in the USA (Holmström, unpublished work, 2004). The study, including 2600 racehorses in the USA and Europe, showed that the scope, as with most other conformational traits, had a non-linear correlation to performance on a mile and longer, while it was of less importance for sprinter performance. It was also less important for the performance on European tracks. The optimal scope increased with race distance, i.e. the longer the race distance, the longer the horse's back relative to the distance between the forelimbs and hind limbs.

Forelimbs

A long and sloping shoulder has always been considered as advantageous for the movements of the forelimbs (Ehrengranat, 1818; Van der Veen, 1996). Sellet et al. (1981) suggested that a long sloping scapula was associated with ergonomic efficiency in 2-year-old pacing fillies. In a study of conformational characteristics of elite dressage horses and show jumpers, both groups had significantly more sloping shoulders (Holmström et al., 1990). There was also a significant correlation between high gait scores and a sloping shoulder in 4-year-old riding horses (Holmström et al., 1993). Nevertheless, in a recent study (Table 11.2), the opposite result was found (Holmström, unpublished data). Apparently, the slope of the shoulder, objectively measured, does not have to be directly connected to elite performance in riding horses. Sport horses can perform at top level with a less sloping shoulder because other qualities are more important. The Royal Dutch Warmblood studbook uses the criterion that horses should have a functional, but nonetheless 'eye-catching' conformation, that would allow and preferably facilitates sports performance at the highest level (Van der Veen, 1996). Henninges (1933), however, found a positive correlation between a sloping shoulder and stride length in walk. Theoretically, a more sloping shoulder might facilitate the forward and upward movement of the forelimbs during the last part of the swing phase in trot (Fig. 11.6). Back et al. (1996) correlated the joint angles at square stance to their kinematics at trot in a group of young adult Warmbloods (n = 24) and proved that a sloping scapula was correlated to a more protracted forelimb.

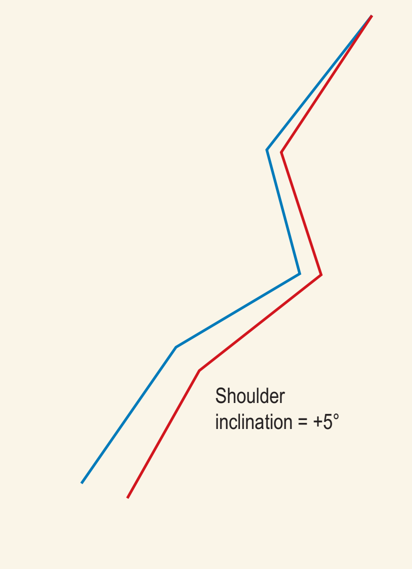


Fig 11.6 Possible effect of different shoulder conformation on forelimb orientation at the beginning of the swing phase retraction: 5° difference in shoulder inclination and all other angles unchanged.

Subjectively, it is very difficult to correctly estimate the real slope of the shoulder. The problem is that in some horses there is a considerable discrepancy between the external outline of the shoulder and the real inclination of the scapula (Fig. 11.7). To be able to judge the slope of the shoulder correctly, it is necessary to palpate the position of the scapula. On the other hand there is one important aspect of the shoulder that might have been underestimated. A seemingly long and sloping shoulder in combination with a long and well-developed withers will place the rider more to the rear on the horse, resulting in better balance. As a result of the better balance, the horse will be able to move its forelimbs more freely, and reach higher and more forward. Thus, the effect of a 'subjectively' sloping shoulder on the forelimb movements might be more important than the real or 'objective' slope.

Of the forelimb conformational details, the length of the humerus showed the strongest correlation to good gaits in 4-year-old riding horses (Table 11.4) (Holmström et al., 1993; Holmström, unpublished data). Elite dressage horses have been shown to have a significantly longer humerus than both show jumpers and 'normal' horses (Table 11.2). In the older literature, the importance of a long

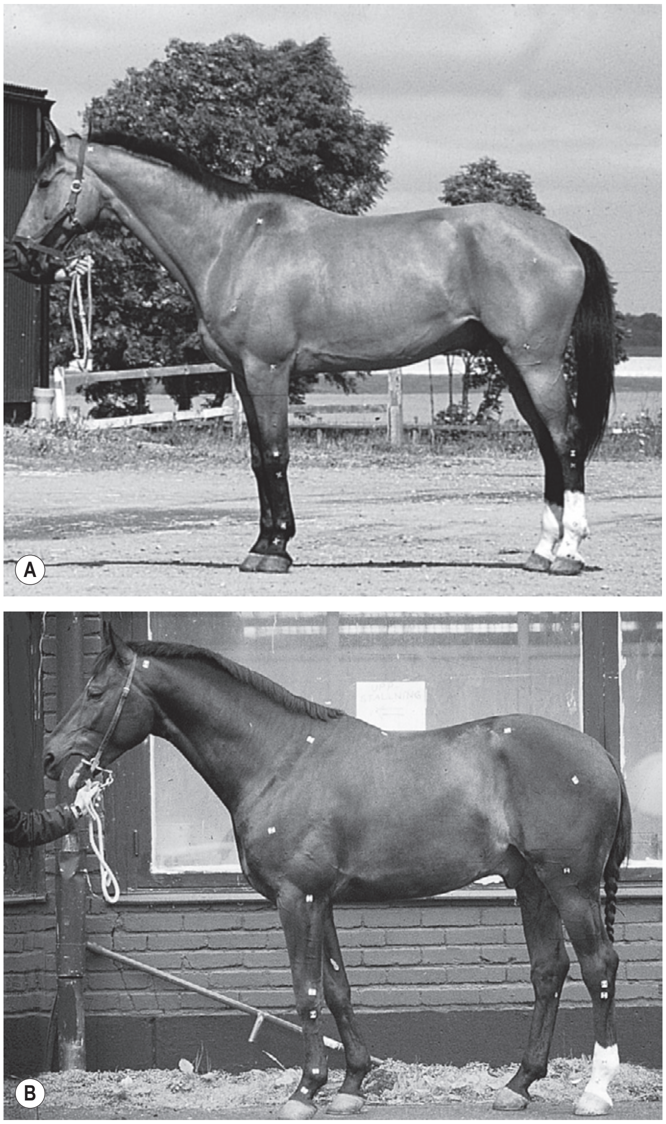


Fig 11.7 (A,B) Horses with different slopes of the shoulders and scapula. Note the discrepancy between the real slope and the outer contour in (B).

Table 11.4 Results from multiple regression analyses of the effects of conformation measurements and scores on gaits under saddle and jumping ability[a]

	Gaits under saddle			Jumping ability		
Variable	**1984**		**1996**	**1984**		**1996**
Objective measurements						
Humerus length	0.16***	0.12**	0.12**	0.10**	–0.12	–0.13
Pelvis inclination	–0.04*	–0.02	–0.005	–0.005	0.05	0.03
Femur inclination	–0.21***	–0.15***	–0.13***	–0.08**	–0.06	0
Stifle angle	0.04*	0.01	–0.006	–0.01	0.09	–0.04
Hock angle	–	–	–	–	0.01	0.11*
Subjective scores						
Type	–	0.11	–	–0.04	0.40	0.02
Head, neck and body	–	0.12	–	0.11	–0.13	0.18
Extremities	–	–0.08	–	0.02	0.18	–0.28
Walk	–	0.98***	–	0.25***	0.08	0.05
Trot	–	0.19**	–	0.45***	0.16	0.11
Coefficient of determination, R2 (%)						
Conformation score	–	26.12	–	25.13	3.86	0
Objective measurements	24.76	24.76	13.32	13.32	1.85	1.31
Score + measurements	–	–	42.24	42.61	3.84	0.42

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

[a] Partial regression coefficients for variables that showed either significant correlation to the performance traits or significant differences between elite and 'normal' horses were calculated. Effects of sex and event (site) were included in the model.

radius and a short fore cannon is often stressed (Ehrengranat, 1818; Schmidt, 1928; Wrangel, 1911–1913), but surprisingly the length of the humerus is never mentioned.

In the subjective judging procedure good forelimb movements are often described in terms of 'freedom of the shoulders'. The analyses of high-speed films have shown that 'freedom of the shoulders' is not a completely adequate expression. The most significant differences between good and poor forelimb movements were found in the elbow and carpal joints, with the elbow being more important (Clayton et al., 2004; Holmström et al., 1994). At the most forward position of the forelimb, the elbow joint was flexed ~30° more in the horses with good forelimb movements compared to those with poor movement. Consequently, the fore hoof was lifted higher above the ground and reached more forward. The effect of the greater flexion in the elbow and carpal joints is shown in Figure 11.8. The significance of elbow joint flexion for the forelimb movements explains why a correlation was found between the length of the humerus and gait score in the conformational studies: a long humerus gives a long triceps muscle that may facilitate a larger range of elbow movements. The difference in forelimb movements between good and poor horses can also to some extent be explained by differences in the rotation of the scapula in the sagittal plane parallel to the thorax. Back et al. (1994) found that high subjective gait scores were significantly correlated to more scapular rotation. The humerus is significantly shorter in horses where less knee action in the forelimbs is preferred, such as Thoroughbred racehorses, or in horses where the forelimb movements have no influence on performance (Holmström, unpublished

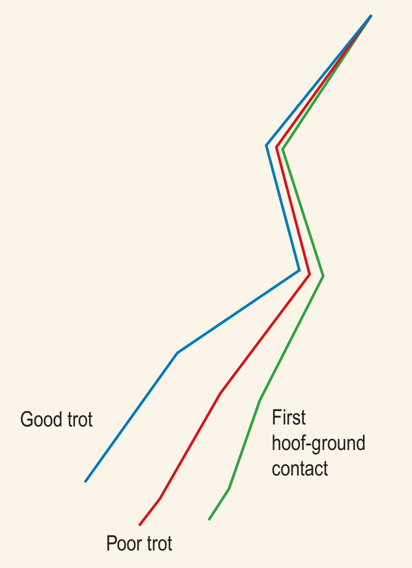


Fig 11.8 Forelimb angles at the most forward position of the limb.

data). According to Sellet et al. (1981) a long forearm is important in pacing Standardbreds.

In Thoroughbred racehorses the slope of the humerus has shown to be of significant importance for the efficiency of the stride (Holmström, unpublished work). A vertical humerus has a negative impact on the performance. The most likely explanation is that a vertical humerus limits the forward reach of the forelimb and the stance duration of the forelimbs, which in turn has a negative effect on the horse's ability to run at high speed and breathe normally. A horse cantering or galloping can only exhale during the stance phase of the front limbs. If the stance duration of the front limbs at full speed becomes too short the horse will not be able to exhale the same volume as it inhales, which will cause it to stop breathing normally.

The fore pastern has been shown to be significantly longer in elite dressage and jumping horses than in other riding horses, while the inclination to the horizontal plane showed no differences (Holmström, 1990). Horses with short, upright fore pasterns are considered to be prone to injuries, as are those with long sloping pasterns (Adams, 1974). Magnusson (1985c) found more swellings of the superficial flexor tendon in horses with upright pasterns. The short upright pastern probably also has a negative effect on the movements due to less elasticity. When joint angles at square stance were correlated to their kinematics at trot in a group of young adult Warmbloods (n = 24), it was proved that a more extended fore fetlock joint (larger palmar angle) was correlated to more extension and more protraction at the trot (Back et al., 1996). This would generate more suppleness in the forelimb with generally a passive 'strut' function, which is correlated to higher scores for the trot and 'good gait' (Back et al., 1994). Ergonomic efficiency in pacing horses has been shown to be correlated to an elastic fetlock joint (Sellet et al., 1981).

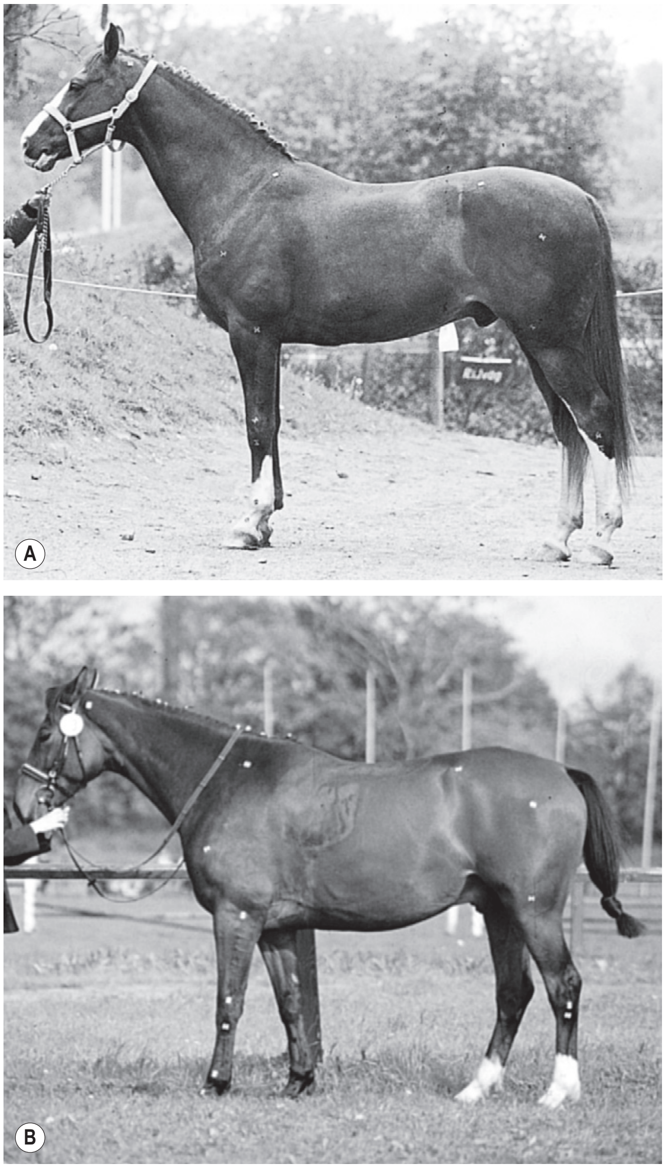


Fig 11.9 Horse with large discrepancy between (A) the slopes of the pelvis and the croup, compared to a horse (B) with rather good correspondence between pelvis and croup.

Hind limbs

The importance of the hind limbs for sport horse performance is obvious (Back et al., 1995). The hind quarters constitute the 'engine' of the horse that, depending on the type of performance, should lift the horse over a fence, push it forward at a high speed or over long distances or, as in dressage horses, carry a lot of weight. Both horsemanship handbooks and many scientific studies indicate that good conformation of the hind limbs is essential for good performance and soundness (Van der Veen, 1996).

A small angle of the pelvis to the horizontal plane has been reported to have a positive effect on performance in dressage and jumping horses. In a recent study, elite dressage and jumping horses had significantly flatter pelvises than 'normal' riding horses (Table 11.2). The same results were found in a similar study in 1988 (Holmström et al., 1990). Holmström et al. (1993) also found a positive correlation between the slope of the pelvis and scores for the walk at 4-year-old tests for riding horses. Ehrengranat (1818) states that a flat croup is desirable for good movements. However, there is not always a good correspondence between the slope of the croup and pelvis. Many horses have a flat croup combined with a steep pelvis (Fig. 11.9). This must be taken into consideration when evaluating conformation subjectively. In analyses of high-speed films it has been found that dressage horses classified as good movers had a larger rotation of the pelvis during the stride than those classified as poor movers (Holmström et al., 1994). Pelvic rotation is one of the biomechanical parameters that contribute to elastic gaits in good dressage horses, while a non-rotating pelvis results in short and inelastic gaits. A flat pelvic conformation facilitates pelvic rotation. Rotation of the pelvis during the stride is more pronounced in passage than in the other paces, and the degree of change in the pelvic movement pattern from trot in hand to passage is approximately the same in all horses, irrespective of the initial pattern (Holmström et al., 1995a,b). Pelvic rotation in the trot might be a determinant of passage performance. Back et al. (1996) found that a flexed hip joint at movement was correlated to a more vertical position of the pelvis and a more horizontal position of the femur at square stance. Furthermore, the more vertical position of the pelvis was correlated to a less retracted hind limb providing a more collected appearance. This does not, however, mean that a more sloping pelvis has a positive correlation to real gait quality or dressage performance. The majority of studies on dressage horses and show jumpers lead to the conclusion that these horses' performances are facilitated by relatively flat pelvises. Thus, it is important to evaluate pelvis slope correctly in riding horses.

In Thoroughbred racehorses Holmström (unpublished work, 2004) found strong correlations between a smaller angle between the pelvis and horizontal plane (flatter pelvis) and top performance. As mentioned earlier a flat pelvis facilitates pelvic rotation, which very important part of an efficient stride in the racehorse.

In Standardbred trotters a steeply sloping pelvis has been reported to be related to synovial distention in the femoropatellar joint and the medial synovial sac of the femorotibial joint, and also to have a negative effect on the soundness of the hock joints (Magnusson, 1985c). On the other hand, a flat pelvis is significantly correlated with pain on palpation of the croup muscles. The length of the pelvis has been reported to have a positive correlation to jumping ability (Langlois et al., 1978) and to stride length in the walk (Kronacher & Ogrizek, 1931).

Probably the most important individual conformational detail for most sport horses is the femur. A long and forwardly sloping femur places the hind limb more under the horse, which allows the horse to keep its balance more easily and carry more weight on the hind limbs, since the hind limb position is closer to the center of gravity. Van der Veen (1996) has suggested that optimally the stifle joint at square stance should be situated below the tuber coxae. In a study of Brandenburg horses, Kronacher and Ogrizek (1931) showed a positive correlation between stride length in walk and the length of the pelvis and femur. The slope of the femur has been reported by many authors to be related to performance. Langlois et al. (1978) showed that good jumping performance was significantly correlated to a forwardly sloping femur, i.e. a small angle of the femur to the horizontal plane (Fig. 11.10). In 4-year-old riding horses the forward sloping femur has been shown to have the strongest correlation to gait quality of all studied variables (Holmström et al., 1993). In a recent study both elite dressage and jumping horses had significantly more forward sloping femurs than 'normal' horses (Table 11.2). More than 150 years ago this correlation was stated by Hörman (1837). Other authors claimed that horses intended for dressage work should be well camped under (Bourgelat, 1750; Magne, 1866), which is very much the result of a forward sloping femur.

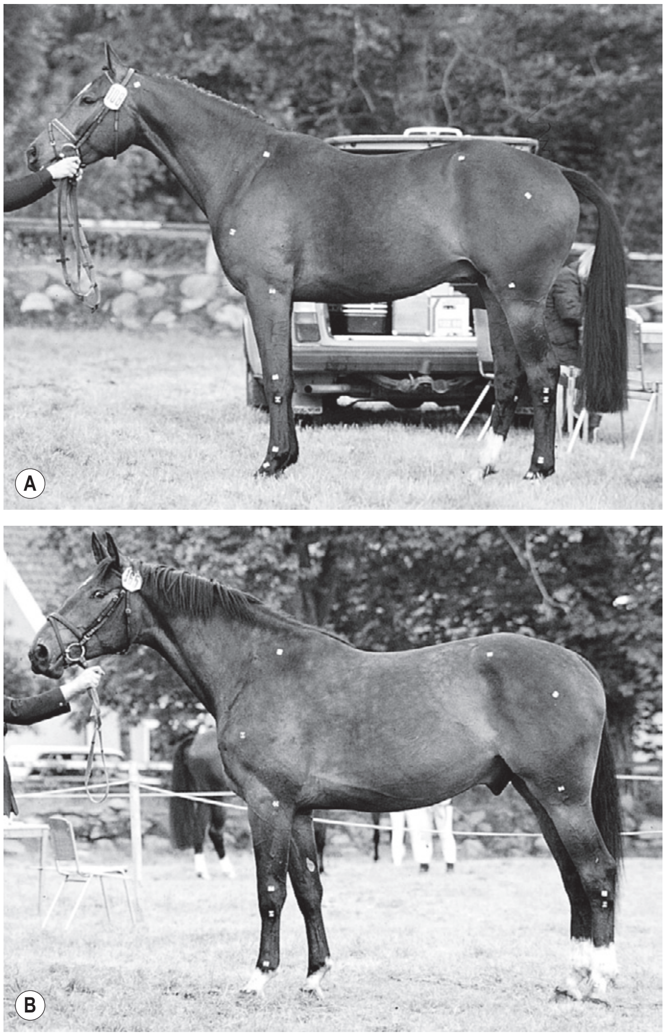


Fig 11.10 Comparison of horses with (A) a forward sloping femur and (B) a vertical femur. Note the effect on the overall replacement of the hind limb.

The femur slope is also important in Thoroughbred racehorses and shows a significant non-linear correlation to top performance (Holmström, unpublished data). There are different optimal femur slopes depending on distance and type of track. The optimal femur in a sprinter is a bit less forward sloping than in a stayer. Furthermore, horses with a femur slope close to the vertical have a better chance for top performance on turf. A combination of a very sloping pelvis and a vertical femur has been shown to disqualify racehorses from top performance. In a study of approximately 17 000 Thoroughbred racehorses with quantitative conformation data (Holmström, unpublished data) there were no grade 1 or group 1 winners with this type of proximal hind limb conformation. The vast majority of the horses with a combination of very sloping pelvis and vertical femur had below average performance records. The reason for the large negative effect on performance is probably that the very sloping pelvis limits the rotation of the pelvis during gallop and also together with the vertical femur limits the range of motion of the femur, especially retraction, resulting in a short and inefficient stride.

A forwardly sloping femur has also been shown to have a positive effect on soundness. In a study of riding horses with recurrent lameness and back problems attending one of the major horse clinics in Sweden, the femur was significantly more vertical than in 'normal' horses and elite horses (Table 11.2). Going through insurance company records of riding horses that were measured at quality events as 4 year olds, horses with recorded recurrent lameness and back problems had a significantly more vertical femur than the sound horses (Table 11.3) (Holmström, unpublished data).

In riding horses, the stifle angle should not be too small. Elite dressage horses have been shown to have a significantly straighter stifle angle than elite show jumpers and 'normal' horses (Table 11.2). A small stifle angle results in a lot of strain to the quadriceps femoris muscle, i.e. the muscle that extends the stifle. The quadriceps femoris probably is the most strained group of muscles when a horse works in collected gaits. If the muscles cannot 'lock' the stifle in an extended position when maximum load is put on the hind limbs, the horse must transfer weight to its forelimbs and it is then no longer working in balance. In Standardbred trotters a positive correlation has been found between stifle angle and performance (Magnusson, 1985d). The same has been found in Thoroughbred racehorses but again, there is a non-linear correlation to performance and an optimal stifle angle, which vary depending on the conformation of the rest of the hind limb (Holmström, unpublished data). Generally a very small stifle angle leads to a weak hind limb and poor performance. The hind limb has to be able withstand the huge load at high speed and at the same time store elastic energy, which not possible with a very small stifle angle.

Comparing the hock angles of elite dressage and jumping horses with 'normal' horses (Fig. 11.11), it has been found that the dressage horses in general had larger hock angles or, more correctly, there were no sickle hocked dressage horses (Holmström et al., 1990). However, it could not be proved that the gaits improved with larger hock angles (Holmström et al., 1993). A more recent study failed to show any differences in the hock angle between elite horses and others, mainly because the mean hock angle in the 'normal' horses had increased from 155.4–159.4°, which was almost the same as in the elite horses (Table 11.2). Horses with lameness and back problems had significantly smaller hock angles than sound horses (Table 11.2).

Magnusson (1985c) found that small hock angles (sickle hocks) were related to more synovial distentions in the stifle and hock joints as well as to more curbs. This has also been reported by several other authors (Smythe, 1963; Pritchard, 1965; Davidson, 1970; Beeman, 1973; Adams, 1974). Rooney (1968) and Hickman (1977) were of the opinion that sickle hocked horses more frequently experienced bone spavin. Icelandic Toelter horses show a significant correlation between small hock angles and bone spavin according to Eksell et al. (1998). Axelsson et al. (2001) found that Icelandic horses with

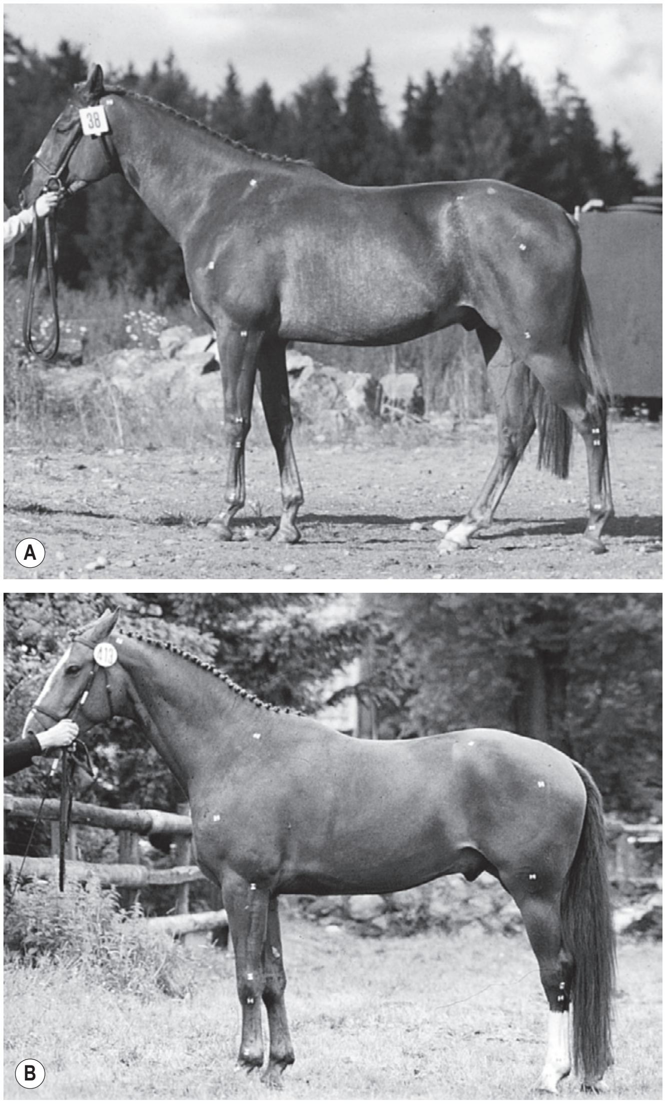


Fig 11.11 Horses with (A) small hock joint angle and (B) large hock joint angle.

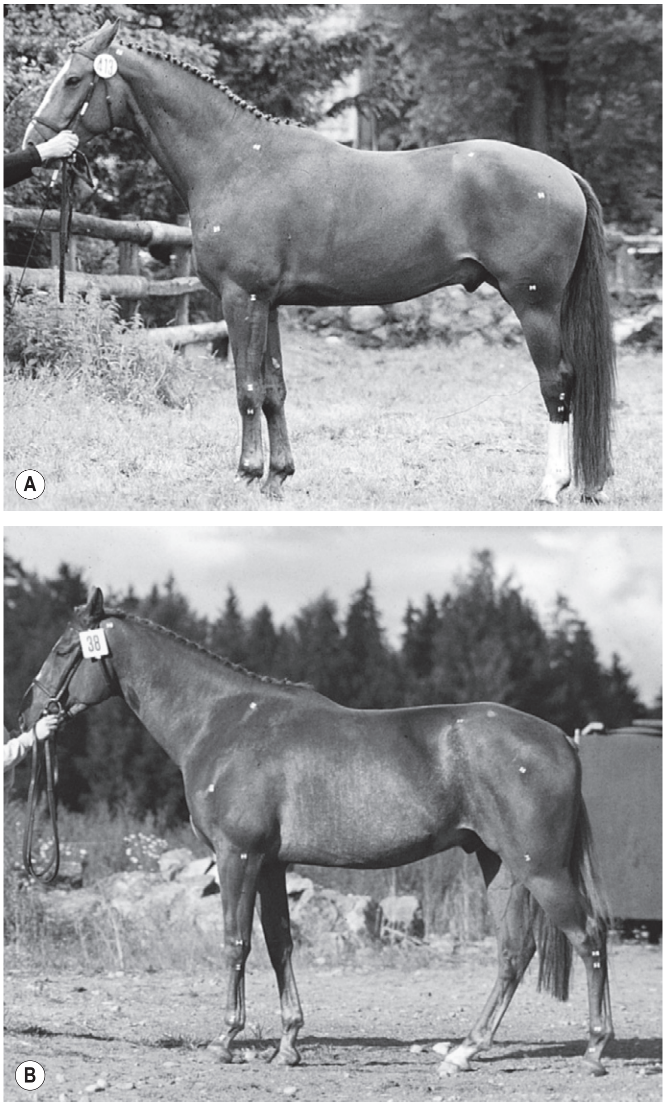


Fig 11.12 Horses with (A) good and (B) poor hind limb conformation.

a larger tarsal angle had a lower prevalence of radiographic signs of degenerative joint disease (DJD) in the distal tarsus confirming that the tarsal conformation is associated with OA in the distal tarsus, probably by altering the biomechanics of the distal tarsal joints. In addition, Björnsdóttir et al. (2004) examined Icelandic horses at young age by high detail radiography and histology and concluded that the development of OA in the centrodistal tarsal joint of young Icelandic horses seems to be due to poor conformation or joint architecture rather than trauma or overloading.

A small hock angle generally has a negative effect on performance in Thoroughbred racehorses (Holmström, unpublished work). The negative correlation between hock angle and performance is stronger on dirt tracks than on turf. All these findings confirm what was said by Schmidt (1928), that a horse with a small hock angle will be able to step underneath itself but will not be able to carry weight on the hind limbs due to decreased resistance and strength in the hock.

Studies using high-speed films have shown that in good dressage horses there is considerable compression of the hock joint (~15°) during the midstance phase in trot and even greater compression in passage and piaffe (Holmström et al., 1995a). In jumping horses and racehorses, the compression is larger than in dressage horses. It is concluded that sickle hocked horses, or horses with small hock joint angles, should be avoided.

The slope of the hind pastern is, to some extent, influenced by the rest of the hind limb conformation. A straight hock is significantly correlated to a more sloping pastern (Magnusson, 1985b). Riding horses with soundness problems had a significantly steeper pastern. This might be an effect of a smaller hock angle in these horses; however, the difference in hock angle was not statistically significant (Table 11.3) (Holmström, unpublished data). In contrast to the forelimb, a straighter hind fetlock joint has been shown to be correlated to a longer stride and swing duration at the trot (Back et al.1996). A straighter hind fetlock is more efficient in storing elastic energy, which contributes to more power from the hind limb.

Generally, the hind limb conformation should be regarded as one unit when evaluated. There are many different combinations of angles that result in a ‘good hind limb conformation’, but it is generally characterized by a somewhat flat pelvis, a forwardly sloping femur, a normal to straight stifle and a normal to straight hock (Fig. 11.12). If the horse is weak in one part this can be compensated by strength somewhere else. The overall result is a strong hind limb that can endure stress, carry weight and store elastic strain energy. Thus, looking at one characteristic at a time is not sufficient.

Fig 11.13 Laterality and uneven feet: demo of a clinical provocation test.

All aspects of hind limb conformation must be taken into account. This makes it more difficult to do an accurate evaluation subjectively, and that is why inclusion of objective measurements improves the accuracy of the evaluation (Holmström et al., 1993).

Preliminary studies on riding ponies and Icelandic Toelter horses indicate that the most favorable conformation for each type of performance is almost the same as that described above in sport horses. The differences found are variations on the same theme (Holmström, unpublished data). These variations are nevertheless important to investigate, and further studies will be carried out in the future.

Extensive studies of the Thoroughbred racehorse conformation have shown that there are surprisingly small differences in conformation between elite sport horses and top class racehorses. The optimal hind limb shape for top performance is very similar, while there are some subtle differences in the forelimb conformation.

Predicting performance and soundness by conformation analysis

There is no doubt that there are significant correlations between conformation and performance and soundness. The efficiency of a selection procedure based on conformation evaluation is, however, highly dependent on the method used. Love et al. (2006) analyzed a limited number of conformational traits assessed by a single veterinary observer against pedigree and racing records of 3916 Thoroughbred yearlings sold at public auctions during a 7-year period. Only a weak association was found between performance and conformation. In the study by Santschi et al. (2006) the validation portion of their study showed that the coefficient of variation for subjective assessment of conformation was greater than 10%, which is well below a clinically useful tool. Weller et al. (2006a,b,c) objectively evaluated the conformation of a group of 108 National Hunt racehorses using a digital motion analysis system. It appeared that Thoroughbreds differed from other breeds, not only with regard to segment lengths but also with regard to joint angles and deviations. The results from these studies illustrate the difficulties scientists face when designing conformational studies in horses. First of all subjective evaluation of the conformation has limitations mainly because of the difficulties to accurately and consistently register the subtle differences between good and poor conformation within a breed with relatively homogeneous conformation and secondly quantitative analysis of the conformation has great potential as a predictive tool only if used with the right approach. Quantitative studies of smaller groups of horses or random samples without inclusion of a sufficient number of top performers might give the wrong answers to the questions asked. Holmström (unpublished data) has found that there are very small and subtle conformational differences between top class Thoroughbred racehorses and Warmblood sport horses when comparing grade 1 winners and Grand Prix dressage horses and show jumpers, while when comparing horses of lesser quality significant differences could be found.

It is also very important to understand that conformation analysis as a selection tool can only work as a negative predictor, i.e. sorting out horses with conformation that gives them a significantly lower chance of being successful in the sport or a significantly higher chance of injuries. The latter information however, would give insurance companies an opportunity to improve their risk evaluation.

Applying conformation analysis as a negative predictor to weanlings, yearlings and 2 year olds within the Thoroughbred racehorse business in the USA has proven that quantitative conformation analysis is a very useful tool in the selection of young horses intended for top class performance. Between 75 and 80% of the horses analyzed as weanlings or yearlings, and that subsequently won grade 1 races, at 8 furlongs or longer, were categorized as horses with 'grade 1 conformation' (Holmström, unpublished data).

There are many studies on the relationship between conformation and soundness in different breeds showing the complexity of the problem. For example, Gnagey et al. (2006) evaluated the effect of standing tarsal angle on joint kinematics and kinetics and compared tarsal kinematics and kinetics in horses with large, intermediate and small tarsal angles. They found that in horses with large tarsal angles, less concussion was absorbed during the impact phase, which may be a factor in the development of degenerative joint disease. At the same time, the smaller net joint moment may reduce the risk of plantar ligament desmitis, illustrating the delicate balance between conformation, kinematics and kinetics of the tarsal joint in relation to soundness (Baird & Pilsworth, 2001).

Recently, the 'grassfoot' phenomenon has been unraveled, as foals with relatively longer limbs and shorter neck and head length seem to have a preference in forelimb position when grazing leading to an asymmetric development of their front feet, the so-called uneven feet (Van Heel et al., 2006; Kroekenstoel et al., 2006; Ducro et al., 2009a). The steep foot is habitually positioned behind and the sloping foot is positioned more forward (Fig. 11.13). Studbooks tend not to select horses that have this asymmetry. The effect of this phenomenon has been evaluated at a population level comparing studbook admission data, scoring the existence of uneven feet, with what horses have delivered in sports (Ducro et al., 2009b). Length of competitive life was shorter for jumping than for dressage. A different set of risk factors was found for each level and discipline, e.g. height at withers was a risk factor at basic level in dressage and jumping, while pastern angle was a risk factor at the elite level of jumping and dressage. The trait 'uneven feet' tended to shorten the competitive life in dressage, but was a significant risk factor at the elite level of jumping (Fig. 11.14). Davies and Watson (2005) proved that there is also such a laterality asymmetry in the third metacarpal bone and midshaft dimensions in Thoroughbred racehorses (n = 40). They proposed that racehorses with longer right MC3 bones were more able to control the loading of the right MC3 than the left during fast exercise. In Warmbloods, this phenomenon has led to a locomotor asymmetry at a young adult age, possibly an explanation for the so-called 'natural asymmetry' in the performance of a horse at the beginning of their career that is a challenge for every rider (Van Heel et al., 2010).

Further studies of conformational effects on soundness is necessary but at the moment there are no data available that contradict that belief that a conformation that facilitates top class performance and longevity of the horses' careers in general also is positive for the horses' soundness.

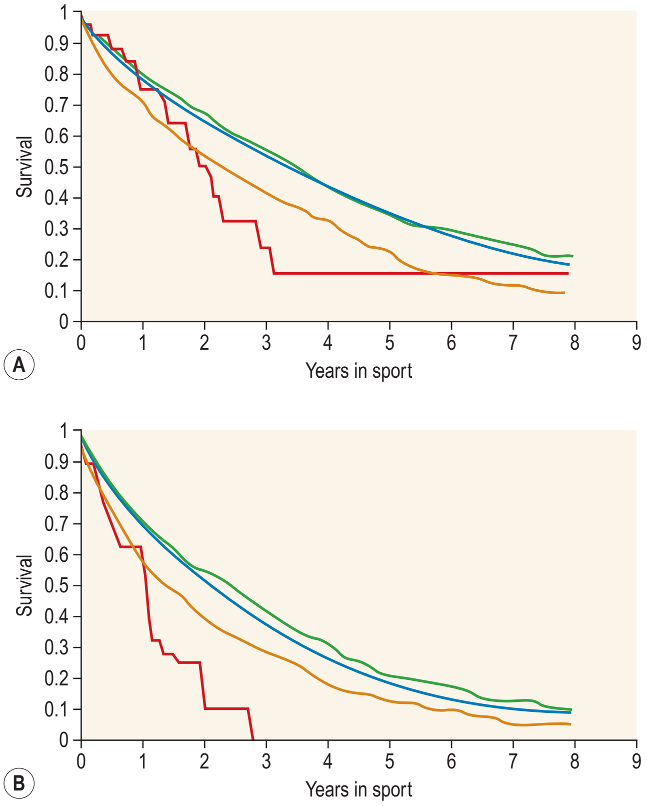


Fig 11.14 Survival curves for (A) dressage: basic dressage (n = 12 776): even feet (n = 11 940; blue); uneven feet (n = 836; green); elite dressage (n = 684): even feet (n = 657; orange), uneven feet (n = 27; red); and (B) jumping performance: basic jumping (n = 8738): even feet (n = 8221; blue), uneven feet (n = 517; green); elite jumping (n = 756): even feet (n = 725; orange), uneven feet (n = 31; red); and the number of years horses were registered as being in competition.

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CHAPTER 12

Genetic contributions to exercise and athletic performance

Emmeline W. Hill, Bart J. Ducro, P. René van Weeren, Albert Barneveld,
Willem Back

Introduction

The genomes of agricultural livestock species and other domestic animals have been shaped by artificial selection for favorable traits for thousands of years. The domestication of animal species led to the manipulation of gene pools by selectively breeding on the basis that various traits were observed to be passed on from generation to generation. In the past millennia, humans have produced many unique phenotypic characteristics in domesticates that clearly demarcate breeds and differentiate livestock from their wild ancestors and related species. Recent rapid advances in genomics technologies have provided platforms from which livestock scientists may understand the genetic variation responsible for such phenotypic adaptation and variation. The availability of the draft genome sequence for the horse (*Equus caballus*) and associated genomics platforms is set to revolutionize the understanding of the genetic variation underlying phenotypic variation. The variation in phenotype is attributed to structural variation that produces variation in gene expression, which has clear phenotypic consequences. Dedicated functional genomics tools for the horse have emerged since around 2010. Equine genomics scientists can now utilize platform-based tools such as the Illumina® EquineSNP BeadChip and gene expression microarrays as well as next-generation sequencing technologies to deepen our understanding of the molecular control of cellular function. In particular these tools may be used to identify key genetic determinants of exercise adaptation in the horse.

In relation to the equine locomotor system, genetics is important at a number of levels. For example, conformation characteristics have been observed to have considerable heritable components and have a strong relationship with athletic capacity. Also, there is a strong relationship between conformation and other performance-determining characteristics, such as the capacity of the circulatory and respiratory system as well as behavioral characteristics of the horse. Additionally, genetics may have an important influence on locomotor capacity by determining susceptibility to musculoskeletal injury. Furthermore, there are a number of genetically determined disorders that may directly influence locomotor performance.

In this chapter the historical role of horse breeding with respect to locomotor performance is outlined. Developments in breeding in the pre-Mendelian era and during the 20th century, when it became possible to introduce quantitative genetic methods to breeding, will be discussed. In particular, attention is paid to a number of disorders of the locomotor system that have a genetic background. Finally, recent developments in equine exercise genomics and the implications for equine athletic performance are reviewed.

Historical background and the pre-Mendelian era

The relationship between conformation and gait and the observation that variation in many conformational traits is, to a large degree, inherited, has formed the basis for the selection of performance horses for millennia. Still, this selection forms the basis for many breeds of horse today. As early as the 4th century BC the Greek hippologist Xenophon gave detailed descriptions of the conformational characteristics of a good performance horse. He made comments on the quality of the horn, the slope of the pastern, the robustness of the metacarpal and metatarsal bones and the desired joint angles in fore and hind limbs. According to Xenophon a well-developed hind quarter was the best sign that a horse would move fast and smoothly; this observation demonstrates a knowledge that propulsion stems from the hind limbs. This insight is also evidenced by the observation that a short, strong lumbar region is preferred to a long back (cited by Schauder, 1923). After Xenophon, all great hippologists stressed the same conformational characteristics as desirable traits. This applies to the great Arab horsemen from the early Middle Ages, such as Akhi Hizam al-Furusiyah wa al-Khayl who published on the conformation of horses in AD 860 (Dunlop & Williams, 1996), and also to the famous European *ecuyers* from the 17th and 18th centuries such as William Cavendysh (1674) and Jacques de Solleysel (1733).

All modern horse breeds descend from common ancestors that roamed the central Eurasian steppe some 6000 years ago (Levine, 1999). Natural selection in different biotopes and selection by man for different purposes has resulted in a wide variety of horse breeds, ranging from the small and sturdy Shetland pony, that stands on average no more than 11 hands, to the Shire, 'the great horse of the Middle Ages,' that carried heavily armored knights. Since horses were domesticated they have been selected for strength, speed and endurance-exercise traits. More recently the development of specific breeds has resulted in selection for athletic phenotypes that enable the use of the horse for riding, recreation, sport and racing. Some breeds are particularly suited to racing (e.g. Thoroughbred, Standardbred, French trotter, Swedish trotter and Quarter Horse) while others have been strongly selected for jumping and other athletic phenotypes (e.g. Warmbloods).

Selection for locomotor performance

In horse breeding, selection has traditionally been based on conformational characteristics and the evaluation of gait. These traits may be scored in a semi-quantitative way, but some degree of subjectivity remains. This is in contrast to many other economically important livestock species where traits such as milk production, growth rate, fat thickness and food conversion can be easily measured and used as a basis for improved breeding programs. It is generally considered that in the horse athletic performance and locomotor characteristics, such as gait, are polygenic traits that may also be largely influenced by environmental factors. Heritability is the term given to the proportion of variation in a particular trait that is attributed to genetics. Estimates of heritability (h^2) provide a means to determine the relative importance of genetics and the environment to a given characteristic.

Performance in the horse may be broadly divided into three categories: working, riding and racing (Hintz, 1980). With respect to working, pulling has been considered by various authors and estimates of heritability range from 0.12 ± 0.14 (Lonka, 1946) to 0.58 ± 0.20 (Varo, 1947) with a mean estimated heritability from several reports of 0.25 (Hintz, 1980). Cutting performance or 'cow sense' has received little attention so far, although Ellersieck et al. (1985) estimated a heritability of 0.19 ± 0.05 for this trait. With respect to riding performance in competition, most of the estimates are in the range of 0.10–0.30 (Ricard et al., 1998).

Although racing performance may seem relatively straightforward to quantify using parameters such as number of races won, best time and (total) earnings, many factors complicate this procedure. For instance, many methods use the ranking in a certain athletic event. However, although high ranking in a certain event may be synonymous with good performance for a given individual horse, this does not necessarily provide information about the genetic value of this individual for the population, as much depends on the level of the event in which the individual took part. Heritability estimates for transformed earnings or best time per kilometer range from 0.20 to 0.40 (Hintz, 1980).

Nowadays, conformation is recorded in a semi-quantitative way by most studbooks, using scoring systems. Traditionally, the scale of scoring has an appreciative character, e.g. the scale runs from 'bad' to 'good'. At the end of the 1980s, the Royal Dutch Warmblood Studbook introduced a system for the linear scoring of conformational traits and gait. This system, together with the assessment of some health-related items, is one of the pillars of the Dutch selection system for stallions and their progeny (Barneveld, 1996). In this system a large number of conformation traits are scored on a 0–40 scale in which a population mean of 20 is assumed. The rather fine scale and the use of more specific characteristics (such as slope of the shoulder, length of the back, slope of the pastern, etc.), makes a better estimation of heritability possible. In general, heritability was found to be low to moderate for conformation traits, ranging from 0.09 (slope of the pastern) to 0.26 (length of the neck and position of the croup) (Koenen et al., 1995). Also, in other studbooks linear scoring systems have been successfully introduced (Van Bergen & van Arendonk, 1993; Samoré et al., 1997).

Some of these conformational characteristics are correlated with performance. A long, sloping shoulder is positively correlated with dressage results (Holmström et al., 1990, 1994). A long and strongly muscled croup is positively related to show jumping performance (Langlois et al., 1978). However, the vast majority of conformational traits that are scored using the linear system do not directly correlate with performance. This fact, together with the low-to-moderate heritability estimates for conformation (Preisinger et al., 1991; von Butler-Wemken et al., 1992), indicate that conformation results should be considered of minor importance in a direct selection for performance (Koenen et al., 1995).

This is different when traits related to moving and jumping are considered. Most studbooks also score gaits and elements of (free) jumping during studbook admission, field tests and station performance tests. From a review of Thorén et al. (2006) it appeared that traits related to gaits showed moderate-to-good heritabilities as well as good genetic correlations to dressage performance in competition. Compared to gaits, jumping traits showed even higher heritabilities as well as higher genetic correlations to show jumping in competition. Genetic parameter estimates were somewhat lower when records were collected at field tests rather than the more uniform station performance tests (Ducro et al., 2007). These results clearly indicate that information from studbook admissions, field tests and stationary performance tests are valuable additions to an efficient breeding program. Most studbooks have therefore adopted such a breeding system.

New genomics technologies for trait mapping and gene expression

For some time, equine genomics resources lagged behind those of other agricultural species, as the horse was not formally recognized as an economically important production species, or a model for human disease. However, more recently, genomics tools for the horse have surpassed those available for other livestock species, and the stage is now set to employ state-of-the-art genomics technologies to understand the genetic basis for athletic performance characteristics, including the complex phenotypes of conformation and gait.

With just a few markers mapped on the equine genome in the early millennium, there have been unexpected advances and a rapid explosion of information, perhaps up to 100-fold, during the past 10 years. A coordinated interest in horse genome mapping began in 1995, when an international workshop on genetics and disease in the horse was held in Interlaken, Switzerland. Various general genetics topics and a large number of inherited disorders were discussed (Rossdale, 1995). The horse genome mapping project began in earnest later that year when ~70 scientists from over 20 countries met in Kentucky, USA, to discuss the initial plan to construct a genetic map for the horse. It was agreed that resources, knowledge and findings would be shared on a regular basis. Thereafter, a biannual International Horse Genome Mapping Workshop funded by The Dorothy Russell Havemeyer Foundation was established. During the past 15 years, hundreds of equine scientists, specialists and breeders have attended workshops in the USA, Australia, South Africa, Sweden, Ireland and UK.

Several genetic maps, including the linkage map (Guérin et al., 1999; Lindgren et al., 1998; Penedo et al., 2005; Swinburne et al., 2000, 2006; Tozaki et al., 2007), radiation hybrid (RH) map (Chowdhary et al., 1992), mapping of specific genes and assigning microsatellite markers by RH panel (Beck et al., 2005; Böneker et al., 2005a,b, 2006; Brenig et al., 2004; Bricker et al., 2005; Dempsey & Wagner, 1999; Dranchak et al., 2006; Klukowska-Rötzler et al., 2006a, b; Leeb et al., 2005; Mickelson et al., 2004; Momozawa et al., 2005, 2007a,b; Müller et al., 2005a,b,c; Perrocheau et al., 2006; Takahashi et al., 2004; Ward et al., 2003; Wittwer et al., 2005), cytogenetic map by fluorescent in situ hybridization (FISH) (Brinkmeyer-Langford et al., 2005; Chowdhary & Gustavsson, 1992; Goh et al., 2007; Gustafson-Seabury et al., 2005; Milenkovic et al., 2002; Perrocheau et al., 2005; Raudsepp et al., 2004b), comparative map (Brinkmeyer-Langford et al., 2005; Caetano et al., 1999; Chaudhary et al., 1998; Chowdhary & Gustavsson, 1992; Milenkovic et al., 2002; Perrocheau et al., 2005; Raudsepp et al., 1996; Yang et al., 2003, 2004), BAC contig map (Brinkmeyer-Langford et al., 2008; Gustafson et al., 2003; Raudsepp et al., 2004b; Tallmadge et al., 2005) and other high-resolution chromosome maps including a comprehensive Y chromosome map (Brinkmeyer-Langford et al., 2008; Dempsey & Wagner, 1999;

Dierks et al., 2006; Goh et al., 2007; Gustafson-Seabury et al., 2005; Lee et al., 2004; Perrocheau et al., 2006; Raudsepp et al., 2004a,b), have been contributed to by collaborations among international laboratories.

A major breakthrough in equine genomics was the selection of the horse for genome sequencing by the US National Human Genome Research Institute (NHGRI). The full length sequencing of the horse genome began in February 2006, and was performed at The Broad Institute, Massachusetts Institute of Technology and Harvard University in collaboration with the Equine Genome Sequencing Consortium. A single female Thoroughbred horse was chosen for sequencing using the whole genome shotgun approach. The 6.8× coverage of the initial assembly (EquCab1.0) was released in January 2007, and the current assembly (EquCab2.0) was released in September 2007 (Wade et al., 2009).

In addition to whole genome sequencing, a single nucleotide polymorphism (SNP) database (EquCab 2.0) containing >1 million SNPs (~1 per 1500 bp) was constructed by comparing sequences from horses of disparate geographic origin, including Akhal-Teke, Andalusian, Arabian, Icelandic, Quarter Horse, Standardbred and Thoroughbred. Stemming from the horse genome sequencing project new technologies such as the Illumina® EquineSNP BeadChip (McCue et al., 2012) and various gene expression microarrays (Bright et al., 2009) have been designed and may be used to understand trait association and gene function.

The recent completion of the draft sequence of the horse genome (Wade et al., 2009), combined with technological and methodological advances in the analysis of complex genetic traits in humans (Steemers & Gunderson, 2007) has provided veterinary genetic epidemiologists with an array of tools for the study of diseases with a heritable component. Specifically, the advent of high-density single nucleotide polymorphism (SNP) based genotyping arrays and the concomitant growth in knowledge of the haplotypic structure of mammalian genomes has led to the adoption of genome-wide association studies (GWAS) for disease gene mapping (Frazer et al., 2007; Orr & Chanock, 2008). These studies, which have recently been successful in the identification of large numbers of genetic loci contributing to disease in humans, exploit the high degree of correlation between genetic variants at any particular region of a chromosome to efficiently interrogate the entire genomes of large numbers of samples using a minimally redundant set of so-called 'tagging-SNPs' (Howie et al., 2006). The GWAS paradigm in human studies has been to genotype hundreds of thousands of SNPs in many thousands of affected and unaffected individuals. These large numbers are a result of the hypothesis that multiple loci with a range of effect sizes contribute to the etiology of complex diseases; large numbers of samples are thus required to attain the requisite statistical power for unambiguous detection of such loci. Charlier et al. (2008) and Karlsson et al. (2007) have demonstrated that association based mapping can be effective in the detection of single locus recessive traits in animals using much smaller numbers of individuals.

The advances in equine genomics have also rapidly enabled the identification of genomic sequence variation associated with athletic performance phenotypes in Thoroughbreds (Gu et al., 2009; Hill et al., 2010b,d; Tozaki et al., 2010a,b). Thoroughbred horses represent a unique opportunity to identify genomic contributions to exercise adaptation and athletic performance as Thoroughbreds have been selected for exceptional racing performance for 300 years and stem from a small number of founder animals. Intense selection for elite racing performance in the Thoroughbred has resulted in a number of adaptive physiological phenotypes relevant to exercise; however, the underlying molecular mechanisms responsible for these characteristics are not yet well understood.

The first report of genes and functional groups of genes contributing to the athletic phenotype in the Thoroughbred employed a population genetics-based approach to identify regions of the Thoroughbred genome that have been selected for exercise-relevant traits (Gu et al., 2009). This work involved a genome scan of genetic variation at 394 autosomal and X chromosome microsatellite loci in four geographically diverse horse populations (Connemara, Akhal-Teke, Tuva and Thoroughbred). Positively selected loci were identified in the extreme tail-ends of the distributions for population genetic parameters and test statistics that identified departures from patterns of genetic variation expected under neutral genetic drift (Gu et al., 2009). Within the outlier loci there was a statistically significant enrichment for genes involved in phosphatidylinositol 3-kinase (PI3K) mediated signaling, insulin receptor signaling and lipid transport – biochemical pathways with well-characterized roles in adaptation to exercise. Furthermore, the importance of muscle function in the recent evolution of the Thoroughbred was highlighted by a significant overrepresentation of sarcoglycan complex and focal adhesion pathway genes located within the selected regions. In summary, these data indicate that recent selection in the ancestors of the present-day Thoroughbred population principally targeted genes associated with fatty acid oxidation, increased insulin sensitivity and muscle strength, highlighting the central role for muscle function and integrity in the Thoroughbred athletic phenotype. More recently, using the Illumina® EquineSNP50 BeadChip platform, the Equine Genetic Diversity Consortium, led by researchers at the University of Minnesota, investigated signatures of selection in over 30 horse breeds that had been selected for different phenotypic traits (Petersen et al., 2013). In this study, the most significant signature of selection in the Thoroughbred was found on ECA17, which was previously implicated as having selective importance in the Thoroughbred (Gu et al., 2009). Among all breeds, the strongest signature of selection was identified in the Paint and Quarter Horse; a 5.5-Mb region of ECA18, which centered on the myostatin (*MSTN*) gene.

To date, three genes with molecular functions relevant to physiological processes important for exercise have been reported to be associated with racing performance, including the myostatin gene [*MSTN*] (Hill et al., 2010b,; Tozaki et al., 2010a,b), the cytochrome c oxidase, subunit 4, isoform 2 gene [*COX4I2*] (Gu et al., 2010) and the pyruvate dehydrogenase kinase isozyme 4, mitochondrial gene [*PDK4*] (Hill et al., 2010c). A variant in the genomic sequence for *PDK4* is the first example of a statistically significant association of a SNP with elite race winning performance (Hill et al., 2010). In a set of n = 278 Thoroughbred samples, segregated by retrospective racetrack performance into elite performers and non-winners, a SNP at the *PDK4* gene locus (g. 38973231A>G) was significantly associated with elite racing ability ($p = 0.0004$, odds ratio = 1.97, C.I. (95) = 1.35–2.87), with the A:A and A:G genotypes more common among elite (70%) than non-elite (47%) racehorses. On average, the A:A and A:G genotypes had a 16.2–16.6 lb handicap advantage over G:G horses. As the *PDK4* gene locus was identified among a set of positively selected loci in Thoroughbreds (Gu et al., 2009), has functions known to be relevant to exercise (Wende et al., 2005; Scarpulla, 2008; Pilegaard & Neufer, 2004), and in horse skeletal muscle is significantly differentially regulated post-exercise (Eivers et al., 2010; Hill et al., 2010) this gene variant represents a promising opportunity to integrate molecular genetic information in selection and decision-making processes in the Thoroughbred.

The locus that has been most extensively studied in regard to an athletic performance trait contains the gene encoding myostatin (*MSTN*). Three studies have identified variation at this locus associated with optimum race distance in European, North American and Australasian Thoroughbreds (Hill et al., 2010; Binns et al., 2010) and with performance rank and lifetime earnings among Japanese Thoroughbreds (Tozaki et al., 2010a,b). Myostatin is a growth and differentiation factor that functions as a negative regulator of skeletal muscle mass development. In several mammalian species, including cattle, sheep, dogs and mice, muscle hypertrophy phenotypes are associated with sequence variants in the *MSTN* gene (Grobet et al., 1997; McPherron et al., 1997; McPherron & Lee, 1997; Schuelke et al., 2004; Mosher et al., 2007).

Employing a candidate gene approach, Hill and colleagues identified a sequence polymorphism in intron 1 of the *MSTN* gene (g.66493737C>T) that may be used to predict sprinting ability and racing stamina in Thoroughbred horses (Hill et al., 2010). In a set of n = 197 elite race winning Thoroughbreds, a very strong association with best race distance has been observed ($p = 3.28 \times 10^{-13}$). Two alleles were observed at this biallelic SNP: a 'C' allele and a 'T' allele, with the 'C' allele more than twice as frequent in the short distance (≤7 furlongs) cohort of animals compared to the long distance (>8 furlongs) group (0.75 and 0.34 respectively), corresponding to an odds ratio of 5.81 (Hill et al., 2010d). It was observed that C:C horses are suited to fast, short-distance races; C:T horses compete favorably in middle-distance races; and T:T horses have greater stamina. Evaluation of retrospective racecourse performance (n = 142) and stallion progeny performance predict that C:C and C:T horses are more likely to be successful 2-year-old racehorses than T:T animals. Histological analysis of gluteal muscle biopsies in Quarter horses showed that the C-allele was associated with higher Type 2B and lower Type 1 muscle fiber proportions, demonstrating a functional consequence for selection this locus. Each copy of the C-allele increased Type 2B muscle fibres by 4.79% (Petersen et al., 2013).

The importance of this locus in determining the type of racing an individual is most suited to, was confirmed in a genome wide SNP association study (GWAS) using the Illumina® EquineSNP50 BeadChip. A study using a set of n = 118 elite Thoroughbreds identified the genomic region on chromosome 18 containing the *MSTN* gene as the highest ranked region for optimum race distance and a set of seven SNPs within a 1.7 Mb region that reached genome-wide significance (Hill et al., 2010d). A comparison of trait association in the same set of samples demonstrated the superior power of the g.66493737C>T SNP ($P_{\text{unadj.}} = 1.02 \times 10^{-10}$) for the prediction of best race distance when compared with the best marker on the array: BIEC2-417495 ($P_{\text{unadj.}} = 1.61 \times 10^{-9}$). A genetic test is now available to horse breeders and trainers for this polymorphism. The Equinome Speed Gene Test may be used to make a prediction about the optimum race distance for an individual and may be used to improve decision-making in selection, breeding and training.

Functional genomics studies provide a mechanism to further understand the importance of genes and gene functions in exercise adaptation. Gene expression studies in an exercise context in the horse are growing (Eizema et al., 2005; Jose-Cunilleras et al., 2005; Barrey et al., 2006; Mucher et al., 2006; McGivney et al., 2009; Eivers et al., 2010; Hill et al., 2010a; Martin et al., 2010; McGivney et al., 2010). The products of many genes are likely to influence system-wide physiological responses. However, the protein products of two genes have been identified as key regulators of the adaptive response to exercise in humans and model species. These are the hypoxia inducible factor 1, alpha subunit (basic helix-loop-helix transcription factor) gene (*HIF1A*), which encodes HIF-1α and the peroxisome proliferator-activated receptor gamma, coactivator 1 alpha gene (*PPARGC1A*), which encodes PGC-1α (for reviews Bonen, 2009; Gibala, 2009; Lundby et al., 2009; Yan, 2009; Lira et al., 2010; Olesen et al., 2010). Eivers and colleagues (2010) have reported the gene expression responses of a panel of HIF-responsive genes in skeletal muscle biopsies collected from the *gluteus medius* before and after a standardized incremental-step treadmill exercise test in untrained Thoroughbred horses. Analyses of mRNA profiles revealed significant transcriptomic differences 4 h post-exercise (T_2) for the *CKM*, *COX4I1*, *COX4I2*, *PDK4*, *PPARGC1A*, and *SLC2A4* genes relative to pre-exercise levels. The observed relationships with measured physiological variables (VHR_{max} and [La]peak) indicated that local transcriptional microadaptations influence the overall athletic phenotype. Also, the data highlighted the roles of genes responsible for the regulation of oxygen-dependent metabolism, glucose metabolism, and fatty acid utilization in equine skeletal muscle adaptation to exercise.

Employing global approaches to gene expression studies is now possible with the availability of equine-specific gene expression microarrays and through the use of next-generation sequencing technologies. Using equine-specific cDNA microarrays McGivney and colleagues (2009) identified novel genes and key regulatory pathways responsible for exercise adaptation in skeletal muscle. Skeletal muscle biopsy samples were collected from a cohort of Thoroughbred horses at rest (T0) and at two time points following a single bout of treadmill exercise (immediately post-exercise (T1), and 4 h post-exercise (T2) (Fig. 12.1)). While only two genes had increased expression at T(1) ($p < 0.05$), by T(2) 932 genes had increased ($p < 0.05$) and 562 genes had decreased expression ($p < 0.05$). Functional analysis of genes differentially expressed during the recovery phase (T2) revealed an over-representation of genes localized to the actin cytoskeleton and with functions in the MAPK signaling, focal adhesion, insulin signaling, mTOR signaling, p53 signaling and type II diabetes mellitus pathways (Table 12.1). At T(1), using a less stringent statistical approach, an over-representation of genes involved in the stress response, metabolism and intracellular signaling was observed (Table 12.2). These findings suggested that protein synthesis, mechanosensation and muscle remodeling contribute to skeletal muscle adaptation towards improved integrity and hypertrophy.

To evaluate changes in gene expression following multiple exercise bouts (*i.e.* conditioning or training) McGivney et al. (2010) used digital gene expression (DGE) mRNA tag profiling, which is based on the high-throughput sequencing by synthesis technology available from Illumina Inc. (Mardis, 2008; Fox et al., 2009; Morozova et al., 2009), to characterize the assembly of genes expressed in equine skeletal muscle and to identify the subset of genes that were differentially expressed following a 10-month period of exercise training. Skeletal muscle biopsies were collected from the *gluteus medius* of seven Thoroughbred horses at rest at two time points: T(1)-untrained (9 ± 0.5 months old) and T(2)-trained (20 ± 0.7 months old). This study found that the most abundant mRNA transcripts in the muscle transcriptome were those involved in muscle contraction, aerobic respiration and mitochondrial function. A previously unreported over-representation of genes related to RNA processing, the stress response and proteolysis was observed. Following training 92 tags were differentially expressed of which 74 were annotated. Sixteen genes showed increased expression, and among the 58 genes with decreased expression, tags representing the gene encoding myostatin (*MSTN)*, had the greatest decrease (−4.2-fold, $p = 0.0043$). This demonstrates the key role of the myostatin protein in the adaptive response and its function as a negative regulator of muscle development. Functional groups displaying highly significant increased expression included mitochondrion, oxidative phosphorylation and fatty acid metabolism, while functional groups with decreased expression were mainly associated with structural genes and included the sarcoplasm, laminin complex and cytoskeleton. Recently, the Illumina® EquineSNP50 BeadChip platform was used in a GWAS to identify a gene having a major effect on gaitedness in horses. Andersson and colleagues (Andersson et al., 2012) identified a premature stop codon in the doublesex related mab transcription factor gene 3 (*DMRT3* gene), which influenced the pattern of locomotion in Icelandic breeds. The presence of the mutation allows for the performance of alternate gaits, i.e. instead of the two-beat contralateral gait of the trot, some horses perform the pace, a two-beat ipsilateral gait. Other natural variations in movement include four-beat ambling gaits characteristic of the Tennessee Walking Horse, Peruvian Paso, Paso Fino, and others, with unique variations in rhythm between breeds. This finding was validated in an investigation of genomic regions under selection in gaited breeds (Petersen et al., 2013). A 186kb region on ECA23 spanning the *DMRT3* gene locus was found to have been targeted by selection in breeds with the ability to perform alternative gaits. Together these studies provide strong evidence that *DMRT3* is a major effect gene for locomotion/gait phenotypes; however specific variations in gait among breeds may be modified by other loci.

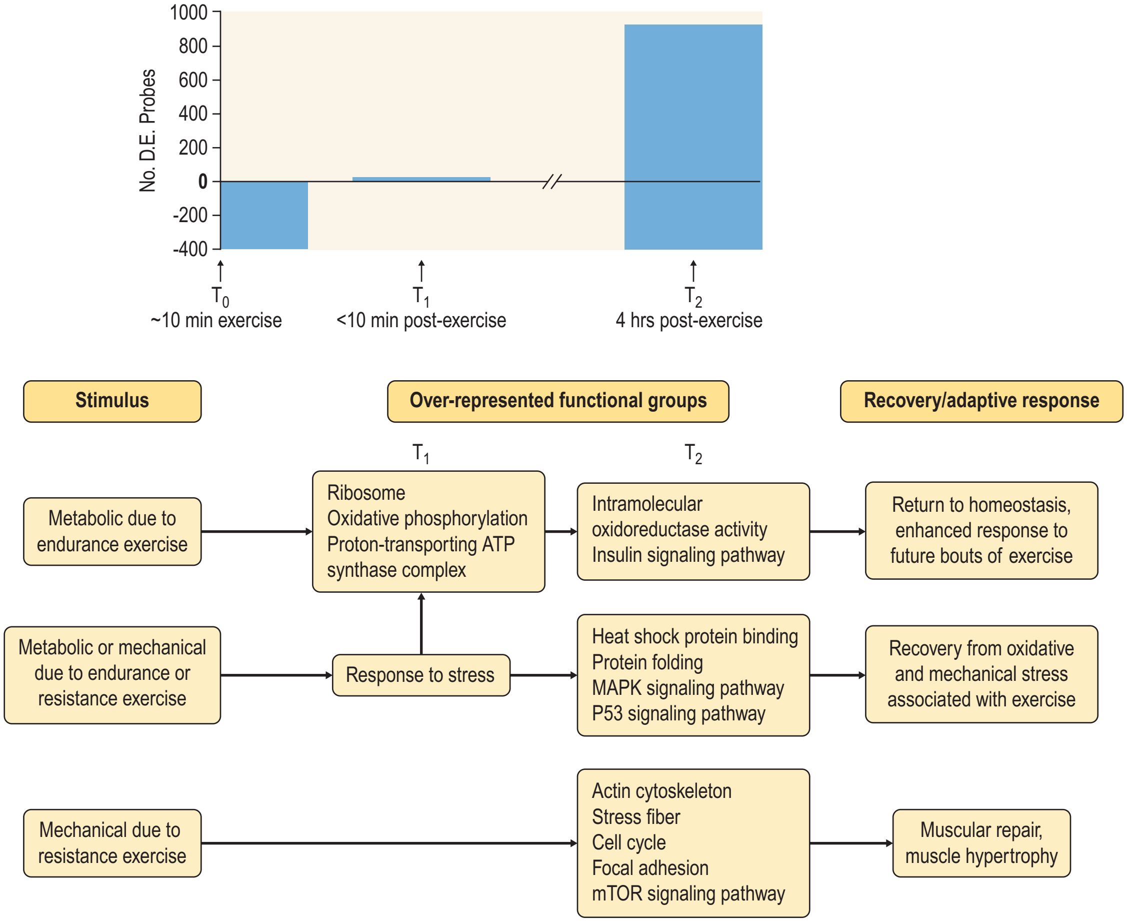

Fig 12.1 Skeletal muscle biopsy samples collected from a cohort of Thoroughbred horses at rest (T0) and at two time points following a single bout of treadmill exercise (immediately post-exercise (T1), and 4 h post-exercise (T2)).

Reprinted from McGivney, B.A., Eivers, S.S., MacHugh, D.E., MacLeod, J.N., O'Gorman, G.M., Park, S.D., Katz, L.M., Hill, E.W., 2009. Transcriptional adaptations following exercise in thoroughbred horse skeletal muscle highlights molecular mechanisms that lead to muscle hypertrophy. BMC Genomics 10, 638, http://www.biomedcentral.com/1471-2164/10/638 ©McGivney et al; licensee BioMed Central Ltd.

Table 12.1 Over-represented functional groups of differentially expressed genes relative to all genes expressed in muscle were obtained using the online tool DAVID. Subsequent clustering of functional groups was aided by the functional group clustering tool in DAVID

Stimulus	Clusters of over-represented functional groups	Number of groups	Number of genes	Adaptive response
Metabolic due to endurance exercise	Oxidative phosphorylation	34	92	Enhanced aerobic capacity Increased Mt volume Enhanced fatty acid metabolism
	Mitochondria	18	162	
	Fatty acid metabolism	14	25	
Mechanical due to resistance exercise	Muscle development	16	27	Increase muscle mass Muscular remodeling Increased protein turnover Enhanced contractile properties
	Actin cytoskeleton	28	81	
	Development/apoptosis	17	185	
	Amino acid metabolism	14	60	
	Muscle contraction	32	42	

Mt, mitochondrial.

Table 12.2 Differential gene expression between pre and post-exercise time-points in a panel of exercise-relevant genes located in positively selected (Dh/SD and FST) genomic regions in Thoroughbred horses

		T0 *Vs* T1		T0 *Vs* T2							
Molecular function	**Gene symbol**	**FC**	***P* value**	**FC**	***P* value**	**Chr**	**Locus**	**Dh/sd**	***P***	**F_{ST}**	***P***
Angiogenesis	***ANGPT2***	**1.29**	**0.051**	**4.35**	**0.001**	27	*VHL150*	−2.863	0.017	0.309	0.038
Carbohydrate/Glucose metabolism	***PDK2***	1.24	0.234	**1.51**	**0.033**	11	*TKY033*	−2.916	0.002	0.392	0.013
	PDK3	1.07	0.583	−1.16	0.486	X	*Lex026*	−3.890	0.006	0.020	NS
	PDK4	**1.80**	**0.010**	**2.19**	**0.001**	4	*TKY222*	−6.117	0.000	0.450	0.005
Fatty acid metabolism/Gluconeogenesis/Glycolysis	***ADHFE1***	**1.54**	**0.020**	**1.51**	**0.060**	9	*COR008*	−9.436	0.000	0.258	NS
Fatty acid biosynthesis/Insulin signaling pathway	*ACACA*	−1.1	0.379	−1.18	0.342	11	*TKY033*	−2.916	0.002	0.392	0.013
	ACACB	−1.05	0.821	−1.02	0.929	8	*AHT025*	−1.360	NS	0.319	0.023
Insulin signaling pathway	***FOXO1A***	**2.17**	**0.008**	**3.69**	**0.002**	17	*NVHEQ079*	−3.602	0.007	0.380	0.018
	GRB2	−1	0.985	−1.06	0.517	11	*NVHEQ040*	−3.848	0.007	0.170	NS
	IRS1	–	–	–	–	6	*UMNe197*	−2.571	0.014	0.315	0.028
	PRKAR2B	−1.05	0.714	**−2.04**	**0.040**	4	*NVHEQ029*	−0.272	NS	0.305	0.041
	PTPN1	−1.01	0.949	−1.1	0.707	22	*HMS047*	−4.444	0.004	0.135	NS
	SOCS3	**4.09**	**0.011**	**4.57**	**0.010**	11	*NVHEQ040*	−3.848	0.007	0.170	NS
Oxidative phosphorylation	*ATPSH*	1.14	0.221	1.13	0.26	11	*NVHEQ040*	−3.848	0.007	0.170	NS
	ATP6V1A	1.07	0.417	**1.58**	**0.008**	19	*ASB011*	−.3646	0.007	0.039	NS
	ATP6V1G1	−1.27	0.079	−1.42	0.071	25	*TKY316*	−6.775	0.000	0.352	0.020
	COX4I1	1.09	0.424	1.08	0.450	3	*LEX057*	−4.752	0.002	0.078	NS
	NDUFA13	**−1.8**	**0.001**	−1.09	0.667	21	*AHT059*	−3.956	0.005	0.160	NS
	NDUFA8	1.17	0.142	1.2	0.139	25	*TKY316*	−6.775	0.000	0.352	0.020
Phosphatidylinositol signaling system/VEGF signaling pathway	***PIK3R1***	1.19	0.085	**1.42**	**0.053**	21	*AHT059*	−3.956	0.005	0.160	NS
PPAR signaling	*PPARA*	1.17	0.327	1.02	0.914	28	*UCDEQ425*	−3.956	0.005	0.160	NS
Insulin signaling pathway /PPAR signaling /Pyruvate metabolism	*PCK1*	–	–	–	–	22	*HMS047*	−4.444	0.004	0.135	NS
Skeletal development	*BMP7*	–	–	–	–	22	*HMS047*	−4.444	0.004	0.135	NS
	MEF28	1.07	0.639	−1.20	0.323	21	*AHTO59*	−3.956	0.005	0.160	NS

Selection for locomotor soundness

A discrimination should be made between inherited conformational traits that may predispose to lameness or other aberrations of the locomotor system and genetically determined disorders of the musculoskeletal system that will affect performance.

Conformational lameness-causing disorders

Stashak (1987a) describes conformation of the horse as 'the key to its method of progression'. He then elaborates on a number of faulty conformations that may predispose to various pathologic conditions of the musculoskeletal system: for instance a toe-out conformation results in a greater likelihood of limb interference and plaiting; a palmar deviation of the carpal joints ('calf knees') may predispose to slab fractures of the carpal bones; and the commonly seen cow hocked conformation may lead to bone spavin. Apart from these conformation-related disorders, there are direct genetically determined aberrations of the musculoskeletal system, which are much rarer than conformational imperfections. Some of these have been known for a long time to have a genetic basis, but have only recently been elucidated using modern molecular genetic techniques. Ducro et al. (2009a) investigated the significance of foot conformation at young age to duration of the career of sport horses. Warmblood horse studbooks aim to breed horses with a conformation that will enable elite future sports performance, but reduce the risk of early retirement due to lameness. Negative conformational traits, such as asymmetrical or 'uneven' forefeet may possibly shorten the career of sport horses. Databases of the Royal Dutch Warmblood Studbook (KWPN) and of the Royal Dutch Equestrian Sports Federation (KNHS) were matched and resulted in a dataset comprising 23 116 records of horses for which their conformation scores and duration of their sports career were available. Survival analysis was used to determine which of the conformation traits had a significant effect on duration of sports career in dressage and jumping at basic and elite level. Duration of competitive life was shorter for jumping than for dressage. A different set of risk factors was found for each level and discipline. The trait 'uneven feet' tended to shorten the competitive life in dressage, but was a significant risk factor at the elite level of jumping. Thus, limb conformation and, in particular, the conformation of the distal limb, are important for duration of competitive life. From the prevalence of uneven feet in sports disciplines, it may be concluded that this is an undesirable trait, particularly at the elite level of jumping, since uneven feet have a detrimental effect on the duration of competitive life in a sport horse population. This study provided evidence that the conformation trait uneven feet has a negative effect on Warmblood jumping performance and, therefore, breeders should be encouraged to avoid this phenomenon at foal age. Moreover, Ducro et al. (2009b) assessed the prevalence and heritability of uneven feet and its genetic relationship to other conformation traits as well as to sporting performance later in life in Warmblood riding horses. Warmblood horse studbooks aim to breed horses with a conformation that will enable elite future performance, but reduce the risk of injuries and lameness. Negative conformational traits, such as asymmetrical or 'uneven' forefeet would possibly diminish performance. The databases of the Royal Dutch Warmblood Studbook (KWPN, n = 44 840 horses) and Royal Dutch Equestrian Sports Federation (KNHS, n = 33 459 horses in dressage and n = 30 474 horses in show jumping) were linked through the unique number of each registered horse (Table 12.3). Therefore, heritabilities and genetic and phenotypic correlations could be estimated from the scores of the jury at studbook admission and the sports

Table 12.3 **Means and description of lower and upper value of traits scored at studbook entry (n = 44 480) and graded in sports (n = 33 459 in dressage, n = 30 474 in jumping)**

	Lower value		Upper value		Mean
	Value	**Description**	**Value**	**Description**	
Score at studbook entry					
Neck length	–40	Short	–0	Long	–19.0
Forelimb conformation	–40	Calf kneed	–0	Buck kneed	–18.5
Pastern angle	–40	Upright	–0	Weak	–20.5
Hoof shape	–40	Narrow	–0	Broad	–19.9
Heel height	–40	Low	–0	High	–19.1
Limb quality	–40	Blurred	–0	Dry	–19.8
Bone circumference	–40	Light	–0	Heavy	–19.4
Conformation grade	40	Bad	100	Good	67.5
Uneven feet (no/yes)	0	Absent	1	Present	0.05
Height at withers (cm)	158.3		178.2		164.8
Grade in sports					
Dressage ranking*	0	Bad	200	Good	52.5
Jumping ranking	0	Bad	200	Good	43.0

*Original marks, before analysis square root transformed.

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Table 12.4 Heritabilities (diagonal, bold and underlined) and genetic (below diagonal) and phenotypic (above diagonal) correlations between traits scored at studbook entry (n = 44 480) and graded in sports (n = 33 459 dressage (Dre), n = 30 474 jumping (Jum))

	HW	NL	UF	FC	PA	HS	HH	LQ	BC	CG	Jum	Dre
Height at withers	**0.67**	–0.12	0.01	0.04	–0.05	0.19	0.03	–0.17	0.12	0.19	–0.02	0.14
Neck length	–0.44	**0.23**	–0.01	–0.12	0.08	–0.03	0.04	0.10	–0.01	–0.30	0.02	0.04
Uneven feet	–0.03	0.10	**0.12**	–0.01	–0.06	–0.17	0.05	–0.03	0.04	–0.06	–0.01	–0.01
Forelimb conformation	–0.06	0.16	–0.05	**0.16**	0.00	–0.04	0.01	0.10	0.00	0.08	–0.01	–0.08
Pastern angle	–0.03	0.01	–0.30	0.21	**0.17**	0.13	–0.16	0.10	–0.04	–0.04	–0.12	–0.04
Hoof shape	0.28	0.01	–0.49	–0.12	0.27	**0.27**	0.07	0.00	0.25	0.03	0.09	–0.07
Heel height	–0.01	0.15	0.47	–0.19	–0.42	–0.41	**0.16**	0.08	0.06	0.15	0.20	0.04
Limb quality	–0.29	0.22	–0.12	0.22	0.22	0.04	–0.01	**0.19**	–0.25	0.33	0.04	0.05
Bone circumference	0.35	0.02	0.20	–0.17	–0.16	0.50	0.18	–0.58	**0.24**	–0.13	0.09	0.03
Conformation grade	0.35	–0.59	–0.04	0.25	0.15	0.08	0.28	0.67	–0.23	**0.30**	0.04	0.19
Jumping ranking	0.01	0.14	–0.12	0.07	0.01	0.11	0.19	0.20	–0.09	0.29	**0.14**	ne
Dressage ranking	0.33	0.32	–0.09	–0.01	0.07	–0.01	0.15	0.36	–0.13	0.67	ne	**0.14**

BC, bone circumference; CG, conformation grade; FC, forelimb conformation; HH, heel height; HS, hoof shape; HW, height at withers; LQ, limb quality; NL, neck length; PA, pastern angle; UF, uneven feet (%).

Standard errors of estimates were below 0.03; ne, not estimated.

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Table 12.5 Least square means of traits scored at studbook entry for level (basic and elite) and for sports discipline (n = 33 459 dressage, n = 30 474 jumping)

	Dressage			Jumping		
	Basic	Elite	Prob	Basic	Elite	Prob
Uneven feet (%)	6.20	5.78	0.78	6.43	5.32	0.32
Height at withers	165.6	166.1	<0.0001	165.6	165.6	0.4
Neck length	–18.36	–17.90	<0.0001	–18.55	–18.00	<0.0001
Forelimb conformation	–20.02	–19.97	0.14	–19.91	–19.98	0.43
Pastern angle	–20.71	–20.42	0.006	–20.61	–20.71	0.05
Hoof shape	–18.99	–18.91	0.62	–18.97	–18.85	0.02
Heel height	–19.38	–19.28	0.05	–19.47	–19.14	0.005
Limb quality	–19.66	–19.10	<0.0001	–19.62	–19.28	<0.0001
Conformation grade	67.62	69.27	<0.0001	67.53	68.33	<0.0001

Prob, probability of equal means of basic and elite level in each discipline.

From Ducro et al., 2009b.

performance of that population in dressage and jumping over the period 1990–2002. The prevalence of uneven feet was 53% on average, and increased from under 4.5% during the first 3 years of recording to over 8% in the years from 2000 onwards. Heritability estimates of foot conformation traits were moderate and ranged from 0.16 for heel height to 0.27 for hoof shape (Table 12.4). The genetic correlation between the trait of uneven feet and performance in competition was negative but weak: –0.09 with dressage and –0.12 with show jumping (Table 12.5). Predisposition to uneven feet can be reduced by selection, as there is a difference in mean prevalence in the offspring of registered breeding stallions (Fig. 12.2). Because of weak genetic correlations, the increased prevalence is not directly associated with selection for better sports performance or higher conformation grade. If the trait 'uneven feet' arises from a disproportionate relationship between height at the withers and neck length, then selection on conformation grade might result in development of uneven feet (Fig. 12.3). In general, limb conformation has a moderate genetic relationship to conformation grade and foot conformation traits have a genetic relationship to sporting performance. Reducing occurrence of uneven feet by selection is possible, without limiting progress in sport performance.

Neuromuscular lameness-causing disorders

Many monogenic anomalies in the horse have been described, a minority of which are related to the locomotor system (Galizzi Vecchiotti Antaldi, 1980a,b). Most of these disorders are inherited as autosomal recessive genes. Björck et al. (1973) described progressive congenital cerebellar ataxia in the Gotland pony breed as being inherited as an autosomal recessive gene with full penetrance. In Arabs a clinically similar condition described by Gerber et al. (1995) caused almost total hypoplasia or atrophy of the Purkinje cell layer. A lethal form of arthrogryposis ('muscle contracture') associated with polydactylia in the Norwegian Fjord horse was described by Nes et al. (1982) as an autosomal recessive mutation, whereas Buoen et al. (1997) suggested a possible relation to autosomal trisomy. Collinder et al. (1997) found for the equine rhabdomyolysis syndrome (RHA) in Standardbreds that gene frequencies for several markers in the RHA groups differed significantly from those estimated for the total population. A rhabdomyolysis risk group could be characterized using 4 or 5 genetic marker loci. Beech and Haskins (1987) described a neuroaxonal dystrophy in the Morgan. Aleman et al. (2009) proved that Malignant Hyperthermia (MH) is a potentially fatal disease of Quarter Horses that could be triggered by halogenated anesthetics and other nonanesthetic factors that may include exercise, stress, breeding, illnesses, and concurrent myopathies. Valberg et al. (1996) gave evidence for a familial basis for polysaccharide storage myopathy and associated exertional rhabdomyolysis in Quarter Horse-related breeds, the pattern of inheritance of which resembled an autosomal recessive disorder.

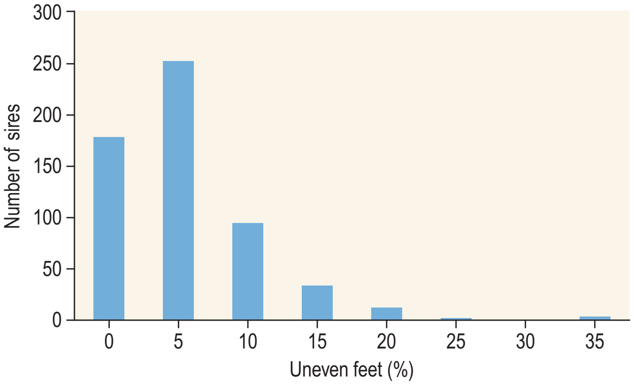

Fig 12.2 Mean prevalence of uneven feet in offspring related to number of sires (n = 44 480 horses from n = 630 sires).

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Some disorders are inherited as dominant traits. An example that has been known for centuries in both animals and man is hereditary multiple exostoses (Li et al., 1989; Leone et al., 1987). In the horse the condition is generally inherited as a single autosomal dominant gene (Gardner et al., 1975; Shupe et al., 1979), though some report that, as in man, three genes are involved, two autosomal and one X-linked (Monteiro & Barata, 1980). The American Association of Equine Practitioners (AAEP) has listed genetic tests for nine single gene diseases (Nollet & Deprez, 2005; Finno et al., 2009) and this number is likely to increase in the coming years as the new genomics tools are utilized to identify the genetic variants underlying key equine disorders. 'Autosomal dominant' disorders include hyperkalemic periodic paralysis (HYPP) in the Quarter Horse, type 1 polysaccharide storage myopathy (PSSM) in different breeds, and malignant hyperthermia in Quarter Horse-related breeds (Aleman et al., 2009; Magdesian, 2009). 'Autosomal dominant' disorders include overo-lethal-white syndrome in the Paint Horse (McCabe et al., 1990; Blendinger et al., 1994), combined immunodeficiency in Arabian Horses (McGuire et al., 1974; Mottironi et al., 1981; Bernoco & Bailey, 1998), glycogen branching enzyme deficiency (GBED) in Quarter Horse-related breeds (Stockham et al., 1994, Wagner et al., 2006), junctional epidermolysis bullosa (JEB) in Belgians (Johnson et al., 1988; Frame et al., 1988; Milenkovic et al., 2003; Mömke & Distl, 2007) and in Saddlebred horses (Lieto et al., 2002; Lieto & Cothran, 2003; Graves et al., 2009), and hereditary equine regional dermal asthenia (HERDA) in Quarter Horse-related breeds (White et al., 2004; Tryon et al., 2005; Graves et al., 2009).

Jamison et al. (1987) described a congenital form of myotonia with dystrophic changes in a Quarter Horse, which later became known as hyperkalemic periodic paralysis (HYPP). HYPP in Quarter Horses is an autosomal dominant disorder with a variable penetrance that has been extensively studied in recent years, not in the least because the disease is homologous to *adynamica episodica hereditaria* or Gamstorp's disease in man (Pickar et al., 1991; Naylor et al., 1992; Valberg et al., 1992; Rudolph et al., 1992a,b; Spier et al., 1993; Meyer et al., 1999; Naylor et al., 1999). It has been shown that the HYPP mutation in the Quarter Horse population can be traced back to a single stallion (Bowling et al., 1996; Valberg et al., 1996). Indications exist that the inherited predisposition for the disease has a positive genetic correlation with muscular appearance. This could mean that the HYPP rate has increased as a result of selection for a more muscular appearance (Naylor, 1993, 1994a). In addition, Quarter Horses affected with HYPP performed

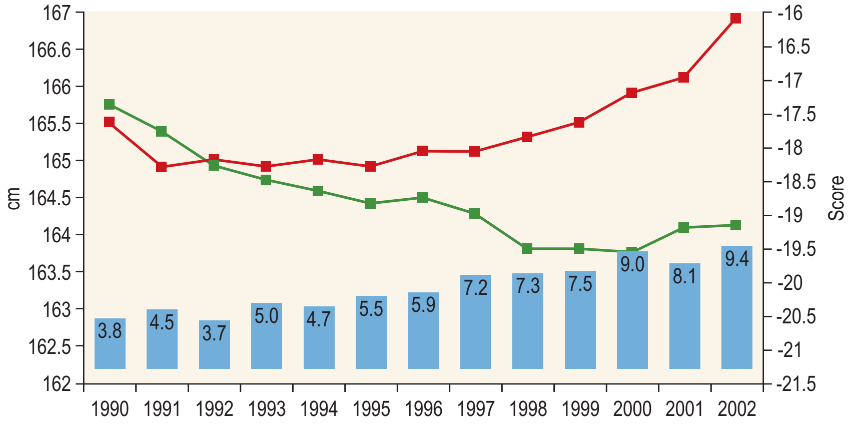

Fig 12.3 Least square means by year of height at withers (**red**, in cm) of neck length (**green**, score) and prevalence of uneven feet (bars, with percentage prevalence on top) (n = 44 480).

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significantly better in halter classes than did unaffected horses (Naylor, 1994b). The mean total performance points were not significantly different. He stated that selection of Quarter Horses affected with HYPP was enhanced by show judges. It has been demonstrated that the disease manifests as a result of a defect in the sodium channel subunit gene (Rudolph et al., 1992; Zhou et al., 1994; Cannon et al., 1995). A mutation in glycogen synthase 1(*GYS1*) has been shown to be associated with equine PSSM and exertional rhabdomyolysis (Valberg et al., 2001; Ward et al., 2003, 2004; McCue et al., 2008a,b, 2009a; Herszberg et al., 2009). The *GYS1* mutation is an important cause of exertional rhabdomyolysis but does not account for all forms of PSSM. However, a significant proportion of horses with histopathological evidence of PSSM and/or exertional rhabdomyolysis have different diseases (Valentine et al., 1997; Valberg et al., 1998; Stanley et al., 2009). Tryon et al. (2009) estimated the allele frequencies of HYPP, lethal white foal syndrome (LWFS), glycogen branching enzyme deficiency (GBED), HERDA, and PSSM genes in elite performance subgroups of American Quarter Horses (AQHs). Accurate estimates of disease-causing alleles in AQHs and APHs may guide the use of diagnostic genetic testing, aid management of genetic diseases, and help minimize production of affected foals.

Degenerative lameness-causing disorders

Frequently encountered lameness-causing disorders of the locomotor system that are not developmental in origin, but are more of a degenerative nature, include navicular disease, sesamoiditis, osteoarthritis of the fetlock joint and bone spavin.

Navicular disease is a degenerative disorder of the podotrochlea including the navicular bone, the navicular bursa, the distal sesamoid impar ligament, the collateral sesamoid ligament and the distal part of the deep digital flexor tendon, has been known as an important cause of lameness for ages (Youatt, 1836). An inherited basis for the disease has been suggested (Numans & van de Watering, 1973).

Using a radiological classification of the navicular bone as a measure for the disease, Bos et al. (1986) found variation between daughter groups consisting of 3-year-old mares from different sires, supporting the theory that navicular disease has, to a certain extent, a genetic basis. However, they also concluded that the results of the radiological evaluation of the sires did not have predictive value for the progeny.

In a large study that included 590 female offspring from 30 sires, the heritability of the radiographic classification of the navicular bone was estimated as 0.26–0.34 (Van der Veen et al., 1994) and were in agreement with heritability estimates ranging from 0.20 to 0.31 found by Willms et al. (1999) on 492 Holstein horses. Winter et al. (1996) analyzed 3566 German Warmblood horses selected for auction sale without clinically manifest navicular disease. The heritability estimate was 0.06 on the observed scale and no transformation to liability scale was performed. The study of Stock and Distl (2006) gave estimates varying from 0.10 to 0.34. From these studies it can be concluded that radiological changes of the navicular bone are genetically influenced. An explanation might be the shape of the proximal articular border of the navicular bone has been found to be inherited and to predispose the pathogenesis of navicular disease; the more concave or undulating, the higher the risk for the disease (Dik et al., 2001). Selection against navicular disease was successfully performed by the Dutch Warmblood studbook. In 1997 selection was started by excluding from breeding the stallions with severest grade (grade 4) of the disease has resulted in a considerable decrease of the two worst grades (3 and 4). From 1997 to 2002 the prevalence of the two most severe grades (3 and 4) decreased from 11 to 2% (Van den Belt et al., 2003). Diesterbeck and Distl (2007) reviewed the genetic aspects of radiological alterations in the navicular bone of the horse and found Genome-wide significant QTL were on ECA2 and on ECA10, whereas Lopes et al. (2009) fine mapped a quantitative trait locus on horse chromosome 2 associated with radiological signs of navicular disease in Hanoverian Warmblood horses. Németh (1974) demonstrated a phenotypic correlation between navicular disease and sesamoiditis. For sesamoiditis a relatively low heritability of 0.11–0.17 has been estimated (Barneveld, 1996). For osteoarthritis or degenerative joint disease of the fetlock joint, which can also be graded using a radiological scale, heritability was found to be comparable (0.13–0.26; Barneveld, 1996). Degenerative joint disease (DJD) of the distal tarsal joints, often called bone spavin, is commonly associated with poor conformation in which sickle hocks and cow hocks are predisposing factors (Stashak, 1987b). It is therefore not surprising that the disease to a certain extent is thought to have a genetic basis. Barneveld (1983) studied 168 3- and 4-year-old Warmblood offspring of 11 stallions and concluded that bone spavin indeed had a hereditary basis and was related to the conformation of the hind limb. In the study by Van der Veen et al. (1994) bone spavin was found to have a heritability of 0.20–0.35. Radiographic examination is considered essential for diagnosis of bone spavin (Butler et al., 1993) but palpation of the distal tarsus and hind limb motion evaluation before and after the flexion test of the tarsus have also been shown to be of importance. In German riding horses, the heritability of bone spavin, based on radiographic diagnosis, has been estimated to be low, 0.02–0.04 on an observed scale (Winter et al., 1996). In Icelandic horses the heritability for bone spavin in the distal tarsal joint was 0.1 (Björnsdóttir et al., 2000) whereas heritability for hind limb lameness after the flexion test was 0.47. The flexion test is regarded as a less specific method for the diagnosis of bone spavin. They suggest to select against bone spavin based on flexion test of the tarsus followed by radiographic diagnosis, since the combined trait has a considerable higher heritability than only considering radiography. This is an interesting example of combining two methods of diagnosis to develop a more accurate measure of the phenotype, resulting in a higher heritability of the disorder.

Developmental lameness-causing disorders

Hermans et al. (1987) investigated the genetic background of congenital luxation of the patella in Shetland ponies. Hermans (1970) described ulnar and tibial malformation (persistence) in the Shetland pony with associated locomotor problems. Vertebral compressive myelopathy or 'wobbler disease' is a pathological disorder of the spinal cord rather than of the locomotor system. However, as it produces ataxia the condition may severely affect locomotor performance. An early report on Wobbler disease stated that the syndrome was familial (Dimock, 1950). However, this could not be confirmed in a later large-scale retrospective study (Falco et al., 1976), nor in a prospective study in which clinically and radiographically confirmed 'wobbler' mares and stallions were mated (Wagner et al., 1985). In the latter study the high incidence of a number of developmental orthopedic diseases (OC, physitis, contracted tendons) was remarkable.

Complex chondrodysplasia: osteochondrosis

Osteochondrosis (OC) can be defined as a disturbance of the process of endochondral ossification as this occurs in the growing individual. Irregular ossification leads to the formation of thick cartilage plugs and areas of focal necrosis, eventually resulting in flattened bone contours and loose fragments, commonly referred to as osteochondrosis dissecans (OCD) (Jeffcott, 1997; van de Lest et al., 1999). Of the group of so-called developmental orthopedic diseases it is by far the most common (McIlwraith, 1986). Epidemiological data suggest that the disorder is present in many breeds of horses in 10–25% of the population (Jeffcott, 1997). The exact pathogenesis of the disease is still unclear and subject to investigation (Jeffcott, 1991; Jeffcott & Henson, 1998). However, there is universal agreement that the disease is multifactorial (Hurtig &

Pool, 1996) and that genetics play a role. Therefore, like many diseases and performance characteristics, the phenotypic expression of OC is influenced by the environment plus a genetic component consisting of many genes in the genome (Gerber & Bailey, 1995).

Van Weeren and Barneveld (1999) showed that osteochondrosis is a very dynamic process in which lesions develop, but may also regress spontaneously. They also demonstrated the presence of osteochondrotic lesions in many joints other than the commonly affected hock and stifle. These findings shed a different light on this condition and ask the question of whether there is a genetic difference between animals that show the condition at 3 years of age and animals that have shown the condition since foals, but in which the lesions subsequently regressed spontaneously. In addition to this, when considering the stifle joint, they found significant difference in the prevalence of the condition in foals that were the offspring of OC-free parents compared with foals whose parents were suffering from the condition in the same joint. This was not the case with respect to oseteochondrotic lesions in the hock joint and might be an indication of a different genetic background in these two joints (Van Weeren et al., 1999).

Osteochondrotic lesions are found in different joints and joints primarily affected are the tarsocrural (TC), femeropatellar (FP), glenohumeral (GH), metacarpophalangeal, (MCP), metatarsophalangeal (MTP) and the cervical intervertebral (CI) joints (Radiostits et al., 2007). Most of the genetic studies are considering only one or a few of the joints, of which the stifle, hock and fetlocks are the most frequent ones (Table 12.6). The large range in prevalence and heritability reported may be attributed to: use of field data, definition of OC, and statistical model of analysis in relation to the scale of OC-scoring. As radiographic examinations are expensive and labor intensive, datasets collected at other occasions (auctions and presale purchases) are often subject to genetic studies. There is a serious risk that these datasets are too small or preselected, leading to inaccurate and/or biased estimates. The heritability estimates may also vary as a result of different definitions of OC, in particular with respect to bony irregularities at different predilection sites in the joints. Depending on the predilection site, lesions are assumed to have either a traumatic origin or an osteochondrotic origin (Jeffcott, 1991). For example, Philipsson et al. (1993) and Grøndahl and Dolvik (1993) only regarded bony fragments at the intermediate ridge of the distal tibia and at lateral/medial trochlear ridge of the talus as OC, whereas McIlwraith (1993a,b) additionally regarded the lateral/medial malleolus of the tibia as a predilection site. Prevalence and heritability are likely affected by the number of predilection sites considered. Similarly, fragments and flattening might have a different genetic basis and it is questionable whether these two forms should be treated alike in a genetic study. Scoring of OC is mostly on binary scales (yes/no OC), which does not give the opportunity to record further details with respect to form and degree of severity of OC. Instead Van Grevenhof et al. (2009b) used a 5-point scale in their study on which form as well as severity of disorder could be recorded. In most joints heritability-estimate improved when using the 5-point scale, compared to a binary scale (Table 12.7). In contrast, Ricard et al. (2002) propagated a binary scale, because heritabilities based on multipoint scales were lower, due to introduction of random noise in the data when using a multipoint scale. This illustrates that the extra categories should be useful differentiators.

After data collection, further differences in heritability estimates could arise from different models of analysis. The binary trait could be treated accordingly using a threshold model, although often an ordinary linear model is used. A linear model reveals the heritability on the observed scale, which is an underestimation of the true frequency because of its dependence on the prevalence in the population. A threshold model estimates heritability on the underlying scale, which can be interpreted as the sensitivity to or risk of developing the disorder (irrespective of having OC), and better reflects the genetic potency. Therefore, estimates on the observable scale often are converted afterwards to the underlying scale, using appropriate formulas (e.g. Dempster & Lerner, 1950).

The analysis is commonly performed using a sire or an animal model. The animal model better accounts for the state of selection in females, whereas the assumption underlying a sire model is that females are unselected. In horse breeding in which assortative mating is common. As a result of poor data quality and treatment, genetic differences between joints and breeds might be compromised.

OC/OCD in the stifle seems to have low heritability with estimates around 0.08 and not significantly different from zero (Tables 12.6 and 12.7). Measuring OC in the stifle is probably more difficult than in the hock, which introduces random noise. The heritability estimate for OC in the stifle might therefore be lower than for the hock, although the prevalence is comparable. This is supported by the significant effect of sedation during radiography (Van Grevenhof et al., 2009a). OC/OCD in the FP more often leads to lameness than OC/OCD in the TC (Auer & Stick, 2006), but OC/OCD in the hock joint is more frequently investigated. When only considering OC, heritability lies mostly in the area of 0.15, whereas OCD is somewhat higher at 0.27 (Stock & Distl, 2006; Van Grevenhof et al., 2009b). OC in trotters might be somewhat higher as indicated by studies of Grondahl and Dolvik (1993) and Philipsson et al. (1993). Grondahl and Dolvik suspected an overestimation in their result, because of a very high incidence of OC in one group of offspring. OC/OCD in the fetlock has a heritability of 0.10 (Schober et al., 2003; Van Grevenhof et al., 2009b); whereas heritability of OCD was somewhat higher at 0.17–0.18 (Stock et al., 2005; Philipsson et al., 1993), which was accompanied by a higher prevalence of 25%. Van Grevenhof et al. (2009b) found only a value of 0.09 when clearly separating fragments from flattenings. They argued that only osseous fragments seen at the proximodorsal parts of the sagittal ridge of the third metacarpal and metatarsal bone can be considered as caused by the same etiology as other OC and not by mechanical injuries (Hurtig & Pool, 1996).

Genetic correlations reflect to what extent traits are affected by the same genetic complex and therefore contribute to unraveling the etiology of traits. Sandgren et al. (1993) found genetic correlations between hock and fetlock close to zero and this corresponds to the findings of Grondahl and Dolvik (1993) and Van Grevenhof et al. (2009b). Stock et al (2005) estimated a moderate positive genetic correlation between hock and fetlock OCD. Genetic correlation of stifle with hock was moderately positive, and of stifle with fetlock was low. Although standard errors in most of the studies were too high to make significant statements, the genetic correlations between joints did not indicate that OC as manifested in the various joints are the same traits (or solely regulated by the same genes). This is supporting the hypothesis of Van Weeren and Van Barneveld (1999) of a different genetic background in the different joints (Van Weeren et al., 1999). Additionally, genetic correlations between the joints are not high enough to rely on measuring in only a part of the joints to set up a selection program to eradicate OC in all joints. Whether the two forms of OC are genetically related was investigated by van Grevenhof et al. (2009b). Genetic correlation between flattenings and fragments over joints was high (0.80) and not significantly differing from one. This finding supports the hypothesis of a common genetic background of both forms of OC.

Genetic correlations of OC with conformation and performance could aid to understanding the etiology as well, and reveals how selection against OC can be implemented in a horse breeding program. There are only a few studies on the relation with performance and expectations are based on phenotypic observations. Affected horses suffering from pain and distress are likely to show reduced performance in sports. However, given the high prevalence of radiographic findings in horses without signs of lameness or stiff joints, the relevance of particular radiographic findings, especially with respect to sport performance, is being questioned.

Table 12.6 Prevalences and heritabilities (h^2) of osteochondrosis (OC) and fragments (OCD), by joint, for different populations of warmblood (WB) horses

Population	n	Radiographic finding	Prevalence	$h^{2\ SE}$	Method of author	Reference*
Femoropatellar (FP) OC/OCD						
Dutch WB stallions	(n = 1965)	OC	11.5	0.09	ATM (REML, DL)	I
French WB	103 sires (n = 733)	OC	1–7	0.00–0.17	LSM	II
Italian WB	75 sires (n = 350)	OCD	16.6	$0.09^{0.24}$	ATM (REML)	III
Tarsocrural (TC) OC/OCD						
Dutch WB stallions	(n = 1965)	OC	16.0	0.11	ATM (REML, DL)	I
Dutch WB mares	30 sires (n = 590)	OC	13.7	$0.01^{0.06}$	LSM (REML)	IV
Dutch WB mares	30 sires (n = 590)	OC	13.7	$0.14^{0.17}$	LAM (REML)	IV
French WB	103 sires (n = 733)	OC	11–13	0.00–0.02	LSM	II
Hanoverian WB	165 sires (n = 624)	OC	10.5	$0.06^{0.06}$	LAM (REML)	V
SB trotters	39 sires (n = 644)	OC	14.3	0.52	STM (REML)	VI
SB trotters	24 sires (n = 793)	OC	10.5	$0.27^{0.08}$	LSM	VII
Hanoverian WB	3725	OCD	9.6	$0.37^{0.06}$	LAM (REML, DL)	VIII
Hanoverian WB	569 sires (n = 5231)	OCD	9.2	$0.28^{0.04}$	LAM (REML, DL)	IX
Hanoverian WB	569 sires (n = 5231)	OCD	9.2	$0.27^{0.04}$	LSM (REML, DL)	IX
Hanoverian WB	569 sires (n = 5231)	OCD	9.2	$0.17^{0.07}$	STM (GS)	IX
Danish Trotters	9 sires (n = 325)	OCD	12.0	$0.26^{0.14}$	STM	X
Metacarpophalangeal/metatarsophalangeal (MCP/MTP) OC/OCD						
French WB	103 sires (n = 733)	OC	8–11	0.04–0.21	LSM	II
Hanoverian WB	165 sires (n = 624)	OC	18.3	$0.12^{0.09}$	LAM (REML)	V
Hanoverian WB	(n = 3725)	OCD	20.8	$0.19^{0.03}$	LAM (REML, DL)	VIII
Hanoverian WB	569 sires (n = 5231)	OCD	23.5	$0.17^{0.03}$	LAM (REML, DL)	IX
Hanoverian WB	569 sires (n = 5231)	OCD	23.5	$0.17^{0.03}$	LSM (REML, DL)	IX
Hanoverian WB	569 sires (n = 5231)	OCD	23.5	$0.12^{0.05}$	STM (GS)	IX
SB trotters	39 sires (n = 644)	OCD	11.8	0.21	STM (REML)	VI
SB trotters	24 sires (n = 793)	OCD	21.5	$0.17^{0.06}$	LSM	VII
All joints (FP+TC+MCP/MTP)						
Italian WB	75 sires (n = 350)	OCD	16.6	$0.14^{0.23}$	LAM (REML, DL)	III

ATM, animal threshold model; DL, Dempster-Lerner transformation; GS, Gibbs sampling; LAM, linear animal model; LSM, linear sire model; REML, restricted maximum likelihood; SB, Standardbred; STM, sire threshold model; WB, Warmblood.

*I, der Kinderen (2005); II, Ricard et al. (2002); III, Pieramati et al. (2003); IV, KWPN (1994); V, Schober et al. (2003); VI, Grøndahl and Dolvik (1993); VII, Philipsson et al. (1993); VIII, Stock et al. (2005); IX, Stock and Distl (2006); X, Schougaard et al. (1990).

Adapted from Van Grevenhof, E. M., B. J. Ducro, P. R. van Weeren, J. M. F. M., van Tartwijk, A. J. van der Belt, and P. Bijma, 2009. Prevalence of various radiographic manifestations of osteochondrosis and their correlations between and within joints in Dutch Warmblood horses (KWPN). Equine Vet. J. 41, 11–16, with permission from the Equine Veterinary Journal.

Reduced sports performance was found in trotters (Grøndahl & Engeland, 1995) and osteoarticular findings were directly responsible for failure to qualify in 31% of the horses participating (Robert et al., 2006). In contrast, no significant differences were found in racing performance of Standardbred trotters with radiographic signs of OCD, relative to their contemporaries (Brehm & Straecker, 2000; Storgaard Jørgensen et al., 1997). These results are indicative for phenotypic correlations, but do not allow us to make inferences on whether sires that inherit potential for a successful sport career also inherit high or low susceptibility to OC. In the study of Stock and Distl (2006) hock-OCD showed high negative genetic correlation to sports performance in both disciplines whereas fetlock-OCD was only negatively related to show jumping. Negative genetic correlations are favorable because they point out that breeding for lower prevalence of OC coincides with breeding for higher sport performance. The authors suspected

Table 12.7 **Heritabilities estimated (h^2) using continuous, binary and '1 to 5' scales**

Level[2]	OC[3]	σ_p	h^2 continuous scale[1]	h^2 binary scale[1]	h^2 1-to–5 scale[1]
Animal	ALL	4.05	0.23 (0.09)	0.15 (0.08)	0.23 (0.09)
	FLAT	3.16	0.08 (0.06)		
	FRAG	2.45	0.22 (0.09)		
FP	ALL	2.09	0.05 (0.05)	0.05 (0.05)	0.06 (0.05)
	FLAT	1.17	0.07 (0.06)		
	FRAG	1.22	0.02 (0.04)		
TC	ALL	2.01	0.36 (0.11)	0.25 (0.10)	0.36 (0.11)
	FLAT	1.47	0.15 (0.08)		
	FRAG	1.39	0.26 (0.09)		
MCP/MTP	ALL	2.24	0.14 (0.08)	0.10 (0.07)	0.11 (0.07)
	FLAT	1.86	0.08 (0.10)		
	FRAG	1.36	0.06 (0.07)		

[1] Heritability values are expressed as h^2 (SE). The continuous scale refers to transforming osteochondrosis (OC) scores on a continuous liability scale; the bivariate scale refers to OC scored as 0 or 1; and the scale of 1 to 5 refers to transforming A to E scores into corresponding values ranging from 1 to 5.

[2] FP = femoropatellar joint; TC = tarsocrural joint; MCP/MTP = metacarpophalangeal and metatarsophalangeal joints.

[3] Refers to the joints level. ALL = both flattened bone contours and fragments; FLAT = flattened bone contours; FRAG = fragments.

Taken from Van Grevenhof, E.M., Ducro, B.J., van Weeren, P.R., van Tartwijk, J.M.F.M., van der Belt, A.J., Bijma, P., 2009a. Prevalence of various radiographic manifestations of osteochondrosis and their correlations between and within joints in Dutch Warmblood horses (KWPN). Equine Vet. J. 41, 11–16.

some overestimation of the correlations, but nevertheless a negative correlation was expected since hock joint lesions are most likely to interfere with load bearing of the hind limbs in dressage sport. The authors therefore concluded that orthopedic status of the horse could genetically be improved, without compromising selection for sports performance. However, Winter et al. (1996) estimated a positive genetic correlation between show jumping and occurrence of OCD.

As intensive sport performance will affect joint biomechanics, so does conformation. Deviating conformation might lead to disproportionate weight bearing and subsequently OC. Many conformational traits are considerably heritable and a genetic relationship to OC might be expected. Taller horses have a predisposition for osseous fragments in the fetlock and hock joints (Stock et al., 2005), which agree with findings in German and Dutch Warmbloods and Swedish trotters (Van der Veen et al., 1994; Pagan & Jackson, 1996; Sandgren et al., 1993; Van Weeren et al., 1999; Winter et al., 1996). This could indicate positive genetic correlations, but the literature shows contradictory results. Negative genetic correlations were found between height at the withers and the incidence of hock OC (Philipsson et al., 1993; Willms et al., 1999). Large carpal circumference was genetically associated with a high incidence of hock OC but a low incidence of fetlock OCD (Philipson et al., 1993). Foals affected with hock OC had a higher average daily weight gain (Sandgren et al., 1993), they had a larger frame and a markedly larger circumference of the cannon bone and the carpus (Pagan & Jackson, 1996; Van Weeren et al., 1999). In contrast to hock OC, foals with lower body weight were found to have a significantly higher prevalence of OC in fetlock joints (Schober et al., 2003). In conclusion, the genetic relation of OC to growth is not straightforward and depends on the joint considered. Development of OC is probably related to how the growth-phase of the body and its components interfere with the (disproportionate) weight bearing of each individual joint, which itself is in a process of growing.

Until now selection against OC has not been very successful, despite the heritable character of OC. Most of the selection programs have been based on the phenotype of the candidate-breeding stallion. Observable heritability is low which has the consequence that stallions' own phenotype is not a reliable predictor of its genotype. A more reliable breeding value can be realized from progeny testing. The limited use of the stallions' phenotype to predict its breeding values is illustrated by the studies of Schougaard et al. (1990) and Van Grevenhof et al. (2009a), where the recorded animals all are descending from breeding stallions which have been checked for OC. Still there was large variation in OC prevalence among the progeny groups.

To date diagnosis of OC has always been on radiographic findings or clinical state and more advanced techniques like magnetic resonance imaging or biomarkers will play a more prominent role in the future (Vervuert et al., 2007). In particular, biomarkers, supported by mRNA expressions factors (Gläser et al., 2009; Austbø et al., 2010; Serteyn et al., 2010), may serve as an early and more objective measure.

Austbø et al. (2010) used a PCR (RAP-PCR) and a real-time RT-PCR and tissue samples of the distal intermediate ridge of the tibia of foals considered predisposed to OC when the parents had OC, and identified two genes not previously correlated with OC as differentially expressed, and which were identical to *TLK2* and an equine EST. Serteyn et al. (2010) compared leucocytes of OC-affected and non-OC-affected horses using digital gene expression analysis (DGE) and real-time PCR. They showed an obvious dysregulation of several signaling pathways related to cartilage formation or cartilage repair, including Wnt, Indian hedgehog, and TGF-β signaling. Other genes, including *ISG*, *APOB*, *MGAT4*, and *TBC1D9*, showed a significantly different expression between groups. They proposed that these genes might play a role in high carbohydrate diet, abnormal insulin metabolism, or inflammation, mechanisms suspected to be involved in OC.

Also, these methods of diagnosis might help to break through the binary measure of the trait currently used and might reveal a more quantitative measure of bone constitution, making it possible to allow horses that are not OC-affected to be distinguished from the never-affected. For the detection of animals at risk genetic markers have the potential to form a basis for reducing OC positive animals in a population (Dierks et al., 2007; Lampe et al., 2009a,b; Wittwer et al., 2007a,b, 2008, 2009). Lykkjen et al. (2010) were the first to perform a genome-wide association study for osteochondrosis of the tibiotarsal joint in Norwegian Standardbred trotters using the recently released Illumina Equine SNP50 BeadChip. On chromosomes (*Equus callabus* chromosome (ECA)) 5, 10, 27 and 28 they found moderate evidence of association representing interesting areas for future research, validation studies and fine mapping of candidate regions. Dierks et al. (2010) refined the quantitative trait locus for equine osteochondrosis (OC) on horse chromosome (ECA) 2 to a genome-wide significant interval at 20.08–30.94 Mb.

Simple chondrodysplasia: dwarfism

Within the Friesian horse breed, congenital dwarfism has been recognized for many years and occurs at a frequency of 0.25% (Osinga, 2000; Back et al., 2008). A full phenotypic

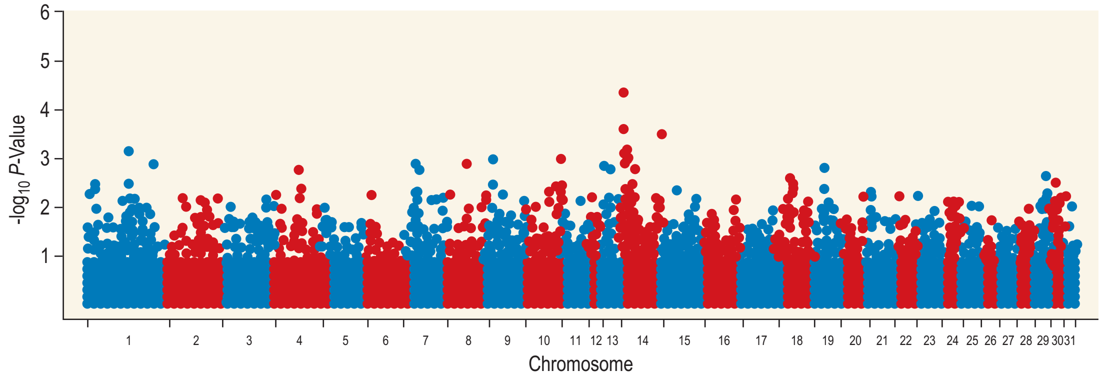

Fig 12.4 Manhattan plot of *P*-value in the Friesian horse dwarfism GWAS. Association of 34 429 SNPs with dwarfism represented by $-\log_{10}$ P-values from a two degree of freedom x^2 test plotted by chromosome and sorted by chromosomal position. No SNP in the GWAS remained statistically significant after correction for multiple testing.

Reprinted from Orr, N., Back, W., Gu, P., et al., 2010. Genome-wide SNP association based localization of a dwarfism gene in Fresian dwarf horses. Animal Genetics 41 (Suppl. 2), 2–7, with permission from John Wiley and Sons.

characterization for Friesian dwarfs has been reported (Back et al., 2008). Briefly, the Friesian dwarf phenotype results from physeal growth retardation in both limbs and ribs, reflected in a characteristic disproportional growth disturbance. The potential for postnatal growth in these animals, albeit at a reduced rate, is responsible for mature dwarfs having a head of the same size as unaffected animals, a broader chest with narrowing at the costochondral junction, a disproportionally long back and abnormally short limbs. Furthermore, radiographs reveal a dysplastic metaphysis of the distal metacarpus and metatarsus. Light microscopy of growth plates at the costochondral junction demonstrate an irregular transition from cartilage to bone, and thickening and disturbed formation of chondrocyte columns, which is similar to findings in osteochondrodysplasia (Back et al., 2008). The molecular mechanism underlying the growth disturbance in Friesian foals has yet to be determined, although the trait is heritable and appears to follow an autosomal recessive pattern of transmission (Osinga, 2000; Back et al., 2008). Orr et al. (2010) have reported the first genetic mapping of the genetic determinants of dwarfism in the Friesian horse using GWAS methodologies in a small number of Friesian dwarfs and normal controls. Ten Friesian dwarf horses were selected by the investigators over an 8 year period (2001–2008) based on their unique phenotype (Back et al., 2008) and availability of DNA. Ten normal Friesian horses (controls) were selected in 2008 based on a normal phenotype.

A peak of association was observed on chromosome 14, the best SNP being BIEC2-239376 ($p = 4.54 \times 10^{-5}$) (Fig. 12.4) and the significance of association at BIEC2-239376 was greatest under a recessive model ($p = 7.74 \times 10^{-6}$). All 10 of the dwarfs in the GWAS were TT homozygotes, while the controls were comprised of 4 CC homozygotes and 6 heterozygotes. Fine-mapping in the region was performed by genotyping 374 SNPs, of which 319 were not on the GWAS array, in the region of association on chromosome 14. The BIEC2-250663 ($p = 4.94 \times 10^{-5}$) SNP was more significantly associated with dwarfism than BIEC2-239376 ($p = 6.12 \times 10^{-5}$) (Fig. 12.5); dwarfs were fully homozygous for both markers and the homozygous genotype observed in dwarfs was not present in controls. An additional SNP, BIEC2-249929 was in perfect linkage disequilibrium with BIEC2-239376. BIEC2-239376 is located 34 Kb from the gene encoding the equine homolog of the prophet of PIT1, paired-like homeodomain transcription factor protein, *PROP1*. Inactivating mutations in *PROP1* are known to cause dwarfism in humans via combined pituitary hormone deficiency. Therefore re-sequencing in the *PROP1* gene was performed resulting in the detection of nine SNPs, all of which were novel based on their absence from the EquCab 2.0 SNP database. Each novel SNP was rare, and many were singletons; none was associated with the dwarfism phenotype. Thus, resequencing analysis of the protein coding components of *PROP1* failed to detect a putative functional variant.

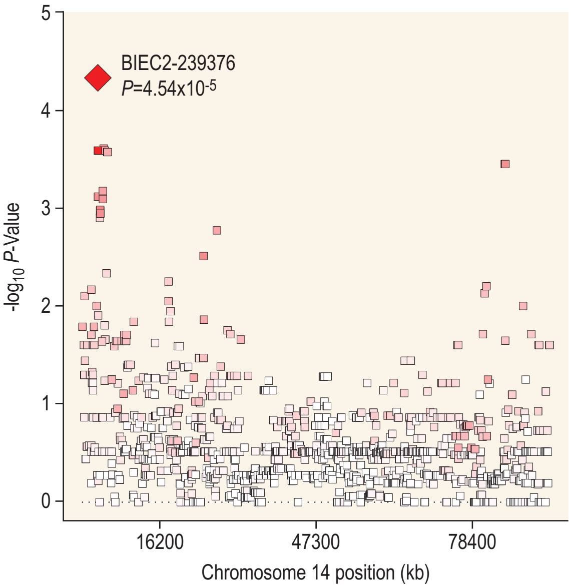

Fig 12.5 Association plot of chromosome 14 SNPs with dwarfism, with chromosomal position on the x-axis and $-\log_{10}$ *P*-value on the y-axis. The most significant chromosome 14 SNP, BIEC2-239376, is indicated by a red diamond. Each square on the plot represents a single SNP; the color of each square represents the strength of correlation between that SNP and BIEC2-239376, with dark red indicating an r^2 of 1.

Reproduced from Orr et al. (2010).

Perturbations in homologous gene families often result in the manifestation of phenotypically similar traits between species. As such, Orr and colleagues screened the Online Mendelian Inheritance in Man (OMIM) database (http://www.ncbi.nlm.nih.gov/omim/) to determine whether any of the genes in the chromosome 14-association region were implicated in dwarfism in humans. The equine homolog of *PROP1* was identified as a strong positional candidate gene for dwarfism in Friesians. Inactivating mutations in *PROP1* cause disruption of the growth hormone (GH) axis and are manifested as a dwarfism phenotype. Simple, central pituitary underproduction of GH leads typically to proportional dwarfism, as seen in the German Shepherd dog (Andresen & Willeberg, 1976;

Hanson et al., 2006). In the Friesian dwarf horses, however, a disproportional growth disturbance is seen, which would imply a local defect or disturbance in one of the regulatory systems for growth plate development. Growth plate development is under the control of many autocrine and paracrine factors (Kronenberg, 2003). Recently, de Graaf and colleagues investigated the functioning of the hypothalamic-pituitary growth axis in three Friesian dwarfs. No evidence of hypothalamic-pituitary dysfunction or failure of IGF-1 production was found, suggesting that the cause of the congenital growth abnormality was located distal or peripheral to the level of the GH receptor in the liver and may have been a defect in a peripheral IGF-1 or GH receptor, or may not involve the GH-IGF-1 axis at all (De Graaf-Roelfsema et al., 2009). Concomitant with this observation, no coding polymorphisms in *PROP1* were detected that were associated with dwarfism in the Friesian horse samples. When the normal bone remodeling process is disturbed in horses, abnormal defects in the growth plate may result. A local defect or disturbance in one of the regulatory systems for growth plate development potentially can result in a disproportional growth disturbance typically seen in Friesian dwarf horses (Vaughan, 1976; Jeffcott & Henson, 1998; Gee et al., 2005). Further screening of the OMIM database for genes in the chromosome 14 region that could be linked to a disturbed bone remodeling process in abnormal growth plate development identified *ZNF346*, *COL23A1* and *B4GALT7* as candidate genes. *ZNF346* is proposed to play a role in apoptosis (cell death), a process crucial for the normal transition of cartilage into bone seen during normal physeal growth (Gibson, 1998; Ballock & O'Keefe, 2003). It could be speculated that disturbed apoptosis plays a role in the physeal growth retardation typically seen in Friesian dwarfism. Both *COL23A1* and *B4GALT7* are proposed to play a role in collagen network formation. Although a disturbed collagen network is known to effect calcification and subsequent transformation of cartilage into bone (Wassen et al., 2000), the specific role of both genes in collagen formation is highly speculative and largely unclear. *B4GALT7* is also proposed to play a role in connective tissue disorders and has been related to disturbed fibril organization and proteoglycan synthesis. Both processes could play a role in abnormal development of bone and subsequent retardation of growth in the growth plate seen in Friesian dwarfism (Kvist et al., 2006; Burdan et al., 2009).

Finally, both *FGFR1* and *FGFR2* are included within the critical region of chromosome 14 flanked by BIEC2-249929 and BIEC2-250663 based on the equine build from UCSC Broad Institute (UCSC Genome Browser: http://genome.ucsc.edu). Both fibroblast growth factor receptors play key roles in skeletal development and mutations have been related to skeletal dysplasia and dwarfing syndromes (White et al., 2005; Eswarakumar et al., 2002). Profound effects on bone elongation have been shown through supposed suppression of chondrocyte and osteoblast function. However, in contrast to the relative normal head proportions seen in the Friesian dwarf syndrome, FGFR1 and FGFR2 mutations seem to have a significant effect on flat bone growth and skull formation.

In conclusion, a putative region that may harbor a gene for dwarfism in Friesian horses has been identified on ECA14. Validation of this finding in a larger group of animals and segregation analysis in known pedigrees is warranted before further localization of the causative mutation is conducted. This may prove extremely challenging given the strong linkage disequilibrium in the region. The study suggests that with the advent of new genomic tools, studies of equine diseases may yield important new insight into pathogenesis and may be translatable to orthologous human traits.

Conclusions

The recent completion of the horse genome sequence and the commercial availability of an equine SNP genotyping array will facilitate an acceleration in the mapping of disease genes in the horse during the coming years. While environmental factors such as management and training play an important role in shaping the equine athletic phenotype, it is likely that genetic testing for conformation, disease and performance traits will become mainstream and that this information will enhance decision-making processes in the selection and breeding of horses. A crucial step in the success of developing gene tests is the phenotyping. Poor phenotyping will severely compromise the success of genotyping. For a set of diseases this is less relevant as the phenotype is clear, but for complex multi-factorial diseases the phenotype is less clear. Defining accurate phenotypes for performance and conformation, in which subjective measurements are involved will be the challenge in the near future.

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CHAPTER 13

The response of musculoskeletal tissues to exercise

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General introduction

There is a constant interaction between any biological entity and its environment, which may consist of other biological systems (such as individuals from the same species, predators or invading micro-organisms), or physical influences such as weather conditions. In fact, the (in)ability to respond actively to these environmental challenges can be seen as a criterion for the discrimination between life and death. The environmental influences can be best accommodated when the individual is optimally suited to cope with these challenges. In other words, when optimal functional adaptation occurs. This is of particular interest when the environmental stimuli are repetitive in nature, such as those generated by the locomotor system. This concept of functional adaptation applies to widely different timescales. On an evolutionary scale the capacity to adapt functionally is decisive for the survival of a species; for a given individual the ability to adapt throughout life determines whether or not vitality is retained and for how long.

The horse has evolved from a forest-dwelling browser called Hyracotherium or Eohippus, which had four hoofed toes in the front feet and three in the hind feet and was not more than 8–9 inches (approximately 2 hands) at the withers, to the contemporary large ungulate measuring up to 18 hands. During the evolutionary process, which started in the Eocene and took some 60 million years, the horse changed from a typical forest inhabitant, which relied on hiding rather than flight for survival into an animal that was optimally adapted for living on the open steppe (Simpson, 1951). Through this process the locomotor system underwent profound change, as it became the most important factor in escaping from predators. The morphological changes that have imparted advantage for high-speed locomotion include the development of long and slender limbs with the muscles located proximally and close to the center of mass, reduced degrees of freedom of joint motion in the distal limbs, which grossly limits motion to the sagittal plane, and the use of collagenous components of muscle and tendon to reduce energy requirements in posture and locomotion. A very important athletic asset of the present-day horse is the storage of kinetic energy in the form of elastic energy in the tendinous structures of (especially) the limb flexors. This spring-like mechanism prevents energy loss and limits the role of the flexor muscles to dampening of these springs rather than using them to generate propulsion, thus greatly reducing the muscle volume needed (Wilson et al., 2001).

The potential of the locomotor system led man to begin domesticating the horse in approximately 3000 BC (Dunlop & Williams, 1996). Unlike most other species, horses have always been used to increase the mobility and transport capacity of mankind, with more tangible products such as meat, milk and leather figuring as by-products only. Although the role of the horse in society has changed dramatically in the past 50–60 years in comparison to the previous five millennia, it is still its athletic capacity that gives the horse its role in present-day society.

On a much shorter timescale, functional adaptation towards optimal locomotion capacity is also of crucial importance for the individual animal. The demands on the equine musculoskeletal system of many modern performance horses seem likely to be substantially more than those borne previously by animals principally used in transport, agriculture and the military, and are most probably much heavier than under most circumstances in the wild. The heavy challenges placed on the musculoskeletal system by present-day equestrian activities, together with the inevitable loss in robustness and sturdiness that goes with the process of domestication, may well lie at the heart of the high incidence of musculoskeletal injury and elevated wastage for orthopedic reasons in the equine species (Rossdale et al., 1985; Williams et al., 2001).

Any musculoskeletal injury can be seen as a failure of the tissues to respond to the (mostly biomechanical) challenges placed upon them. Such failure may be the consequence of a high-impact single traumatic event, but more often follows the accumulation of repetitive micro-trauma. In the latter, training may be helpful to enhance the resistance of the musculoskeletal tissues to biomechanical loading. In fact, training is the artificial and purposeful enhancement of the degree of functional adaptation of tissues. Classically, there has been much interest in the effect of training on cardiovascular performance and on muscle strength, but other tissues respond to training too, though it should be clear that the extent of response of different tissues to the same training protocol may differ vastly. Another complicating factor is the age of the individual. Traditionally, research has been done in young horses, mostly aged 2–4 years, because of the early onset of the athletic career in the racing breeds and resulting commercial pressure. These horses cannot be classified as juvenile, nor have they yet reached full skeletal maturity (Gabel et al., 1977; Strand et al., 2007). There has been little interest in the effects of exercise on older horses, but some large studies have been conducted in the past decade on the effects of exercise in very young animals, e.g. in newborn foals. The latter research has made it clear that age indeed does matter. Whereas bone and muscle are known to respond to exercise throughout life, articular cartilage, tendons and ligaments are tissues that are much less, if at all, responsive in mature individuals. However, there is mounting evidence from recent research that these latter three tissues, which rank among the first with respect to injury prevalence and are notorious for their poor healing tendency, might be much more responsive to exercise in juvenile animals. This might open up new avenues for better adapting the equine musculoskeletal system to athletic challenge through programs of conditioning exercise at young age. However, such programs could be developed only if the exact effects of exercise on the diverse musculoskeletal tissues are known, if the exercise regimen to effect adaptation is known, and the appropriate time window in which to apply it. In the following chapter the major constituting tissues of the musculoskeletal system: bone, articular cartilage, tendons and muscle, are discussed with respect to their responsiveness to exercise. Discrimination is made between the effect of exercise in mature individuals and in the growing and still developing juvenile animal.

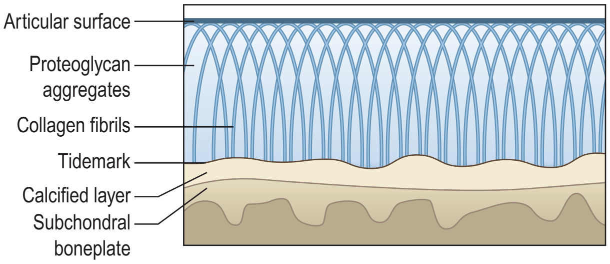

Fig 13.1 Schematic drawing of articular cartilage showing the arcade-like architecture of the collagen fibrils as first described by Benninghoff (1925). Typically, the collagen fibrils emerge from the calcified layer perpendicular to the tidemark and start to arch in the intermediate zone, to become aligned with the articular surface in the superficial zone.

Articular cartilage

Introduction

Joint disorders have a major impact on equine athletic performance, as they rank either first or second as causes for wastage in performance horses, depending on the equestrian discipline involved (Rossdale et al., 1985; Todhunter & Lust, 1990; Williams et al., 2001). A joint is a complex entity that is made up of subchondral bone, articular cartilage, synovial membrane, and fibrous joint capsule and ligaments. Sometimes other structures such as a physis, tendon insertions, menisci or ligaments are present intra-articularly as well. Articular cartilage plays a pivotal role in the physiology of the joint because of its triple function: transmission of the forces generated by locomotion, acting as a shock absorber and providing a smooth gliding surface to enable supple joint motion. Articular cartilage has a crucial role in joint pathology, as in most joint disorders it is the principally affected joint tissue and has, at least in mature individuals, a very limited capacity for repair. In the following section first a brief synopsis will be given of some essential principles of articular cartilage biology, followed by a paragraph on the developmental aspects of articular cartilage, which are essential to appreciate the effects of exercise on young, growing individuals and the possible implications thereof. The section ends with a paragraph on the effects of exercise (or lack thereof) in more mature individuals.

Basic principles of articular cartilage biology

Articular cartilage plays an important role in both the transmission and attenuation of forces generated by locomotion, which leads to seemingly contradicting requirements of both elasticity and great strength. Nature provides a solution to this problem by conceiving an extracellular matrix (ECM) that consists of two principal components: collagen fibrils and proteoglycan aggregates. The collagen fibrils are made up of collagen type II molecules (3 α_1-chains in triple helix configuration) and form a three-dimensional arcade network, as was first described by Benninghoff (1925). The fibrils start from the layer of calcified cartilage just above the subchondral bone, then course perpendicular to this layer towards the joint surface and bend back, running tangentially to the joint surface and directly under it, to close the arch by returning perpendicularly again to the calcified cartilage layer (Fig. 13.1). Cross-links that interconnect α_1-chains within the same collagen molecule and interconnect collagen molecules and different collagen fibrils provide structural coherence and extra strength. Cross-link formation is one of the so-called post-translational modifications of collagen and is the last chemical modification that occurs during the formation of the primary collagen structure. There are various types of cross-links with the pyridinoline cross-links that form between lysyl and hydroxylysyl residues in the collagen network (lysylpyridinoline or LP-cross-links and hydroxylysylpyridinoline or HP-cross-links respectively) as the most common covalent cross-links. Cross-links have a major influence on structural and consequently biomechanical characteristics of the collagen network (Eyre & Wu, 1995) and the formation of cross-links is mainly an irreversible process (Ray et al., 1996). A special category of cross-links is formed through the process of non-enzymatic glycation. As collagen molecules have an exceptionally long lifetime once incorporated into the ECM of cartilage (see later), they are susceptible to the accumulation of advanced non-enzymatic glycation end products (AGEs) via the so-called Maillard reaction (Monnier, 1989). The process results in increased cross-linking, such as pentosidine formation from lysine, sugar and arginine moieties. Pentosidine is one of the few Maillard cross-links of which the structure has been elucidated, and is used as a sensitive marker for the entire process (Vlassara et al., 1995). The accumulation of AGEs depends on the turnover rate of a protein or tissue and is thus a measure for the metabolic rate of that structure (Verzijl et al., 2000).

Interspersed between the collagen fibrils and connected to them either directly or via hyaluronan or hyaluronic acid molecules are proteoglycan aggregates, of which aggrecan is the most important. Aggrecan consists of a core protein with large numbers of sulphated glycosaminoglycans (chondroitin sulphate and keratan sulphate) as side chains. Because of their sulphate groups, these side chains are negatively charged and attract water. The combination of the swelling pressure of the sulphated glycosaminoglycans and the confinement due to the stiffness of the collagen network creates an intrinsic pressure within the ECM of articular cartilage that gives it the unique combination of resilience under compression and great resistance against tensional and shear forces (Todhunter, 1996).

Different areas of articular cartilage are subject to different types of loading, such as low-level constant loading, intermittent loading, and very high impact loading (Fig. 13.2). These variable loading conditions can only adequately be met, without being damaged in the long term, by cartilage possessing different mechanical properties (Herzog & Federico, 2006; Palmer & Bertone, 1996) through appropriately different biochemical and ultrastructural characteristics over the cartilage surface (Brama et al., 2000b,c; Brommer et al., 2005; Murray et al., 2001a; Palmer et al., 1995a,b) (Fig. 13.3). Two sites of the proximal first phalangeal bone, known to be subjected to strongly differing loading conditions and exhibiting a difference in predisposition to cartilage disease, have received considerable attention with respect to topographical heterogeneity in cartilage composition and loading characteristics (Brama et al., 1999b, 2001, 2002) (Fig. 13.4).

Cartilage also displays zonal heterogeneity along its depth. The superficial layer contains flattened chondrocytes, has densely packed type II collagen fibrils oriented parallel to the surface, a small

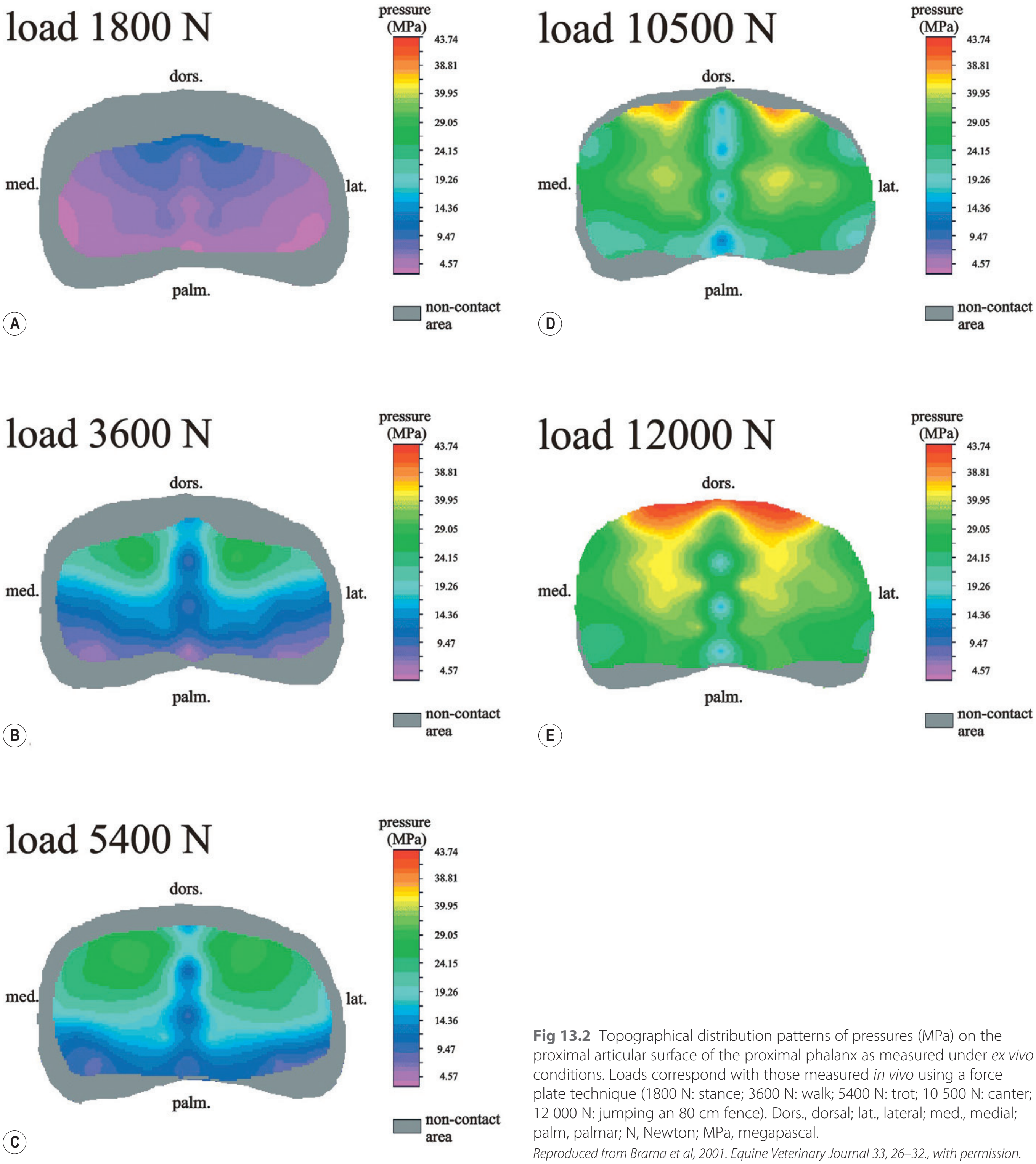

Fig 13.2 Topographical distribution patterns of pressures (MPa) on the proximal articular surface of the proximal phalanx as measured under *ex vivo* conditions. Loads correspond with those measured *in vivo* using a force plate technique (1800 N: stance; 3600 N: walk; 5400 N: trot; 10 500 N: canter; 12 000 N: jumping an 80 cm fence). Dors., dorsal; lat., lateral; med., medial; palm, palmar; N, Newton; MPa, megapascal.

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amount of proteoglycans (PG) and high water content (Aydelotte et al., 1988; Aydelotte & Kuettner, 1988). The middle (transitional) zone has lower water content, a higher concentration of PG, and a lower concentration of collagen fibrils that are less organized, and rounded chondrocytes dispersed irregularly in the extracellular matrix. The deep zone has collagen fibrils oriented perpendicular to the articular surface, the highest concentration of PG, lowest percentage of water of any zone, and chondrocytes arranged in columns perpendicular to the subchondral bone (Todhunter, 1996).

Articular cartilage is, like any living tissue, not a static entity but undergoes constant remodeling through anabolic and catabolic processes. The chondrocyte, the only cell type found in normal articular cartilage, produces all ECM components. Collagen

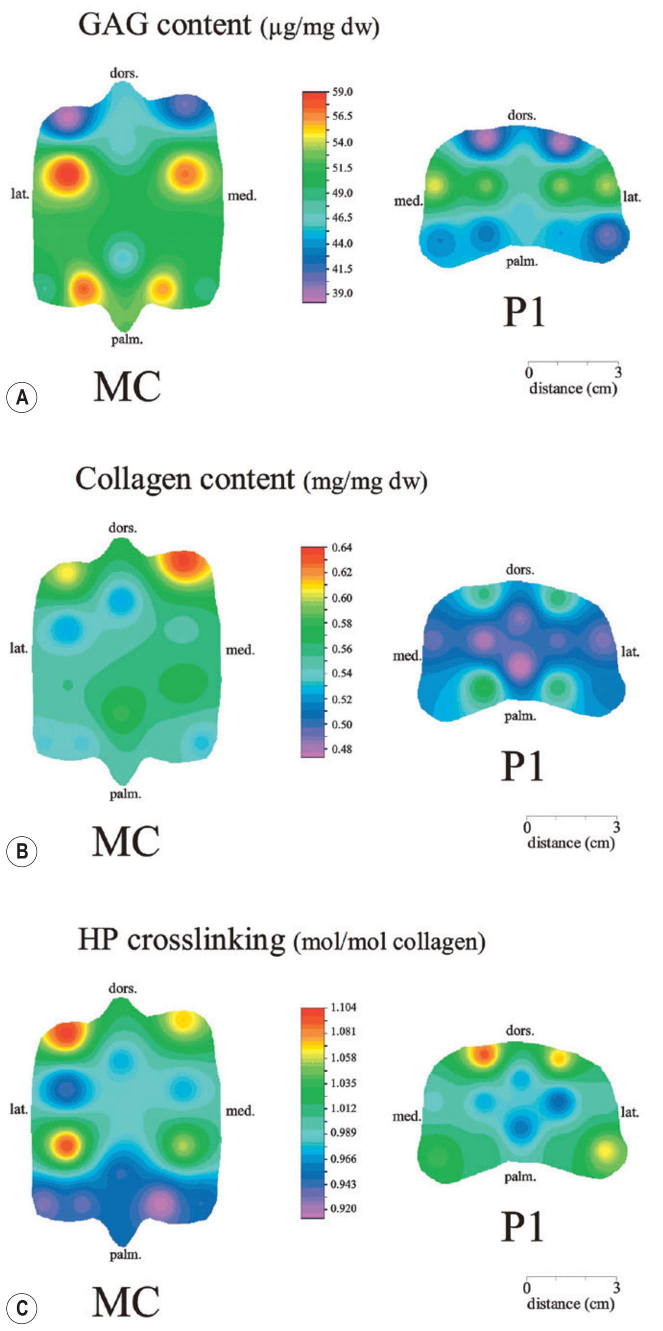

Fig 13.3 Patterns of distribution of glycosaminoglycan content (GAG), collagen content, and hydroxylysylpyridinoline (HP) cross-linking over the proximal articular surface of the proximal phalanx and the distal articular surface of the third metacarpal bone. Dors., dorsal; GAG, glycosaminoglycan; HP, hydroxylysylpyridinoline; lat., lateral; MC, distal third metacarpal bone; med., medial; palm., palmar; P1, proximal first phalanx.

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molecules are produced intracellularly as pro-collagen and are extracellularly modified by enzymatic cleavage of the C- and N-terminal propeptides before they are integrated in the collagen network. Degradation of ECM is effectuated by various proteinases, of which the matrix metalloproteinases (MMPs) and aggrecanases (members of the disintegrin and metalloproteinase with thrombospondin motifs (ADAMTS) gene family) are the most important. However, the principal constituents of the cartilage ECM, collagens and proteoglycans, have very different turnover rates. Normal turnover time of proteoglycans is variable and ranges in mature individuals from about 300 days for overall turnover in canine articular cartilage to around 20 years for the long-lived globular hyaluronic acid binding domain of aggrecan in human cartilage (Maroudas, 1980; Maroudas et al., 1998; Verzijl et al., 2001). However, collagen turnover times have been estimated to be up to 350 years in mature human cartilage (Maroudas et al., 1992). Comparable data for the horse do not exist, but are assumed to be in the same order of magnitude. It is this very low turnover rate and thus extremely limited repair capacity that lies at the basis of the famous observation by William Hunter (1743) that 'ulcerated cartilage when destroyed, will never repair', and that makes OA in both humans and horses into such a debilitating disease with a very poor long-term prognosis.

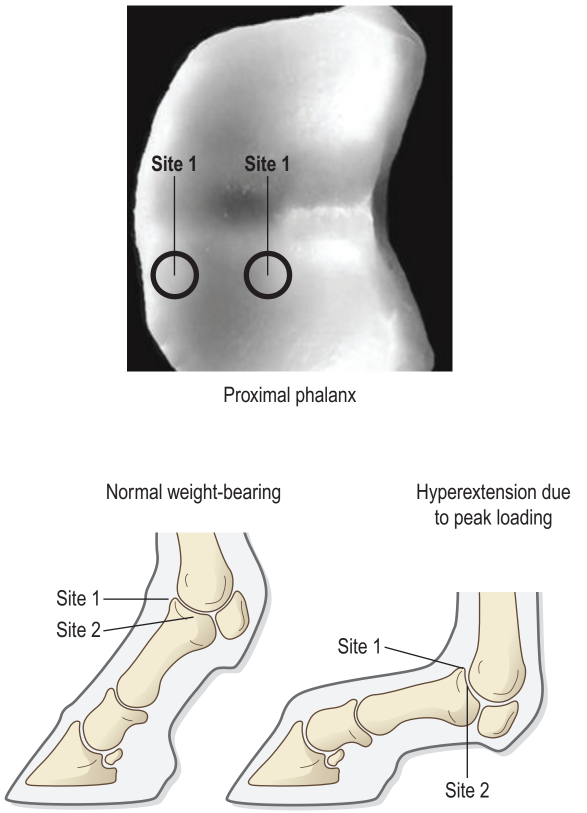

Fig 13.4 Differently loaded sites at the proximal articular surface of the proximal phalanx. Site 1 is located at the medial dorsal margin of the joint surface. This site is not loaded when standing still or in a slowly moving animal, but it is subject to high intermittent peak loading in overextended joints at high speeds and during jumping. Site 2 is located in the central fovea of the articular surface and is continually loaded when the limb is weight bearing, but the site experiences lower absolute forces than site 1.

Developmental aspects of articular cartilage

Theoretically, there are two possible origins of topographical heterogeneity of articular cartilage biochemistry: genetic predetermination or formation during early life when cartilage metabolism is still high during active growth. The first indication that the latter could be true came from a study, which showed that proteoglycan content was identical all over the joint in neonatal lambs, unlike the situation in adult sheep where there is topographical heterogeneity (Little & Ghosh, 1997). The same was true for the horse, in which proteoglycan content and collagen, including post-translational modifications of collagen such as cross-links, were homogeneously distributed, at least when looking at average values of full thickness samples, across the joint of the newborn in what has been called a 'blank joint' (Brama et al., 2002). Most of the topographical heterogeneity appeared before the age of 5 months, but HP cross-links (the most abundant pyridinoline cross-link in articular cartilage) did not reach their mature values until after 12 months (Brama et al., 1999a, 2000b, 2002). Recently, this maturation process of articular cartilage in early life was confirmed by an investigation using equine-specific cDNA micro-arrays. The expression of genes encoding matrix proteins and matrix modifying enzymes was clearly different between neonatal and mature individuals with the former expressing more collagens, matrix-modifying enzymes and provisional matrix non-collagenous proteins and the latter showing a transition from growth to homeostasis and tissue function related to coping with shear and compressive forces (Mienaltowski et al., 2008).

The changes in biochemical composition of the extracellular matrix of articular cartilage during early life are accompanied by structural changes. The arcade structure of the collagen network as described by Benninghoff (1925) is typical for mature cartilage, but not yet present in the newborn. Polarized light microscopy has shown that at birth collagen fibril orientation is predominantly parallel to the joint surface and subchondral bone and then gradually changes to the more classic Benninghoff arcade structure (Rieppo et al., 2008). Preliminary data from the horse suggest that here too the mature configuration is basically formed during the first 5–6 months of life (van Turnhout et al., 2008).

The effect of exercise on articular cartilage during growth and development

If the topographical heterogeneity of the extracellular matrix of articular cartilage enables the joint to meet the biomechanical challenges to which it is subjected and if this topographical heterogeneity is formed from scratch in the young individual in the so-called process of functional adaptation (Brama et al., 2002), then biomechanical loading is the most likely driving force of this adaptive process. The first evidence that this is true came from a study that was originally designed to study the influence of exercise on the developmental orthopaedic disease osteochondrosis (van Weeren & Barneveld, 1999a). In that study, named EXOC, a group of 43 Warmblood foals was divided into three groups from the age of 1 week. One group (boxed; n = 14) was kept in box stalls for 24 h/day; the second group (boxed/sprinted; n = 14) was kept in similar box stalls, but given exercise in the form of a number of short sprints during a restricted period, i.e. in this group high-intensity exercise was alternated with a very sedentary lifestyle; the third group (pastured; n = 15) had free pasture exercise for 24 h/day. The exercise regimens were maintained until weaning at 5 months of age, at which age 8 foals from each group were euthanized and their tissues harvested for biochemical and other analyses. The remaining 19 foals were then kept together in a single group and allowed a moderate exercise regimen. These animals were euthanized at age 11 months and had their tissues analyzed to see if any difference provoked by the different exercise regimens at 5 months would remain or was reversible once a similar exercise regimen was given to all foals (Fig. 13.5).

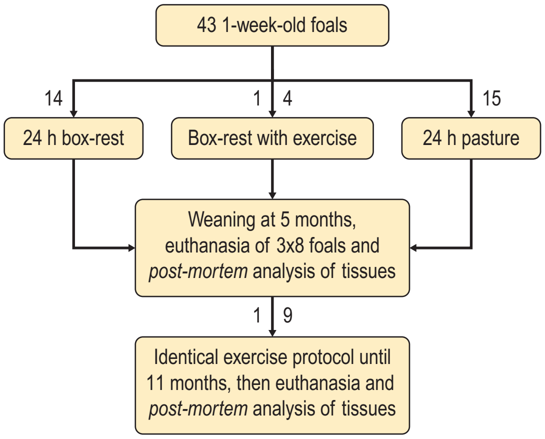

Fig 13.5 Schematic diagram of the experimental set-up of the so-called EXOC study. Forty-three Warmblood foals were divided into three different exercise groups at age 1 week. Exercise regimens consisted of 24 h/day box rest (n = 14), a similar sedentary protocol but with additional high-intensity sprinting exercise for 30 min/day (n = 14), and free pasture exercise (n = 15). After weaning at age 5 months, 8 foals from each group were euthanized and their tissues harvested. The remaining 19 foals were housed together and given a moderate exercise regimen. These animals were euthanized at age 11 months for tissue harvest.

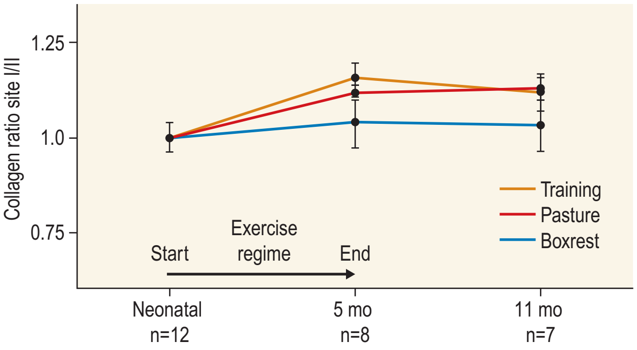

Fig 13.6. The influence of different exercise levels during the first 5 months after birth on the collagen ratio of site 1/site 2 (see Fig. 13.4). Values are given as mean ± standard error of the mean. Pasture: pasture exercise; training: box rested/sprinted animals; box rest: box rested animals (see also Fig. 13.5). n, number of animals; *, $p < 0.01$. Note that both groups that were exercised develop a site 1:site 2 ratio that is significantly different from one in the first 5 months of life, indicates that they developed topographical heterogeneity. The box rested animals do not develop this topographical heterogeneity and fail to compensate for this in the following 6 months when undergoing a moderate exercise regimen.

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The study showed that topographical heterogeneity, expressed as a significant difference from zero of the ratio of two very differently loaded sites within the joint, developed in the pastured group and in the boxed/sprinted group alike, but failed to develop in the boxed foals. The most interesting observation, however, was that, where proteoglycans became normal after the common training program from 5 to 11 months (as did exercise-induced differences in other tissues from the same experimental animals such as bone mineral density (Cornelissen et al., 1999; Firth et al., 1999b)), levels of collagen or the collagen-related hydroxylysine levels remained abnormal and failed to develop the topographical heterogeneity that is characteristic of mature individuals (Fig. 13.6) (Brama et al., 2002). Therefore, whereas this study unequivocally demonstrated the importance of biomechanical loading for the development of the topographical heterogeneity of the extracellular matrix, it showed also that, at least with respect to the collagen component, there is a limited window in time when this process of functional adaptation can take place. This stresses the importance of sufficient exercise in the early juvenile phase.

Another interesting observation was made in the boxed/sprinted animals that had been subjected to a combination of short bouts of high-intensity exercise with a sedentary lifestyle. The degree of development of topographical heterogeneity in this group was comparable to the pastured animals, which were regarded as controls. However, when culture experiments were carried out with chondrocytes harvested at age 11 months from animals from the former exercise groups, it appeared that chondrocytes from the former box/sprinted group could not be stimulated to increase metabolic activity, in contrast to samples from both other groups. This was interpreted as a deleterious long-term effect of the combination of sedentarism with bouts of high intensity exercise, possibly representing a kind of cellular exhaustion that might be due to overstimulation during the first 5 months of life (van den Hoogen et al., 1999). Similar phenomena were observed in other tissues from these animals (Barneveld & van Weeren, 1999). Also, forced exercise (box/sprinted) had a negative effect on collagen turnover, as measured by serum markers CPII and Ctx1, when compared to pastured foals (Billinghurst et al., 2003).

Another large-scale exercise study concerning foals was conducted by the Global Equine Research Alliance (GERA, a consortium of the equine orthopedic research groups from Massey University, New Zealand, Colorado State University, USA, Royal Veterinary College, UK and Utrecht University, the Netherlands). This study became known under the acronym GEXA. In the GEXA study, 33 Thoroughbred foals were raised from 0–18 months under different exercise conditions. One group (PASTEX, n = 15) had free pasture exercise all year round, in agreement with common New Zealand practice; the second group (CONDEX, n = 18) was raised under similar conditions, but subjected to an additional exercise program as well. The exercise program consisted of cantering and sprinting on a track which increased overall workload by a moderate, but significant, 30% (Rogers et al., 2008a). At age 18 months, 12 animals (six from each group) were sacrificed and their tissues harvested for detailed analyses. The remaining animals were broken in and trained and raced as 2- and 3-year-olds (Rogers et al., 2008b) (Fig. 13.7).

The articular cartilage of the metacarpophalangeal and metatarsophalangeal joints from the GEXA animals harvested at 18 months was meticulously researched using a variety of techniques. Biochemical and biomechanical analyses of full-thickness samples from the distal metacarpal bone showed site-related differences, but no exercise effect (Nugent et al., 2004). The same applied to the metabolic rate of chondrocytes (measured by ^{35}S-uptake) from third metacarpal cartilage (Kawcak et al., 2010). However, the exercised horses had more viable chondrocytes in the more heavily loaded sites than in the less loaded sites of the same metacarpal cartilage (Dykgraaf et al., 2008). Also, a detailed study of contiguous approximately 100-μm thick slices taken from the proximal articular surface of the proximal phalanx down to the tidemark at differently loaded sites (see above) showed not only obvious site differences, but also exercise-related changes. There was no exercise effect on proteoglycan content, indicating that the exercise level had not been strenuous and confirming the work by Nugent et al. (2004) and Kawcak et al. (2010); but at 18 months old the normal physiological increase in collagen at the site located at the joint margin was less in CONDEX animals (Brama et al., 2009a). This was interpreted as a precocious cessation of collagen remodeling at this site due to advancement in time of the normal maturation process. The biochemical analysis of similar slices from the same site in the metatarsophalangeal joint pointed in the same direction: in the CONDEX animals, hydroxylysine, HP cross-links and pentosidine cross-links were all higher, all indicative of advancement of the normal process of functional adaptation (van Weeren et al., 2008). The increased pentosidine levels in the CONDEX animals are of particular interest, because they indicate a lower metabolic activity in this group, confirming more rapid progression of the physiological age-related decrease in matrix turnover and thus indicative of an advanced degree of maturation compared to the PASTEX animals (Fig. 13.8).

Other evidence for the difference in maturation rate came from ultrastructural and biomechanical studies. Polarized light microscopy techniques were used to investigate the spatial arrangement of the fibrils of the collagen network throughout the depth of the cartilage, measured as parallelism index (PI, a measure of the degree to which the collagen fibrils are aligned with each other) and orientation index (OI, a measure of the average angle of collagen fibrils with respect to the articular surface). Parallelism index was higher in CONDEX animals, again indicating advanced maturation (Brama et al., 2009b) (Fig. 13.9). An interesting observation was that orientation of collagen fibrils in the deep zone of the cartilage was less perpendicular than expected, which is possibly an adaptation of the direction of collagen fibers to high shear forces in the equine metacarpophalangeal joint, which is a heavily loaded joint with an exceptionally high range of motion where an oblique insertion of

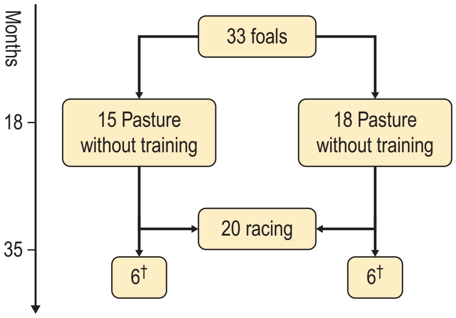

Fig 13.7 Schematic diagram of the experimental set-up of the so-called GEXA study. Thirty-three Thoroughbred foals were divided into 2 different exercise groups from average age 3 weeks until age 18 months. Exercise regimens consisted of 24 h/day pasture exercise (PASTEX, n = 15), or pasture exercise with additional track training that increased workload by 30% (CONDEX, n = 18; for details of training protocol see Rogers et al. 2008a). At age 18 months, six animals from each group were euthanized and their tissues harvested. One PASTEX animal was lost due to an accident and the remaining 20 animals were trained for racing as 2- and 3-year-olds. Cross symbol indicates euthanasia.

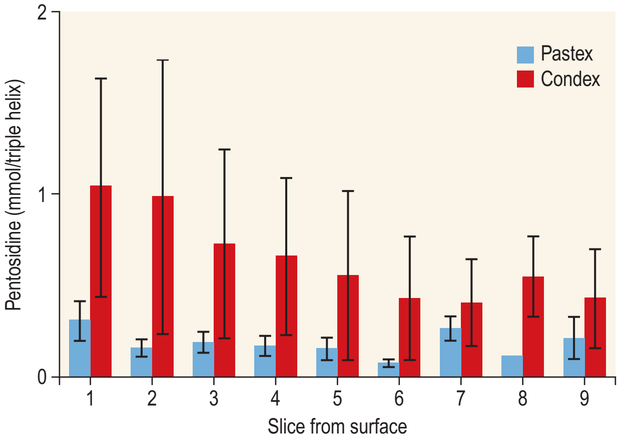

Fig 13.8 Mean values for pentosidine cross-link content (expressed as millimole per mole triple helix) for the slices produced at site 1 and 2 for both PASTEX and CONDEX animals. The most superficial layer (slice 1) is located at the joint surface; the deepest layer (slice 9) is adjacent to the calcified cartilage.

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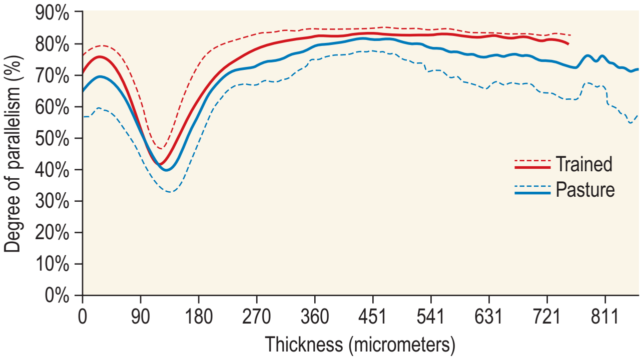

Fig 13.9 The average degree of collagen parallelism (PI; mean ± SD) over the entire depth of the cartilage, measured with quantitative polarized light microscopy at points 9 µm apart from each other from the cartilage surface to the osteochondral junction. A PI of 0% indicates random course of fibrils and 100% complete parallelism. Pastured animals (PASTEX) compared to exercised animals (CONDEX).

the collagen fibers in the calcified cartilage layer may yield better resistance to repeated shear forces than would a perpendicular configuration. Based on this observation it was hypothesized that the Benninghoff arcade model may be more flexible than commonly thought and that local adaptation includes a predominantly non-perpendicular direction of the collagen fibrils in the deep zone. Biomechanical analysis of samples from different sites showed that in CONDEX animals site-related differences known to develop with age (Brommer et al., 2005) were less marked than in PASTEX animals with respect to Young's modulus (ratio of axial stress and strain in unconfined compression) and dynamic modulus (proportional to the elastic and viscous energy dissipated in the loading process and essentially a measure of dynamic stress and strain (Palmer & Bertone, 1996)). This may have been caused by earlier down regulation of collagen metabolism in trained animals, as signaled earlier (van Weeren et al., unpublished results). The quicker maturation of the collagen matrix and associated other pattern of topographical heterogeneity need not necessarily be deleterious, as the same study showed that the cartilage degeneration index (CDI) as described by Brommer et al. (2003) was significantly less in the CONDEX animals, indicating better surface integrity in this group (van Weeren et al., unpublished results).

There is also evidence from other species that the exercise regimen at early age may affect cartilage properties and that this effect need not always be reversible. Kiviranta et al. (1987) showed in young Beagles in which one of the hind limbs was immobilized for 11 weeks that GAG content may be reduced by almost 50% in the non-weight-bearing limb, whereas cartilage thickness and GAG-content was increased in the contralateral limb. When the study was repeated, but now followed by a 15-week rehabilitation program, the normal situation was not fully restored; the authors concluded that immobilization of skeletally immature joints may affect cartilage development such that recovery is very slow or alterations are permanent (Kiviranta et al., 1994).

The effect of exercise on articular cartilage in young adult animals

No large studies have been conducted on the effect of exercise on cartilage from completely mature or elderly horses, but work has been performed on 2-year-old Thoroughbreds. These animals can be classified as 'young adult', although they cannot be considered as fully skeletally mature yet because they are still growing (Green, 1976), although at a much lower rate than the foals that were discussed in the preceding paragraph. In the so-called short-term Bristol study 2-year-old Thoroughbreds were subjected to a 19-week exercise regimen that consisted of three times/week galloping on a treadmill, trotting in a mechanical horse walker three times weekly and 40 min walking exercise six times weekly. The control group was only walked for 40 min six times per week during the same period (Murray et al., 1999b). In the MUGES study (Massey University Grass Exercise Study), a group of 2-year-old Thoroughbreds was trained for 13 weeks on grass and sand tracks, after which their musculoskeletal tissues were analyzed (Firth et al., 2004a).

Cartilage taken from the proximal articular surface of the radial, intermediate and 3rd carpal bone from exercised animals that had participated in the Bristol study had a thicker calcified, but not hyaline cartilage layer than from non-exercised animals (Murray et al., 1999a). The cartilage of the strenuously trained animals was biomechanically less stiff, showed more fibrillation and more chondrocyte clusters than the gentler trained animals, suggesting that strenuous exercise may lead to deterioration of cartilage (Murray et al., 1999b). Also fibronectin (Murray et al., 2000) and cartilage oligomeric matrix protein (COMP) distribution (Murray et al., 2001b) appeared to be influenced by exercise. When cartilage from animals of the 19-week Bristol study was cultured to measure chondrocyte metabolic activity, proteoglycan synthesis rates were higher in the trained animals than in the controls, confirming the overall effect of strenuous exercise on the proteoglycan component of articular cartilage ECM (Bird et al., 2000). There were no overall effects on collagen levels, but sites predisposed to clinical signs contained significantly less collagen in horses undergoing the exercise program; also, strenuously exercised animals had higher glycosaminoglycan content than horses from the more gently trained group, which was most marked in the cartilage from the dorsal radial and dorsal intermediate carpal surfaces, sites known to be heavily loaded during exercise (Murray et al., 2001a). Mechanistically, the hypothesis that the degrading enzymes Cathepsin B and D might be involved in the exercise-induced alterations could not be confirmed, but it was demonstrated that the two enzymes were regulated differently by mechanical loading (Bowe et al. 2007). In contrast to the Bristol study, the MUGES study found a significant increase in thickness of (hyaline) cartilage after 13 weeks of training (Firth & Rogers, 2005), compared to pasture-raised controls, in particular in sites within the intercarpal joint. At these sites there was no patho-anatomical damage, leading to the conclusion that the response of the tissue was adaptive and not degenerative in nature. However, there was a difference between joints, because in the metacarpophalangeal (MCP) joints of the same animals wear lines and fibrillation were present and water content was increased while HP cross-links had fallen compared to the controls, which was interpreted as signs of loosening of the collagen network due to micro-damage (Brama et al., 2000a). The metacarpophalangeal joint is known to be the equine joint most susceptible to damage (Pool, 1996) and predilection for patho-anatomical damage in the MCP joint has been shown in both treadmill-exercised horses (Kawcak et al., 2000) and in wild horses (Cantley et al., 1999). Also the study by Little et al. (1997) showed that there is a level at which exercise may become deleterious. In an *ex vivo* study in which material from the dorsal radial facet of the third carpal bone, an area well-known to be subjected to high contact stresses in galloping horses, was cultured that came from horses having undergone a strenuous exercise regimen, a significant reduction in aggrecan synthesis and a concomitant increase in decorin synthesis could be determined compared to less vigorously trained controls. The suggestion was made that this alteration in articular cartilage metabolism could be a predisposing factor for cartilage degeneration and OA at a later stage.

An effect of exercise on the biomechanical properties of cartilage was shown in a relatively short (6 weeks) treadmill study (Palmer et al., 1995a), in which the permeability constant increased at all sites investigated, but the Poisson's ratio increased only at specific sites, stressing the topographical variation in response to biomechanical stimuli, which is most probably related to local differences in joint architecture and geometry.

The overall metabolism-enhancing effect of exercise on articular cartilage has been studied indirectly in several studies that focused on a variety of potential biomarkers in either serum or synovial fluid. Plasma GAG levels, and serum keratan sulphate and COMP all increased after moderate to strenuous exercise (Calatroni et al., 2008; Okumura et al., 2002; Helal et al., 2007). Brown et al. (2007) looked in more detail into changes in glycosaminoglycan metabolism due to exercise and found higher chondroitin sulphate peak chain lengths, but shorter hyaluronic acid chain lengths in exercised versus rested horses. Investigating both serum and synovial fluid, Frisbie et al. (2008) confirmed the increase in proteoglycan markers after exercise, and showed that the same was true for a number of collagen markers. However, moderate exercise did not affect MMP-1 activity in synovial fluid (Brama et al., 2004). There is a reciprocal interaction between synovial fluid and articular cartilage and the former is not just a reflection of the status of the latter. The effects of joint loading on cartilage are, at least in part, mediated by alterations in the synovial fluid, as cartilage explants cultured in post-exercise synovial fluid showed enhanced GAG synthesis and diminished release when compared to cultures using pre-exercise synovial fluid (van den Hoogen et al., 1998).

Also in other species there is evidence for an influence of exercise on articular cartilage, at least in young individuals. In young Beagle dogs, moderate loading levels tended to increase GAG production, while strenuous exercise led to GAG depletion in high-load areas (Arokoski et al., 1993; Kiviranta et al., 1988, 1992, 1994; Säämämen et al., 1994). In man it has been shown that children not undergoing programs of vigorous activity had approximately 25% less cartilage than children that had been mildly active (Jones et al., 2003).

Conclusion

There is no doubt that articular cartilage is responsive to biomechanical loading and that responsiveness is highest in the youngest animals. In fact, there is now substantial evidence that the characteristic topographical heterogeneity in composition and ultrastructure of the extracellular matrix of mature cartilage is formed under the influence of loading, i.e. through physical exercise. It has been suggested, therefore, that the collagen network of juvenile animals that are in a phase of rapid growth might respond to loading in a fashion similar to that in which trabecular bone is known to respond according to Wolff's law (van Weeren & Brama, 2003). The difference with bone is that, whereas bone will continue to respond to exercise throughout life, the collagen network can most probably do so only in the young, growing animal before the collagen remodeling rate falls to the extremely low level related to the very long collagen turnover times in mature animals mentioned earlier. Indeed, although some studies have shown a response of the proteoglycan component of the ECM of cartilage to exercise in (young) adult horses, no adaptive response of collagen has ever been demonstrated in this age group. This makes the early juvenile period the only window of opportunity to manipulate the collagen network through modification of loading, e.g. differences in exercise. Recent studies show that such manipulation is possible and may irreversibly delay the normal maturation process as the result of a decreased exercise level or lead to accelerated maturation resulting in a different topographical pattern in animals subjected to more exercise than free pasture exercise. There is thus reason to believe that exercise at an early age may indeed have long-lasting effects on the collagen matrix of articular cartilage, lending credibility to the hypothesis that variations in exercise regimens of juvenile persons or animals may influence the risk for the development of degenerative joint diseases later in life (Helminen et al., 2000). This may mean for the horse that it might be better to start athletic training rather than later, as has been suggested (Smith et al., 1999). However, long-term epidemiological studies are necessary to establish whether differences in the development of the biochemistry and ultrastructure of articular cartilage that are now known to be modulated by early exercise have significant implications for the orthopedic health and/or performance of the equine athlete during its career.

Bone

Introduction

Bone is the tissue that confers rigidity to the musculoskeletal system and its intimate association with articular cartilage allows both tissues to sustain the large forces generated by normal and athletic locomotor activity. Bone derives its resistance to deformation from the hydroxyapatite crystals that are laid down on a collagen matrix, providing the tissue with great strength, but also reducing elasticity substantially. The responsiveness of bone to biomechanical influences has been recognized universally since the late 19th century when Julius Wolff proposed his law, stating that bone will adapt both architecturally and with respect to composition to changes in mechanical loading (Wolff, 1892). Failure of bone results in (micro) fractures. The incidence of bone failure in equine orthopedics varies strongly with the discipline involved, but can be substantial, particularly in racing (Rossdale et al., 1985; Williams et al., 2001). Clinically, bone failure in the horse may vary from relatively mild, yet economically important, micro-fractures and fissures as seen in sore shins (Boston & Nunamaker, 2000), to catastrophic fractures of long bones (Parkin et al., 2006). In the following section an introduction on the morphology and physiology of bone is given first, followed by a discussion of the influences of exercise on bone in general and more specifically for the horse. Most of the earlier work has been done in young adult animals; recently the effect of exercise on foals has become an area of interest.

Morphology and physiology of bones

The diaphysis of long bones has a marrow cavity, which allows a better strength/weight ratio to resist bending and torsional forces, while positively affecting gait velocity by minimizing the weight of the distal limb. Most features of a long bone and cuboidal bone are illustrated in Figure 13.10. There is a gradual transition from the dense bone of the diaphyseal cortex to the metaphysis, in which the junction of the outer compact bone with the cancellous bone is indistinct. The epiphysis is contained within a dense shell of compact bone, which in articulating regions is referred to as the subchondral bone (SCB), is regionally thickened at various sites, and has a gradual transition into the bulk epiphyseal trabecular bone (BETB). The orientation and architecture of the trabecular bone of the metaphysis and epiphysis is central to how load is transferred from the diaphyseal cortex to the joint surface and thence across the joint. The metaphyseal cortex is thin, and this is most obvious close to the physis, and especially in the young presumably because of the rapid growth rates in early life. The cross section of the whole bone is greatest at the level of the physis, and the contact area of the articulating surface of the bone with its opposing counterpart in the close-packed position is also large. This maximization of the force-bearing surfaces allows articular and physeal cartilage and immature bone to sustain lower stress, although the force transmitted across the joint and through the physis and metaphysis equals that borne by the diaphysis, which is much more dense and much smaller in cross-section than elsewhere in the bone.

The extracellular matrix of bone is made up of a framework of osteoid, consisting of about 90% collagen (type I), around and in

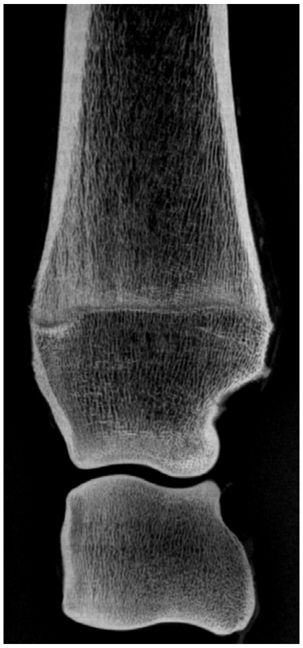

Fig 13.10 Radiograph of a 1.5-mm thick sagittal slice of the radius and intermediate carpal of a 19-month-old pasture-raised Thoroughbred filly. The radial cortex blends gradually with the trabecular bone of the metaphysis, and the cortical shell of the epiphysis with the bulk epiphyseal trabecular bone. At the joint surfaces, the subchondral bone is evident as a radiodense line of uniform thickness.

which hydroxyapatite crystals are precipitated. After suitable stimulation, the osteoid is 70% calcified within a period of days, but complete mineralization takes several months (Hayes, 1991). About 50% by volume and 75% by weight of bone is mineral, consisting mostly of calcium phosphate and calcium carbonate in the form of hydroxyapatite. The importance of collagen in determining bone strength has been rarely included in analyses of variance of bone strength, most likely because bone mineral density parameters became dominant, being so easy to measure. Conversely, quantification of collagen in bone was, until recently, much more difficult and required invasive sampling. But the central importance of collagen and its orientation is clear since bone mineral is deposited in and on collagen; and the directionality of the collagen fibrils determines the orientation of the mineral plates or spindles (Wassen et al., 2000; Viguet-Carrin et al., 2006).

Compact cortical bone contains spaces within it, including osteocyte lacunae, blood vessels in Haversian and Volkmann canals, and resorption spaces, the volume of which varies with age, recent loading regimen, metabolic status, injury, endocrine status, and lactation. Bone matrix is the same material in diaphyseal cortex and a single trabecular plate. However cancellous bone tissue has a bone volume fraction (proportion of total volume occupied by bone) of 0.47–0.82 in the normal third carpal bone (Young et al., 1991a), which is significantly less than the range 0.92–0.98 for the mid-radius cortex (Riggs et al., 1993), because the inter-trabecular spaces are far larger than the spaces in the cortex. Within (any given) whole bone, the amount of mineral will differ between its regions, due to differences in the relative amount and placement of cancellous and cortical tissue at different sites. The word ‘bone’ is applied to three different entities: bone material, bone tissue consisting of bone material plus the spaces and tissues interposed around the material, and bone as an ‘organ’ or ‘whole’ bone. The three entities have different mineral densities, which have been referred to as material, compartment, and total bone mineral densities respectively (Rauch & Schoenau, 2001).

General response of bone to exercise

It is possible to measure if bone responds to exercise in various ways including biochemical, gene expression, biomarkers, morphological and compositional change, functional change, and results of that change (such as athletic performance) the latter two of which might not be specific to change in bone. The relationship between, for instance, serum biomarker elevation or altered gene expression on phenotypic effect may not be known, and thus careful whole animal study is required before the significance of such changes can be known. It is paradoxical that now it has become easier to produce data from sophisticated laboratories, it appears to be more difficult to obtain performance data to test the validity of the alterations detected.

Most methods used to assess the response of bone to exercise are based on quantifying the amount and disposition of mineral within the bone. The mechanical properties of bone are closely related to mineral in the matrix, and the modulus of elasticity is directly related to volumetric bone mineral density (BMD_v) of the bone tissue (Currey 1988b; Ferretti et al 1996), at least within the physiological range of BMD_v. Collagen orientation and cross-linking also affect variance in mechanical properties of bone (Riggs, 1993; Oxlund, 1995; Viguet-Carrin et al., 2006), but the extent to which collagen parameters affect bone strength, and when this is rate limiting in the growing and training horse if injury is to be prevented, have not been established.

Bone responds to exercise in one or more possible ways. These include increase in mineralized mass (Goodship et al., 1979; Woo et al., 1981; Gordon et al., 1989) , increase in bone material density (Boyde & Jones, 1996), increase in bone mineral density of the whole bone (Cornelissen et al., 1999; Firth et al., 1999b, 2000), change in trabecular bone density and orientation (Young et al., 1991b; Firth et al., 1999a,c) alteration in remodeling, and increase in maturation of secondary osteons (Reid & Boyde, 1987), change in geometry through size increase as a result of changed endosteal and subperiosteal apposition rates (Gordon et al., 1989; Kontulainen et al., 2003), change in collagen cross-link concentrations (Oxlund et al., 1995; Köwitz et al., 1997), change in predominant collagen fiber orientation (Martin & Ishida, 1989; Boyde & Riggs, 1990; Martin & Boardman, 1993; Riggs et al., 1993) and change in bone collagen synthesis and remodeling (Tidswell et al., 2008).

Changes in bone geometry and density resulting from exercise are highly significant in altering the bone’s resistance to bending. The extent of the changes and the specific stimuli under which they occur provide an understanding of the extent and rate of bone strength changes at the time of early conditioning exercise, training, athletic competition, or lack of any of these stimuli.

The diaphysis of immature individuals consists of primary osteonal bone embedded between more highly mineralized concentric plates of woven bone. Bone formed post-natally at the periphery is more porous, contains wider, less mineralized lamellae, and has osteons of greater diameter than does cortical bone formed pre-natally. The bone shaft can respond to exercise by enlargement as a result of the formation of woven-fibred bone in the periosteum, which then forms lamellar bone and becomes connected by radially oriented bony plates, with apposition of bone leading to new primary osteons (Stover et al., 1992). This allows prompt and rapid periosteal new bone formation, with an increase in resistance of the bone to bending and torsion. Compared with this periosteal response in the diaphysis and metaphysis, the capability for epiphyseal enlargement in response to the biomechanical stimuli is apparently limited, in both extent and rate, and occurs largely in early life.

The need for exercise

The development and maintenance of tissues requires the delivery of a certain number of cycles per day at certain strain rates, in order to stimulate various tissues: for instance, in young rats taught to jump, five cycles per day of this unusual activity produced as great a response in terms of resistance to fracture than did 40 jumps (Umemura et al., 1997). The effect on other tissues and species may differ, and each may have its own stimulus requirements if it is to adapt. Unfortunately, the number of other activities that deliver these novel higher forces to tissues is not documented in either domesticated or wild horses. It is assumed to include the playing, fighting, fast locomotion and other exuberant activities that young mammals engage in habitually and adults less often. The duration of these high-intensity exercises need not be long. The natural grazing and social slow movement behavior of wild horses is known to occupy ~17 h/day, whereas Dutch Warmblood foals at pasture did not canter more than approximately 3 min per day (Kurvers et al., 2006).

The animal management systems of agricultural and competition animals have been in place for some hundreds of years, so it is perhaps understandable that some profess to know the normal exercise requirements at all stages of a horse's life. It is less reassuring that the literature contains hardly any data on how horses are managed, and much less data on how much horses move, whether they be domesticated, wild or feral. It is only recently that modern tracking technologies such as GPS have been applied in the equine field, and it is assuring that their price is falling to an affordable level. The upshot remains that we have no data to know how much exercise a horse requires, in terms of duration, frequency, number of cycles, and when repetitions of different types of activity are spread over time. In turn this implies firstly, that we may under- or over-estimate how much exercise animals require physiologically, secondly, the ideal amount of imposed exercise or imposed rest may be doubly difficult to estimate, and thirdly, the control group of some experiments may not have been 'normal' but rather abnormally inactive or sedentary, which may mean the effect of an imposed exercise regimen appears greater than if it had been imposed on a normal control regimen (whatever that is).

This lack of knowledge is one reason for the current interest in the area of exercise in the young foal. But there is also little research in the area of training for particular athletic objectives. There is close similarity of equine structure and function to that in people, and there is increasing interest from the human health community in the responses of the tissues of children to exercise, or the lack of it. The outcome parameters that have been used to quantify a bone response include radiography, radiogrammetry, radiographic bone aluminium equivalence, point projection radiography, dual X-ray absorptiometry (DXA), computed tomography (CT), peripheral quantitative computed tomography (pQCT), magnetic resonance imaging (MRI) (Firth, 2004), and clinical and pathological features associated with, for instance, cartilage and subchondral bone lesions related to imposition of exercise. The latter are not considered in this chapter.

The response of bone to exercise in the horse

The following is a summary of evidence so far available on bone tissue responses of horses, grouped in order of age when the exercise began, because there is difference in the response of the immature as opposed to the older skeleton, possibly because of the turnover time of collagen and its maturation in older subjects. The responses presented are mostly in either BETB or SCB of the epiphysis or of a particular cuboidal bone, or diaphyseal cortex. Few studies mention responses in the metaphysis, perhaps because this area is considered to be of less interest after a young age and because of the difficulty in using sensitive imaging methods to examine it, partly caused by the inability to separate trabecular from cortical metaphyseal bone in projected radiographic images.

Several aspects of bone development became evident in an investigation (EXOC study) of the relationship between exercise and osteochondrosis in Warmblood foals. Three groups of foals were kept from birth for 5 months in one of three exercise conditions: in a box stall with the mare (boxed group), boxed but exposed to sprint exercise 5 days per week in a 50-m long walled enclosure from a young age (boxed/sprinted), or kept at pasture continually (pastured). After euthanasia of some foals at 5 months of age, the remaining foals until 11 months of age were out of the weather in a large stall, which was always open to a small enclosure. The change in exercise regimen meant that the previously boxed group had greater opportunity for exercise, the previously boxed/sprinted and pastured groups had less (van Weeren & Barneveld, 1999a).

At 5 months, pQCT showed that the cross sectional area (CSA) of the third metacarpal bone (Mc3) was significantly less in the boxed than pastured group, but the BMD_v was not different between groups, although BMD_v in the dorsal cortex was significantly higher in the boxed group, possibly due to a difference in the remodeling rate. The between-group differences had disappeared in the foals aged 11 months, and the pooled values at 11 months for area were higher and for density were lower than at 5 months (Cornelissen et al., 1999), although there was no decrease in other foals pastured from birth, and scanned at 6 and 9 months of age (Grace et al., 2003), possibly due to different experimental design and technique (Firth, 2006).

In the proximal sesamoid bone, the trabecular BMD_v was highest in the boxed/sprinted group, and lowest in the boxed group, and the value in the latter increased greatly after the exercise regimen changed at 6 months if age. The BMD_v of the previously pastured group had increased by 11 months, but that of the previously boxed/sprinted group had not. Confinement apparently had resulted in a retardation of normal development which was compensated for, at least partly, when the restriction on exercise was lifted (Cornelissen et al., 1999).

The BMD_v of the medial aspect of the third carpal bone was significantly less in boxed foals at 5 months old, with the effect of sprint training being similar to that of pasture exercise. By 11 months old, the reduced exercise possibility in previously pastured and boxed/sprinted groups and the greater exercise in previously boxed foals were associated with a significantly greater BMD_v than at 5 months old, but no difference between groups. The average dorso-palmar depth of the third carpal bone was not significantly different between foals of 5 and 11 months old (Firth et al., 1999b). BMD_v was determined in the SCB of the proximal articular surface of the proximal phalangeal bone of these six groups (three exercise regimens, two ages) at 1-, 2-, 3-, 4- and 5-mm depth from the articular surface at two differently loaded anatomical sites (site 1 at the proximo-dorsal eminence and site 2 at the middle of the medial articular surface; site 2 is continuously loaded, site 1 intermittently). At 5 months BMD_v was significantly higher at site 2 than 1 with highest values and most apparent difference at depths to 3 mm. By 11 months, site differences were less, due to a greater increase in BMD_v at site 1 in the previous 6 months, and BMD_v was significantly higher in site 2 than 1 in previously boxed/sprinted and trained groups but not previously pastured foals. The significantly higher BMD_v in pasture and boxed/sprinted than boxed foals at 5 months was no longer present at 11 months at site 1, and at site 2 the previously boxed/sprinted foals had significantly higher BMD than previously boxed and pastured groups. Continuous loading in the central area of the metacarpophalangeal joint surface, which is present even during standing and slow gaits, apparently stimulated distinct and significant changes in the SCB to a greater extent than intermittent loading at the proximal eminence of the proximal phalangeal bone (Brama et al., 2009).

In the GEXA study 18 of 33 Thoroughbred foals born and raised at pasture began gentle exercise at 3 weeks of age and continued until ~17 months of age. The remaining 15 foals had spontaneous pasture exercise only. The bone parameters of the foals having only spontaneous pasture exercise (PASTEX group) were compared with those of the foals subjected to additional exercise (1030 m per day, 5 days/week; CONDEX group) (Rogers et al., 2008a), by pQCT undertaken serially at average ages of 4 days, and 2, 4, 12 and 17 months (Firth et al., 2010). The mid-diaphysis of the proximal phalangeal and third metacarpal bone increased its resistance to deformation by increasing bone mass, circumference, and mean cortical thickness. The imposed exercise resulted in highly significant differences in these parameters when serial values over time were pooled, but were significant at specific ages (12 and 17 months) only in the phalangeal bone. There was no significant difference between PASTEX and CONDEX groups with regard to cortical bone density, indicating that the increase in bone strength is related to a far greater extent to increase in bone size and mineral content or to other factors such as collagen characteristics (see above) than to change in BMD$_v$. In the proximal metaphysis, the trabecular BMD$_v$ (inner 45% of the scan slice) was lower in the CONDEX than PASTEX group at 2 months of age and over the whole 17 months when values were pooled, most likely associated with the bone area of the CONDEX group being greater, although not significantly. In the outer ring of the metaphysis, consisting of both trabecular and cortical bone, bone mineral content was significantly greater over time in CONDEX than PASTEX; bone area was also greater but not significantly. The interpretation is that the increase in size and mineral content of the outer part of the metaphysis made the bone stiffer, resulting in lower strain and less mineral accretion response in the central part of the metaphysis of the CONDEX group. The conditioning exercise from 3 weeks to 17 months of age appeared to have no negative effects on bone, since no clinical radiographic abnormalities were detected. Also, the reduced bone density in the sagittal groove detected by CT (Kawcak et al., 2009) and previously described (Doube et al., 2007) were present in both PASTEX and CONDEX foals. Point projection radiography (Firth et al., 2009) of the same joints of both conditioned and non-conditioned horses showed osteochondrosis lesions at the disto-dorsal aspect of the sagittal ridge, which apparently heal spontaneously without negative effect on subsequent athletic activity (Kane et al., 2003). This supported previous indications (Barneveld & van Weeren, 1999; van Weeren & Barneveld, 1999b) that the presence and severity of osteochondrosis is not affected by exercise in the young horse.

In nineteen of the GEXA trial horses the bone response to race training and withdrawal from training was determined (Firth et al., 2007; Firth et al., 2012) by pQCT scanning immediately before training began, after training stopped, and after the horses had been at pasture for some months. In the diaphysis, the density of the third metacarpal bone was approximately 0.8% higher at the end of 2-year-old training than before it started, but it had returned to the previous value after being at pasture for several months. During training, diaphyseal bone strength index (the resistance of the bone to bending and torsion) increased, due to both the slight density increase but much more to the increase in size of the bone; the strength index continued to increase after pasturing, most likely because the horses were still growing, although the independent effect of the training exercise itself on diaphyseal size increase could not be tested. In the epiphysis, there was no increase in cross-sectional area, but substantial and significant increase in mineral content and BMD$_v$. In the inner zone of the epiphysis, trabecular bone density increased, as did density of the outer zone consisting of trabecular and more compact bone fractions; in neither did withdrawal from exercise for several months at pasture result in significant decrease in BMD$_v$.

In 19-month-old Thoroughbred fillies, which had been treadmill exercised for 18 weeks, bone density of the distal radius, radial carpal bone, third carpal bone and proximal third metacarpal bone was significantly greater than in age-matched horses that had been given only walker exercise (Firth et al., 1999b). The adaptive changes in the trabecular bone was very obviously localized to the load path of the higher forces resulting from the higher speed exercise, and resembled those found in horses that had been exercised for 19 months in an earlier experiment (Firth et al., 1999c). Some of these changes were discernible after 13 weeks of early training (Fig. 13.11). Difference in bone density and in radionuclide uptake in carpal bones was not detected between 2-year-old horses exercised on a treadmill 5 days per week for 6 months and control horses walked for 7 min daily; that there were differences in the fetlock joints shows not only the specific adaptive response within bones, but also a regional difference in the response of different bones to the exercise imposed upon the animal (Kawcak et al., 2000). Recently, study of carpal bone tissue from Thoroughbreds aged 3–22 years showed that increased bone formation was accompanied by increased bone collagen synthesis and remodeling, particularly within the trabecular regions of the bone of horses in racing compared to those with no such history. The increase in bone density would lead to greater stiffness, particularly in the ‘stiffer’ cortical bone, the failure of which was suggested to be associated with reduced support from the weaker underlying trabecular bone because of lower mature cross-link content (Tidswell et al., 2008). These findings and their suggested significance, in terms of end-stage disease that supervenes in racehorses (Pool, 1996), remain unclear at this time.

Fig 13.11 Radiograph of an identical preparation to that in Figure 13.10 from a 19-month-old pasture-raised Thoroughbred filly that underwent 13 weeks of early training for racing. The orientation of the metaphyseal and epiphyseal trabecular bone is different from that in the untrained horse in Fig. 13.10, there is increased radiodensity in the dorsal load path in the intermediate carpal and radial epiphysis, and the subchondral bone line is regionally thickened. The dorsal cortical shell of the radial epiphysis and intermediate carpal bone is thicker. The changes are typical of the general changes present after galloping exercise.

Horses aged 22 months trained conventionally on grass and sand racetrack surfaces were compared with horses kept in large grass yards for 13 weeks. Four horses completed the training program, and three completed only cantering exercise and did almost no galloping (Firth et al., 2004). The latter had Mc3 diaphyseal bone CSA, mineral content, periosteal circumference, and bone strength similar to untrained horses, but less than those horses that had galloped. However, cantering exercise had not caused growth of the bone shaft, and cortical BMD$_v$ of horses that had cantered only was similar to that of galloping horses, both being significantly higher than that in untrained horses, despite numbers being small (Firth et al., 2005). The results were consistent with the previous studies in which metacarpal cortical thickness increased in treadmill-trained yearlings that had galloped (McCarthy & Jeffcott, 1992). Significant relationships existed between months in training and Mc3 bone geometry and moment of inertia in 2–4-year-old racehorses (Sherman et al., 1995). It was further shown that lunging yearling Quarter Horses for 20 min/day for 8 weeks had no significant effect on osteocalcin concentrations (Fenton et al., 1999), and that velocities >12 m/s were required to affect the Mc3 dorsal cortex dimensions (Davies et al., 1999).

In the Mc3 epiphysis, early training resulted in highly localized BMD_v increases, with different patterns to that in Mt3 (Firth et al., 2005), which was described in detail (Boyde & Firth, 2005). The changes in the galloped horses resembled those found in the proximal sesamoid bone of 2-year-old racehorses, in which 5 months of training on dirt tracks was associated with significantly higher densities and greater trabecular width compared with horses at pasture (Young et al., 1991b). Similar regional adaptive changes were present in the medial facet of the third carpal bone, in which the remodeling response of the SCB was not uniform between horses, with higher densities being present in those that had galloped least. The bulk trabecular bone apparently responded by formation of increased bone mass in an arrangement resembling pillar structures deep to the SCB (Firth & Rogers, 2005). Such changes are consistent with indentation studies in the dorsal aspect of third carpal bones of 2- and 3-year-old Thoroughbred horses that had raced or trained, which had higher density and stiffness of the third carpal bone than did untrained horses. Area fraction and stiffness were closely related, and were higher in horses with than without pathological change (Young et al., 1991a).

Lastly, in this cohort of 2-year-old horses, changes in subchondral bone were detected in subchondral bone and articular calcified cartilage of the distal Mc3. The lesions were present in both trained and untrained horses, and it was suggested that the forces associated with athletic training might be less important than factors related to bone development (Boyde & Firth, 2008). Although it is impossible to quantify the etiological significance of either, the findings are mentioned here to reinforce the point already alluded to above under cartilage, namely that optimal development requires a certain biomechanical environment to proceed optimally, and inappropriate exercise imposed early or later in juvenile life, can negatively affect bone development.

The age at which horses are considered adult remains less than definitive, but if adulthood is accepted as being around the end of the horse's fourth year, there are almost no studies of the effect of exercise on bone of mature horses, besides studies of cumulative or excessive exercise loads resulting in pathology and/or clinical signs which are not considered in this text. There remains difficulty in assessing the effect of exercise since much of the adult response most likely is influenced by adaptive changes in earlier years, the nature of which will vary between individuals. This explains why the little information on adaptive responses to exercise in adult horses is confined to cross-sectional information, such as that concerning carpal change (see above) and radial diaphyseal BMD_v (Riggs, 1993b).

Conclusion

This section dealt principally with the young horse and the effects of early exercise and its possible relationship to development and readiness for later athletic endeavour. It does not deal with excessive or long-duration exercise that, through supra-maximal impact or wear-and-tear, may lead to (pre-) lesional change.

It can be concluded that, in compliance with Wolff's law, the changes elicited by the forces that are applied to bone are regionally specific and consistent with the load path. Increase in strength of the diaphysis is more dependent on increase in size than in density. Interestingly, when loading is discontinued, e.g. when horses are withdrawn from training, diaphyseal circumference will not diminish, but the (relatively minor) increase in bone density will be reversed. In the epiphyses, which are for the larger part made up of trabecular bone, increased loading through the intensification of exercise programs will lead to a substantial increase in density, which is apparently retained after withdrawal from training exercise.

When assessing the effect of exercise on bone it should be realized that the area is complex, with the nature of the exercise program itself being only one of the factors involved. Possible confounding factors include the base exercise in the subjects of study, and the effects of the early environment in which they were raised. Also, the background of the control group matters, as no exercise effect can be assessed against a nil option. To obtain better insight into the effects of exercise in the horse, it is imperative that exercise levels of individual horses be recorded on a large scale, including various age classes over prolonged, preferably career-spanning, periods of time. Relating workload patterns to data on performance, orthopedic health and wastage may then provide better clues regarding the effects of specific exercise programs under field conditions for a variety of equestrian disciplines.

Muscles

Overview

The horse's skeletal musculature is highly developed, particularly in athletic breeds. In contrast to most mammals, in which 30–40% of bodyweight consists of muscle, and to non-athletic horse breeds (~42%), more than half (~55%) of a mature Thoroughbred's body weight comprises skeletal muscle (Gunn, 1987). Low body fat and a large amount of muscle likely reflect adaptation and selective breeding of animals used for elite endurance and sprint racing (Kearns et al., 2002). Total muscle blood flow in horses that are exercising at a level when O_2 consumption is at its maximum (VO_{2max}, 134 ± 2 mL/min/kg) has been estimated at 226 L/min, which represents approximately 78% of total cardiac output (Armstrong et al., 1992). During exercise and locomotion metabolites and oxygen reach skeletal muscle fibers via the respiratory, cardiovascular, and hematologic systems; in turn the muscle fibers produce energy in the form of adenosine triphosphate (ATP), which, via the contractile machinery, is converted into mechanical work. The structural arrangement of the musculoskeletal system permits the use of this energy to move the horse's limbs in a characteristic rhythmic pattern that is well established for each gait.

Equine skeletal muscle is relatively heterogeneous and has considerable potential to adapt during training, largely mediated by the structural and functional plasticity of muscle fibers. These long-term (weeks to months) adaptations occur independently from the immediate or short-term muscular metabolic responses to either a single bout of sub-maximal or near-maximal exercise. They are associated with altered rates and regulation of transcription of specific genes and consequently a change in the amount of specific isoforms of proteins expressed within individual fibers (Williams & Neufer, 1996). Depending on the basal muscle status (e.g. breed, age, sex, level of fitness and training history of the horse), and characteristics of the stimulus (e.g. nature, intensity, duration, and frequency of exercise bouts, and total length of the conditioning program), the adaptive response to training can take two different forms (Table 13.1). First, the quantitative responses, when myofibers increase in size (hypertrophy) but otherwise retain their basal structural, physiological, and biochemical properties. And secondly, the qualitative responses or remodeling without hypertrophy, where myofibers do not change in size but acquire markedly different enzymatic and structural characteristics (e.g. fiber type transitions). In practice, the most common adaptive responses of equine skeletal muscle to training is a mixed form of remodeling with discrete

Table 13.1 **Summary of the two basic responses of skeletal muscle to training; possible stimuli and the nature of the responses and main physiological implications are indicated**

Quantitative responses: hypertrophy	Qualitative responses: remodeling
Stimulus	
Short isometric actions	Tonic and prolonged actions
Light and prolonged overextension	Repeated activities (endurance training)
Compensatory hypertrophy	Interval and high intensity actions
Plyometric contractions	
Responses	
Muscle fiber hypertrophy	Intracellular reorganization
Increased synthesis of muscle proteins	Changes in the expression of metabolic proteins
Increase in thickness and length of muscle mass	Increase in mitochondria and capillaries
	Changes in the expression of contractile proteins
Implications	
Improvement of muscle strength generation	Increase of muscle resistance
Improvement of explosive actions	Decrease of muscle shortening velocity
Increase in power generation	Higher efficiency and economy of metabolism

or substantive hypertrophy, that is often accompanied by increases in the number of capillaries (see Rivero, 2007; Rivero & Piercy, 2008).

As already mentioned, the modality and amplitude of the muscular responses to training also depend significantly on the muscle profile before training (Pette & Staron, 1997) because the increased contractile activity that is associated with training always induces a change toward slow and oxidative muscle profiles. Hence fast-twitch fibers (and therefore muscles that contain a higher proportion of fast-glycolytic fibers) can show a relatively greater training adaptation than slow-twitch fibers. As a general rule, this response is particularly prominent in young, inactive (Yamano et al, 2002) and aged, sedentary (Kim et al, 2005) horses, which have a high percentage of glycolytic (low oxidative) type IIX fibers (Fig. 13.12A,B), in contrast to active mature horses, which have muscle fiber type profiles that are more oxidative (Fig. 13.12C,D). Although it can be hard to differentiate muscular adaptations caused by growth and training, specific training effects have been delineated in growing foals (Dingboom et al, 2002; Eto et al, 2003; Rietbroek et al, 2007a,b), and young horses (Essén-Gustavsson et al, 1983; Ronéus et al. 1992, 1994; Rivero & Serrano, 1999; Serrano & Rivero, 2000; Serrano et al, 2000; Yamano et al, 2002).

From the extensive literature available, there is now sufficient evidence that equine skeletal muscle has great potential to adapt during exercise and, overall, these adaptations have important physiological implications for locomotion that include effects on power generation (strength), resistance to fatigue (stamina), and maximum velocity of shortening (speed) (Table 13.1). Much of this work is summarized in the excellent review chapter by Snow and Valberg (1994). But most of these earlier studies on muscular responses to training failed to describe accurately the training-induced muscular changes. As a consequence, results from many of these studies are of little, if any, application in practice. In recent years, however, a considerable number of experimental studies, with enhanced standards for training protocols and updated methods, have been published in this field. The readers of this book can be referred to recent book chapters (Rivero & Piercy, 2004, 2008), and reviews (Rivero, 2007; Rogers et al., 2007; Votion et al., 2007; Rivero et al., 2008) by the author covering these aspects. Although the majority of these studies have been conducted on racehorses (Thoroughbreds, Standardbreds, and endurance horses), there are a small number of specific studies about muscular adaptations to training in horses from other disciplines (show jumpers, dressage, and driving). Altogether, these recent studies provide valuable information about two particular aspects: 1) what can be modified in horse muscle by training? and 2) how can this be obtained. It is certain that answers to these two capital questions are of great interest to people involved in equine sport practice. But to achieve this goal, some preliminary considerations about muscle exercise physiology are mandatory in order to provide an appropriate scenario for subsequent considerations.

A synopsis of equine muscle exercise physiology

Since the pioneering study by Lindholm and Piehl (1974), analysis of equine muscle physiology has centered on the use of the percutaneous needle biopsy technique (Fig. 13.13), which has proved to be an invaluable tool in defining the morphological, histochemical, and biochemical properties of equine skeletal muscle. A detailed review of the technique for performing percutaneous needle muscle biopsy and sample preparation can be obtained elsewhere (Rivero, 1996; Rivero & Piercy, 2004).

Biochemical analysis of homogenized equine muscle samples has enabled the study of broad metabolic responses to exercise, and metabolic adaptation to training through analysis of selected muscle enzyme activities, their substrates, and intermediary metabolites (see Snow & Valberg, 1994 for a review). Histochemical evaluation of muscle, combined with image analysis (Henckel et al., 1998), has also provided invaluable information about contractile and metabolic properties of equine muscles, specifically regarding fiber types, oxidative and glycolytic capacities, fiber sizes, and capillary density. Cellular and molecular diversity within equine muscle has also been addressed via study of myofibrillar and non-contractile proteins by immunohistochemistry (Rivero et al., 1996a), gel electrophoresis (Rivero et al., 1997), and enzyme-linked immunosorbent assay (Rivero et al., 1999). Molecular biology and genomic techniques have also recently been applied to the field of equine muscle physiology (Eizema et al., 2003, 2005; Chikuni et al., 2004). The fact that during the early phase of transformation between fiber types, isoforms-specific mRNA should be detectable some time before a change in the specific protein, proves invaluable for examining exercise and training effects (Eizema et al., 2005).

Locomotor muscles are mainly located proximally on the appendicular skeleton, which has the effect of reducing the weight of the lower limb and decreasing the energy necessary to overcome inertia when the limb swings back and forth (Barrey, 2008). Movements of the distal limb are mainly passive and result from the release of elastic energy of the digital flexor tendons and suspensor ligament when the limb is unloaded (Wilson et al., 2001). In contrast, movements of the proximal limb result from active muscular contraction. In general, most locomotor muscles are active during the propulsion stage of weight bearing in each limb (Robert et al., 1998). Muscle activity, as measured by electromyography, is positively correlated with running speed, but shows that muscles within the same synergic group have significant differences in their activities when a horse exercises at constant speed (Hyyppä & Hänninen, 1998).

The total force exerted across a muscle is the sum of an active force generated by the contractile proteins and a passive force provided by structures that are arranged in parallel with the

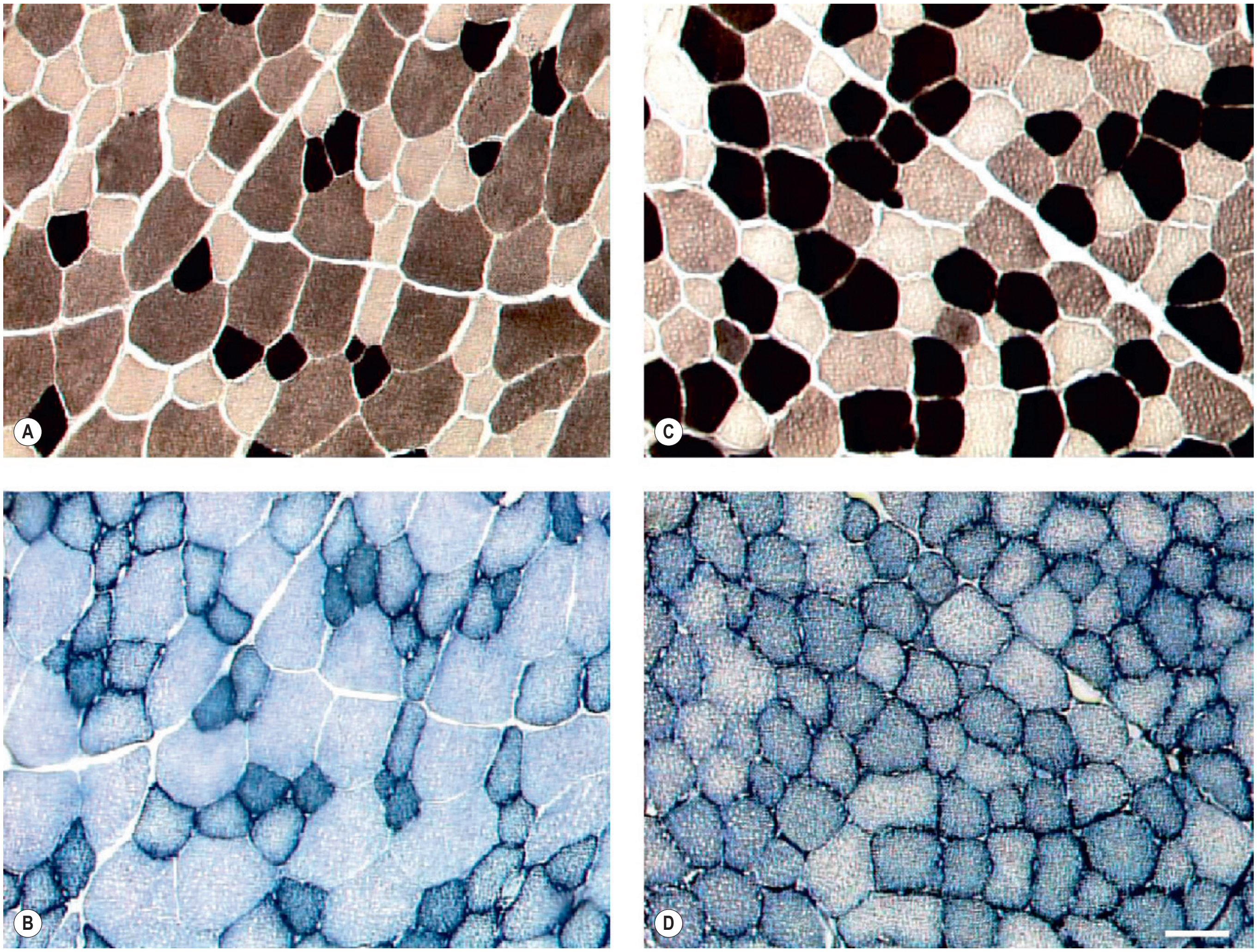

Fig 13.12 Transverse serial sections of *gluteus medius* muscle biopsies stained with myofibrillar ATPase after acid preincubation at pH 4.45 (A and C) and succinate dehydrogenase (B and D) in a young adult (3-year-old) and untrained Andalusian horse (A and B), and in an adult and regularly trained (10-year-old) Andalusian horse (C and D). Note that the young animal has a lower proportion of type I fibers (black fibers in A and C) and a higher percentage of low-oxidative type IIX fibers (gray fibers in A and C) than the adult horse; furthermore, differences in fiber size are much more pronounced in the young animal than in the adult. This therefore may explain the broader range of adaptive responses to training in young untrained horses than in adults or regularly trained animals. Bar = 50 μm.

contractile elements. Most of the natural equine gaits typically consist of stretch-shortening exercise cycle (plyometric muscular contractions), characterized by multi-joint actions, rapid eccentric phases and explosive concentric muscular contractions potentiated by the stretch reflex. More than 90% of a muscle is made up of myofibers, with the rest consisting of nerves, blood vessels, and the fat and connective tissue that separate the individual fibers (endomysium), the fascicles (perimysium), and the whole muscle (epimysium). The connective tissue merges with both the origin and the insertion tendons of the muscle, as well as with internal tendons in compartmentalized muscles. Regional functional architecture and specialization of muscles of the pelvic and thoracic limbs have been reported in horses (Payne et al., 2005a,b). In general, the proximal limb is characterized by muscles with large volumes, long and parallel fascicles, and extremely short tendons/aponeuroses, whereas the distal lib is characterized by muscles with small volumes, short, pinnate fascicles and long tendons. Hence, in general, proximal limb musculature is specialized for work output, while the distal limb musculature is specialized for generating force economically.

The unit of muscular contraction is the sarcomere, which is formed by thick and thin filaments of contractile proteins. Muscle contraction occurs when, within each sarcomere, thin myofilaments slide over thick myofilaments, bringing the adjacent Z disks closer together. The myosin head of thick filaments is the motor domain that contains the ATP-blinding site, and the myofibrillar ATPase enzyme. The force that is generated in sarcomeres is transmitted via the contractile apparatus to intermediate filament proteins that provide a structural link first to the sarcolemma and then to the extracellular matrix and the connective tissues of tendons, and ultimately to the bones of the skeleton.

Functionally, muscle fibers are organized as motor units. A motor unit consists of an α-motoneuron and the set of skeletal muscle fibers that it innervates. The ability of equine muscle tissue to perform efficiently in spite of very different types of exercise is enhanced by the muscle heterogeneity. Equine skeletal muscle is composed of three main pure fiber types termed I, IIA, and IIX, and a fourth hybrid phenotype termed IIAX, which express myosin heavy chain (MHC) isoforms (Fig. 13.14). There are important differences in the physiological, biochemical, and morphological

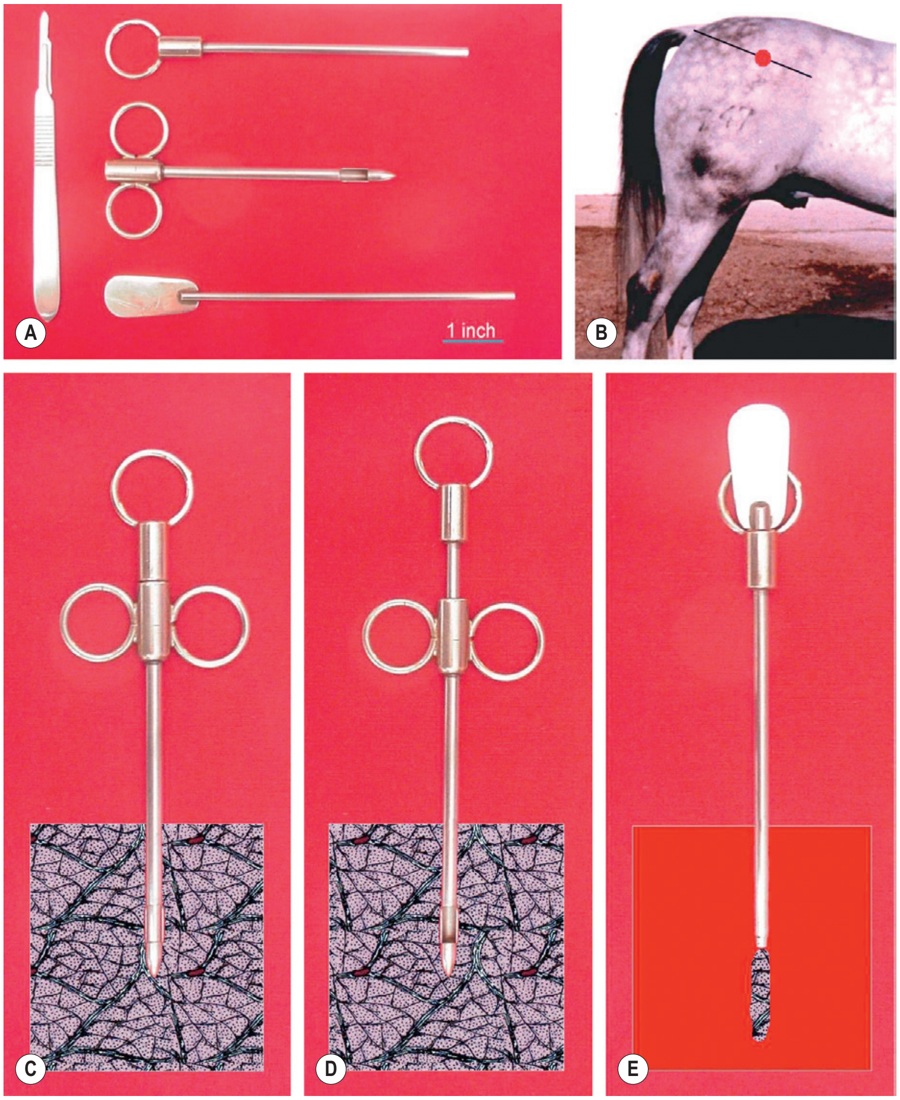

Fig 13.13 (A) Instruments used in percutaneous muscle biopsy. Scalpel (left) and biopsy needles (right). The top needle, which has an outer diameter of 6 mm, was first introduced by Bergström (1962) and was further modified with finger and thumb rings by Henckel (1983). (B) Site for the collection of biopsy specimens from the right *gluteus medius* muscle according to Lindholm and Piehl (1974); this fixed site is located one-third of the distance along a line running from the tuber coxae to the root of the tail. (C–E) An illustration of the various steps for the needle biopsy technique; (C) the needle, together with the internal cutting cylinder, is inserted into the muscle; (D) within the muscle, the cutting cylinder is partially withdrawn so that the window is opened, allowing muscle to enter the slot, and a piece is then cut by pushing down the internal cylinder; (E) between 50 and 150 mg of muscle tissue is usually acquired.

properties of these muscle fiber types. Hybrid IIAX fibers exist in equine locomotor muscles in significant numbers (Dingboom et al., 1999; Linnane et al., 1999), although the co-expression of IIA and IIX MHCs at the protein level seems not to be reflected by co-transcription of the corresponding genes (Eizema et al., 2005). This suggest that hybrid fibers may represent fibers that are undergoing committed fiber type switching, towards the type corresponding to the mRNA currently being expressed, and that this conversion occurs spontaneously in equine muscle not subjected to any specific training stimulus.

All fibers within a single motor unit are of the same histochemical type. Motor units are selectively recruited in a specific pattern that changes according to the gait and the intensity and duration of exercise (Eto et al., 2006). For the maintenance of posture, only type I motor units are recruited. As the intensity and duration of exercise increase, further motor units are recruited, in the rank order: I→IIA→IIAX→IIX. Type IIX motor units are only recruited at near-maximal exercise intensity (sprint and jumping), and during extremely prolonged submaximal exercise (Valberg, 1996; Yamano et al., 2006).

The percentage of each muscle fiber type present in a muscle (e.g. fiber type composition) varies from horse to horse (Fig. 13.15), and multiple factors, both myogenic (lineage, breed, age, and sex), and non-myogenic (neural input, neuromuscular activity, and extracellular substances) in nature, regulate this percentage. Much more important is, however, the significance for performance of this muscle fiber type diversity. For example, endurance ability is correlated with high percentages of types I and IIA fibers (Rivero et al., 1993), whereas speed ability is correlated with high percentages of fast-twitch type IIA and IIX fibers (Barrey et al., 1999), and power generation (strength) is proportional to fiber size (Rivero et al., 2001). Interestingly, some myofibers characteristics are positively correlated with both the percentages of IIA fibers (Persson et al., 1991) and fiber size (Rivero & Clayton, 1996), and the stance time of the stride is inversely correlated with the percentage of IIX fibers (Ronéus et al., 1995) and fiber diameter (Rivero & Clayton, 1996). Furthermore, certain primary muscular adaptations to training occur with concomitant modifications in the temporal characteristics of the stride (Rivero et al., 2001).

Muscle cannot contract without a source of energy provided by the hydrolysis of ATP that occurs at the head of the myosin molecule. As muscle (ATP) is limited and it is metabolized within a few seconds of the exercise, replacement of ATP is mandatory. There are different metabolic pathways for this goal within the muscle during exercise (see Votion et al., 2007). Within mitochondria, β-oxidation of free fatty acids, the tricarboxylic cycle and oxidative

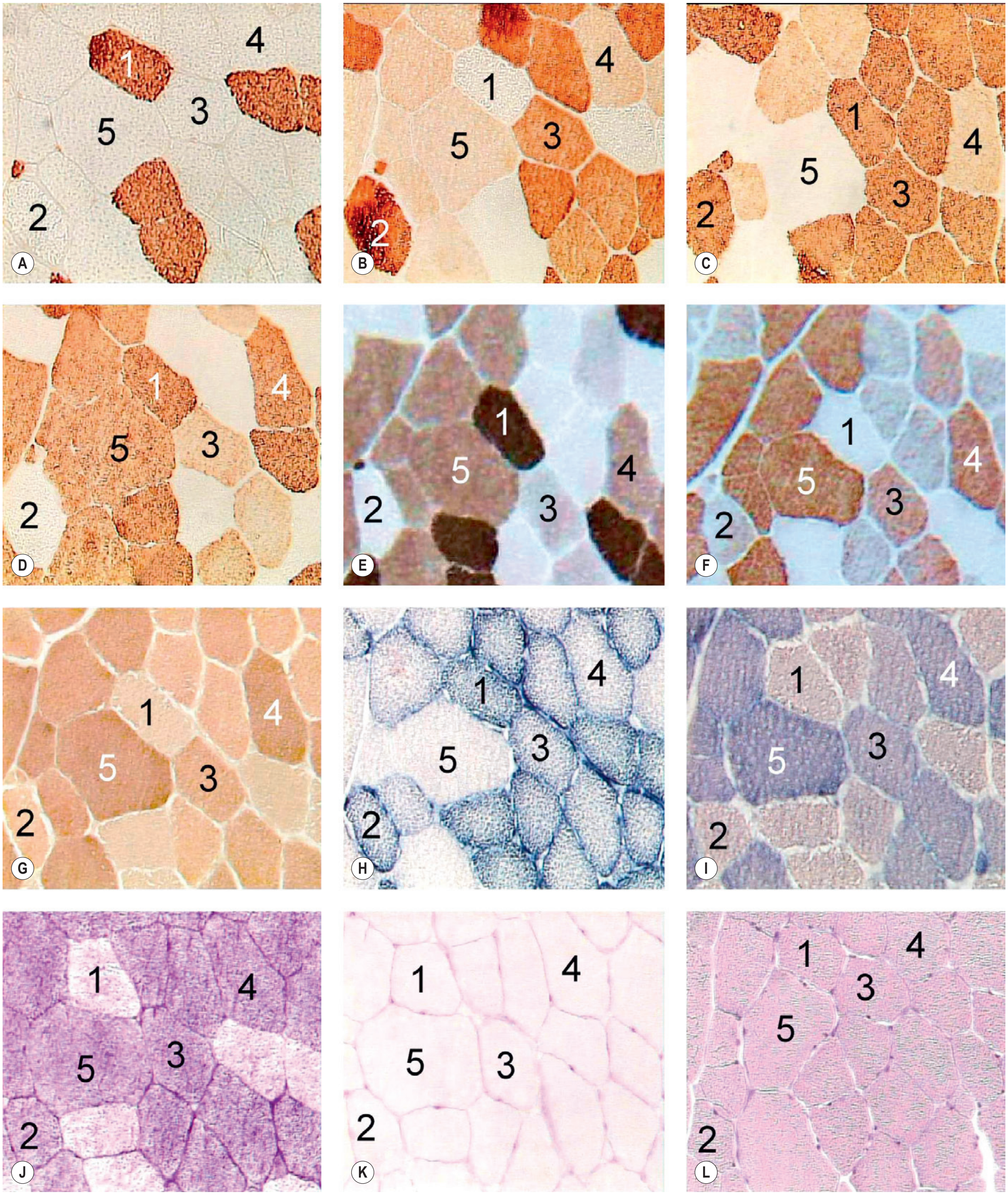

Fig 13.14 Serial cryosections of adult horse M. *gluteus medius* stained by immunohistochemistry, enzyme histochemistry and histology. (A–D) Sections were stained with a number of monoclonal antibodies against specific myosin heavy chain (MHC) isoforms: BA-D5 (A, anti MHC-β/slow), SC-71 (B, anti MHC-IIA), BF-35 (C, anti MHCs β/slow and IIA), and S5–8H2 (D, anti MHCs β/slow and IID/X). (E–G) Sections were assayed for myofibrillar actomyosin adenosine triphosphatase activity after acid (pH 4.45, E) and alkaline (pH 10.45, F) preincubations, and by Blanco and Sieck's quantitative histochemical procedure. (H–J) Sections assayed for succinate dehydrogenase and (H), glycerol-3-phosphate dehydrogenase activities (I) and periodic acid-Schiff (PAS) for selective staining of glycogen (J). (K–L) PAS with α-amylase digestion, for visualizing capillaries (K) and hematoxylin and eosin for visualizing myonuclei (L). The fibers labeled 1, 2, 3, 4 and 5 are types I, IIA, IIAx (e.g. a hybrid fiber with more MHC-IIA content than MHC-IIX), IIaX (e.g. a hybrid fiber with less MHC-IIA content than MHC-IIX), and IIX, respectively. Bar = 50 μm.

(G) Reproduced from Blanco & Sieck (1992).

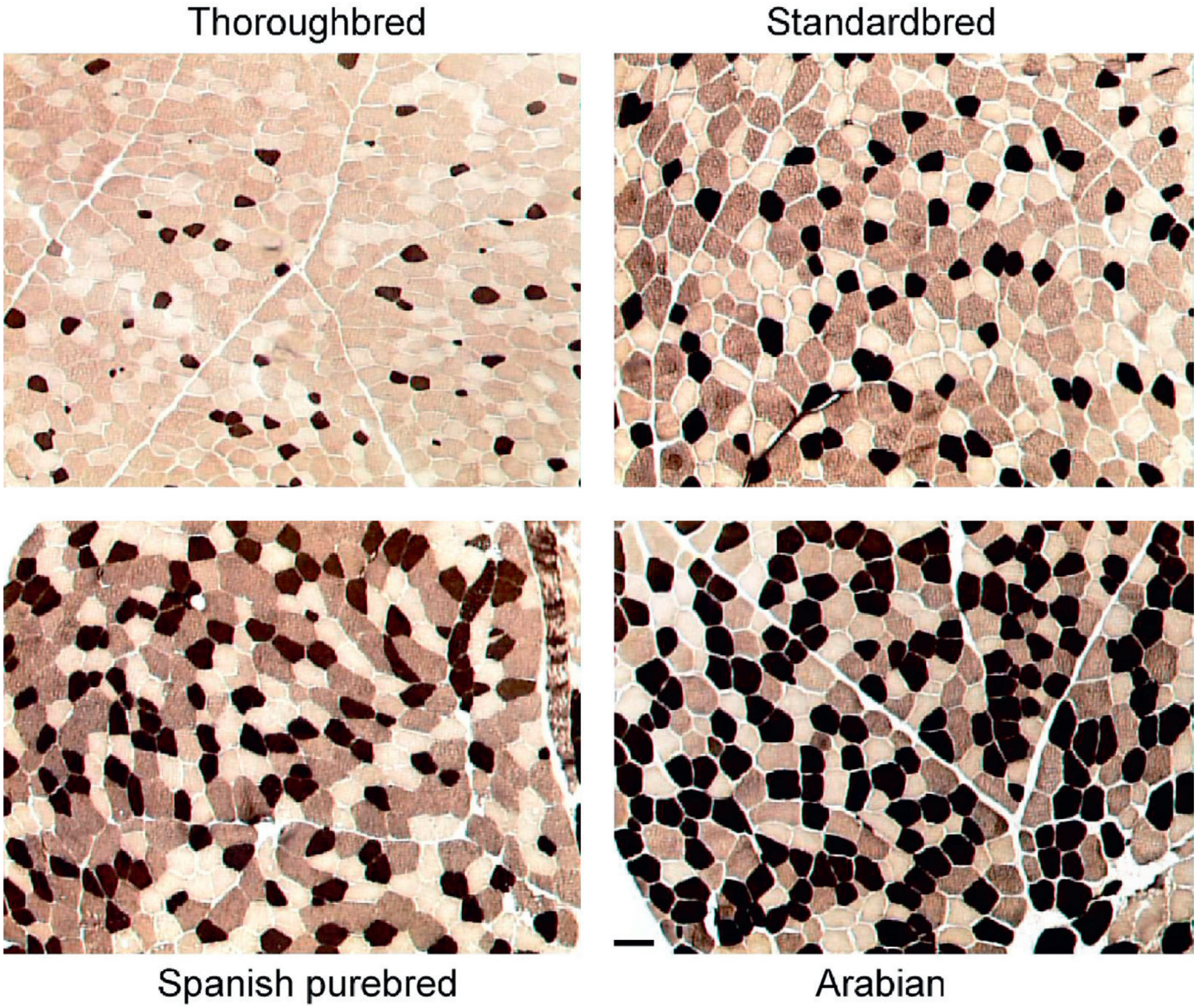

Fig 13.15 Transverse sections of M. *gluteus medius* specimens (equivalent depth) stained with myofibrillar adenosine triphosphatase after acid preincubation (pH 4.4), removed at the same depth, from four different breeds of athletic horses. Note how the percentage of type I (oxidative) fibers (black fibers) and the fiber size increases from the fastest breed (Thoroughbred) towards the slower, more endurance-suited breed (Arabian). Bar = 150 μm.

phosphorylation (via the electron transport chain) combine to produce ATP aerobically (aerobic pathways). Two additional anaerobic mechanisms (anaerobic pathways) exist: the high-energy phosphate pathway and glycolysis. Aerobic production of ATP is a relatively slow but efficient process, while anaerobic pathways produce energy rapidly but relatively inefficiently. Although both pathways are active during exercise, the relative contribution depends on the nature, intensity, duration and frequency of the exercise, the muscle's fiber type composition, the availability of oxygen and substrates, and the presence of intermediary metabolites that may potentially activate or inhibit selected enzymes.

In exercise of low or moderate intensities, the main energy provision for muscular functions comes from aerobic pathways. As exercise intensity increases, a greater proportion of the energy is supplied by the anaerobic pathway. At the point where the availability of oxygen becomes a limiting factor in mitochondria, pyruvate from the anaerobic glycolysis cannot be converted into acetyl-CoA (the substrate for the Krebs' cycle), but it is converted to lactate. The point when the increased rate of lactate production can be detected in the plasma is known as the anaerobic threshold. This threshold varies and depends on several factors, including the muscle's fiber type composition and the level of fitness. In practice (and henceforth in this chapter), aerobic capacity is defined as the maximum amount of energy provided by aerobic pathways, whereas anaerobic capacity is the maximum amount of energy provided by anaerobic pathways (Hinchcliff et al., 2002).

At the beginning of the sub-maximal exercise (<85% of VO_{2max}), muscle glycogenosis is the main mechanism for providing acetyl-CoA from pyruvate. Either intramuscular glycogen or blood glucose are the substrates for this pathway. But as energy demands increase, higher rates of pyruvate oxidation tend to cause a shift towards free fatty acids β-oxidation. The overall effect is that muscle glycogenesis declines over time during sub-maximal exercise, whereas free fatty acids β-oxidation increases. Although lipids are the predominant fuel utilized during prolonged sub-maximal exercise, fatigue occurs by intramuscular glycogen depletion, as the main cause.

During maximal exercise (>85% of VO_{2max}), the high functional demands require recruitment of most motor units. At this time, intramuscular glycogen and blood glucose act as the predominant fuels to replenish ATP through anaerobic glycolysis. Limitations imposed by this high-intensity exercise result in greater amounts of pyruvate being converted to lactate rather than acetyl-CoA. As a consequence, muscle (lactate) increases in a rate proportional to the percentage of type II fibers. Initially, intracellular lactate accumulation is removed from the cell by active transport into the blood, but saturation of this mechanism results in a sudden exponential rise in intracellular lactate accumulation (anaerobic threshold), that generally occurs when the plasma (lactate) reaches about 4 mmol/L. The rise in intracellular lactate results in a significant reduction in cytoplasmic pH, the main cause of fatigue during maximal exercise. Local acidosis leads to impairment of both muscle structure and function. A fall in cytoplasmic pH is partially overcome by a buffering system within myofibers.

From the biochemical perspective, the main goal of muscle conditioning is to increase performance by: (1) increasing aerobic and/or anaerobic capacities, (2) reducing the major causes of fatigue during sub-maximal (e.g. heavy intramuscular glycogen depletion) or near-maximal (e.g. intramuscular acidosis) exercise, or (3) both situations.

Muscular adaptations to training

Muscle fiber size

The effects of training on equine muscle fiber size are still controversial. In general, the adaptive response of equine skeletal muscle to early and long-term exercise training takes the form of remodeling with minimal, if any muscle fiber hypertrophy (see Snow & Valberg, 1994; and Rivero, 1997 for reviews). However, specific muscle fiber hypertrophy can be stimulated with bursts of high resistance muscle activity (Heck et al, 1996; Serrano & Rivero, 2000) and by prolonged stretch beyond normal resting length (Tyler et al, 1998; Serrano et al, 2000). Weight bearing, as a form of progressive resistance exercise training, has been investigated in ponies for improving strength, and resulted in increased muscle power, muscle size, and increased (though not statistically significant) type II fiber cross sectional area, without parallel changes in MHC composition (Heck et al, 1996). Six months of conventional jump training in competitive show jumpers also induced a selective hypertrophic growth of type II fibers, with minimal switching between myofiber phenotypes (Rivero & Letelier, 2000). Other longitudinal studies have also reported significant and early (less than 3 months) increases in the mean cross-sectional areas of type I and/or IIA fibers after training (Gottlieb et al, 1989; López-Rivero et al, 1992; Rivero et al, 1995a, 2001, 2007; Tyler et al, 1998; Miyata et al, 1999; Serrano et al, 2000; Yamano et al, 2002; D'Angelis et al, 2005), a result also noted in horses less than a year of age (Eto et al, 2003; Rietbroek et al, 2007b). A marked and generalized fiber hypertrophy (~50%) has recently been documented in endurance-trained Arabians performing moderate intensity exercise (~80% of VO_{2max}) of long duration (50–80 min/day), 4 days/week for 3 months (D'Angelis et al, 2005). Even though a fiber transition occurs towards more oxidative fibers (IIX → IIA → I) with normally smaller cross sectional area, the hypertrophy may represent either the new fiber's retaining size characteristics of its previous type, or generalized increased protein production (or both). In contrast, other studies of Standardbreds and Thoroughbreds reveal minimal changes (Henckel, 1983; Lindholm et al, 1983; Foreman et al, 1990; Rivero et al, 1996b) or even a reduction in fiber cross-sectional area (Essén-Gustavsson & Lindholm, 1985; Essén-Gustavsson et al., 1989; Ronéus et al, 1992, 1993; Rivero et al, 2002). These observations are hard to reconcile with the prominent increase in muscle mass, especially in the hindquarters, generally observed in horses after most training programs (Snow & Valberg, 1994; Heck et al., 1996). When considered together, the only explanation for an increase in muscle mass, despite either no change or a reduction in fiber size, is a parallel increase in the number of muscle fibers (hyperplasia), as previously demonstrated in humans (Sjöström et al., 1991).

Muscle fiber type transitions

Muscle fiber type distribution and MHC composition are strongly influenced by training (Figs 13.12, 13.16, 13.17). Studies on endurance training in horses have demonstrated (by myofibrillar ATPase histochemistry, immunohistochemistry and electrophoresis), increases in the fraction of type IIA fibers and a concomitant decrease in the proportion of IIX fibers (Essén-Gustavsson & Lindholm, 1985; Essén-Gustavsson et al., 1989; López-Rivero et al., 1991; Sinha et al., 1993; Rivero et al., 1995a, 2001, 2007; Rivero, 1996; Tyler et al., 1998; Miyata et al., 1999; Rivero & Letelier, 2000; Serrano & Rivero, 2000; Serrano et al., 2000; Yamano et al., 2002; D'Angelis et al., 2005; Gondim et al., 2005; Kim et al., 2005; Rietbroek et al., 2007b). In addition, several endurance training studies in horses have reported fiber transitions beyond type IIA fibers, e.g. an increase in hybrid I+IIA fibers and pure type I fibers (Henckel, 1983; Ronéus et al., 1987; Rivero et al., 1995a; Serrano et al., 2000). Fiber type transitions during resistance training appear to resemble qualitatively, those observed in endurance training. Hence, strength training in horses has been shown to result in both increased IIA : IIX fiber ratio (Gottlieb et al., 1989; Rivero & Serrano, 1999) and, when training is long enough, the I : II fiber ratio (Serrano et al., 2000). Similarly, sprint training in horses results in increased numbers of type IIA and decreased numbers of type IIX fibers (Lovell & Rose, 1991), with a corresponding change in their respective MHC content (Miyata et al., 1999; Rivero et al., 2002). In contrast to endurance and strength training, a specific decrease of type I fibers has been reported as an early and probably transitory response to high-intensity training (Lovell & Rose, 1991; Rivero et al., 2002).

When these various training studies are considered in combination, it is reasonable to assume that fiber type transitions occur in a graded and orderly sequential manner and typically change from faster, more glycolytic fibers to slower and more oxidative fiber types, e.g. IIX → IIAX → IIA → IIA+I → I (Pette & Staron, 1997). A dose–response relationship between the duration (in total) of the training program and the magnitude of induced changes has recently been demonstrated at the molecular level (Serrano & Rivero, 2000; Serrano et al., 2000). This relationship can be explained more readily in terms of a threshold for the type IIX → IIA transition during the early phase of training, and then a further threshold for the type IIA → type I transition. Thus, a single fiber is capable of a complete fast-to-slow transformation in response to a sufficiently long physiological training stimulus. Finally, although many reports describe the training response shown by muscle fibers in terms of the MHC component, it is important to remember that many other protein isoforms of the sarcomere (such as the regulatory proteins of the thin filaments) and the calcium regulatory proteins of the sarcoplasmic reticulum, change in parallel (Pette, 1998).

Metabolic changes and increased capillary density

Perhaps the most commonly detected and earliest muscular adaptation to training is an increase in the activity of enzymes of aerobic metabolism, such as selected enzymes of the TCA cycle, the electron transport chain and fat oxidation (Lovell & Rose, 1991; Ronéus et al., 1991; Rivero et al., 1995b, 2007; Eaton et al., 1999; Miyata et al., 1999; Rivero & Letelier, 2000; Serrano et al., 2000; Yamano et al., 2002; McGowan et al., 2002; Eto et al., 2003; Kim et al., 2005; Rietbroek et al., 2007b). These changes are

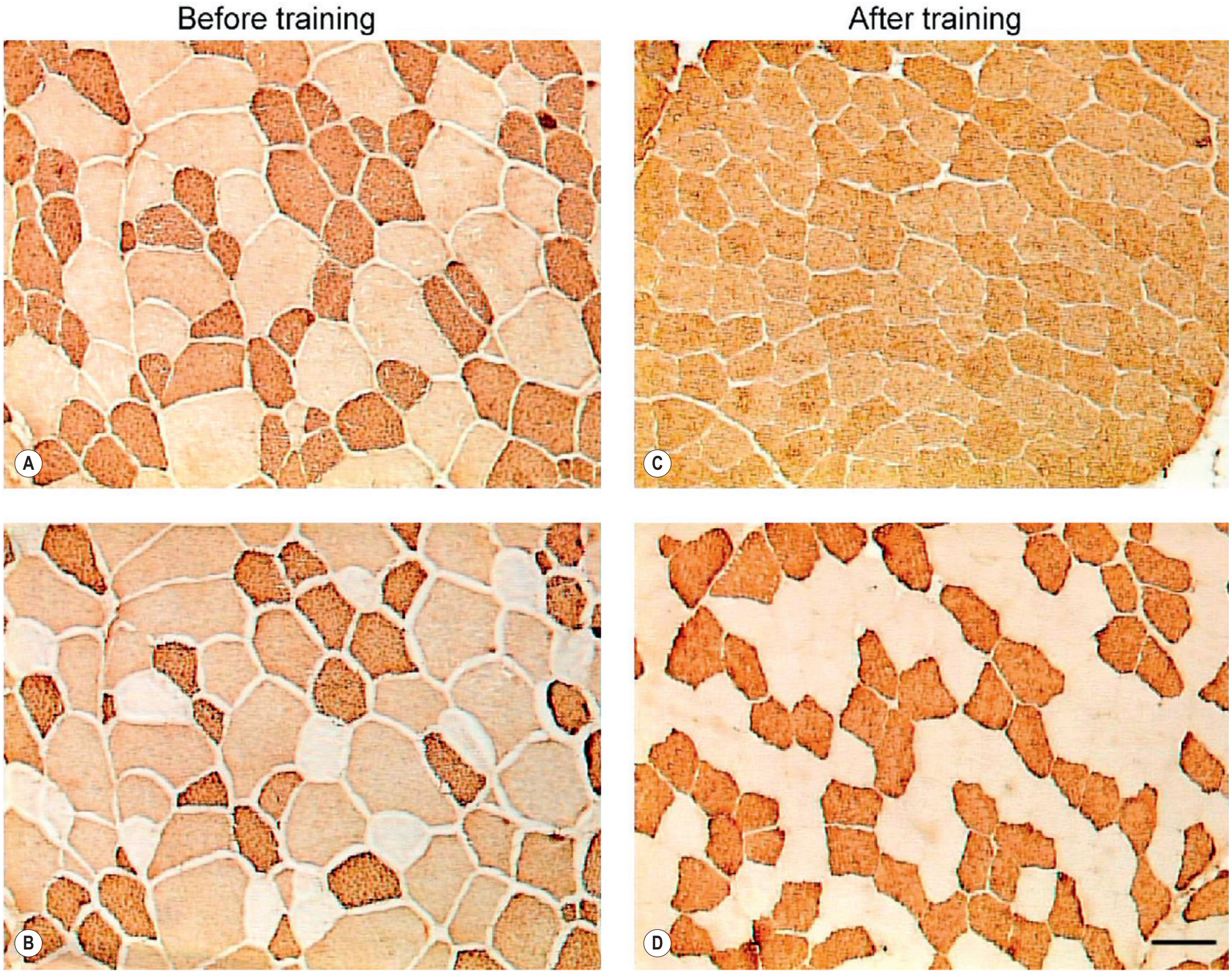

Fig 13.16 Transverse serial sections of *M. gluteus medius* biopsies (depth, 6 cm) of the same horse before (A and B) and after (C and D) a long-term endurance training program (9 months in total). (A and C) Sections are stained by immunohistochemistry with a monoclonal antibody to types I or IIA myosin heavy chain isoforms; note that almost all muscle fibers express either or both of these isoforms after training. (B and D) The same sections stained by immunohistochemistry with a monoclonal antibody specific to type IIA myosin heavy chain isoform; note the significant increase in the number of fibers expressing this isoform after 9 months of training. Bar = 50 μm. Details of the training program are described in Serrano et al. (2000).

associated with increased mitochondrial and capillary densities (Fig. 13.18) (Sinha et al., 1993; Misumi et al., 1995; Rivero et al., 1995a, 2007; Ronéus et al., 1995; Tyler et al., 1998), the latter response promoting improved oxygen diffusion and more expeditious removal of waste products (such as CO_2). A recent study in growing foals has reported, however, that exercise training had a negative effect on both the capillary supply and oxidative capacity of skeletal muscle in horses (Rietbroek et al., 2007a).

The activities of key anaerobic enzymes, such as phosphofructokinase and lactate dehydrogenase, either do not change or decrease following training (Snow & Valberg, 1994; Rivero et al., 1995b; Geor et al., 1999; Miyata et al., 1999; Serrano et al., 2000). However, high-intensity training (~80–100% of VO_{2max}, 5 min × 2, 5 days/week for 12–16 weeks) for both young (Yamano et al., 2002) and adult (Eto et al., 2004). Thoroughbreds did result in increased glycolytic phosphofructokinase enzyme activity. Histochemical assessment of glycerol-3-phosphate dehydrogenase enzyme activity, an enzyme well correlated with other glycolytic enzymes, was also increased by exercise consisting of alternating days of either high-intensity, short duration exercise (~100–140% of the speed that results in a blood lactate of 4 mmol/L, (or V_4) for 15 min, or moderate intensity, long duration exercise (~65% of V_4, 60–90 min) exercise for a total of 5 weeks (Rivero et al., 2002). Similar results have recently been reported in adolescent Thoroughbreds after 3 weeks of high-intensity training (Rivero et al., 2007). Although training also causes increased AMP deaminase activity along with other purine nucleotide cycle enzymes, such as creatine kinase (discussed in Snow & Valberg, 1994), the concentration of total nucleotide stores is usually not affected by training (Lovell & Rose, 1991). Nevertheless, moderate intensity (~55% of VO_{2max}) and long duration (60 min, over ~13–14 km) exercise for 10 consecutive days, increases muscle phosphocreatine concentration and reduces muscle creatine content at the point of fatigue (Geor et al., 1999).

Training has also been shown to result in a modest increase in muscle glycogen storage (Foreman et al., 1990; Gansen et al., 1999; Serrano et al., 2000; McGowan et al., 2002; Rivero et al., 2002) that may well be associated with reduced activities of glycolytic enzymes, since the capacity to mobilize endogenous glycogen is partially

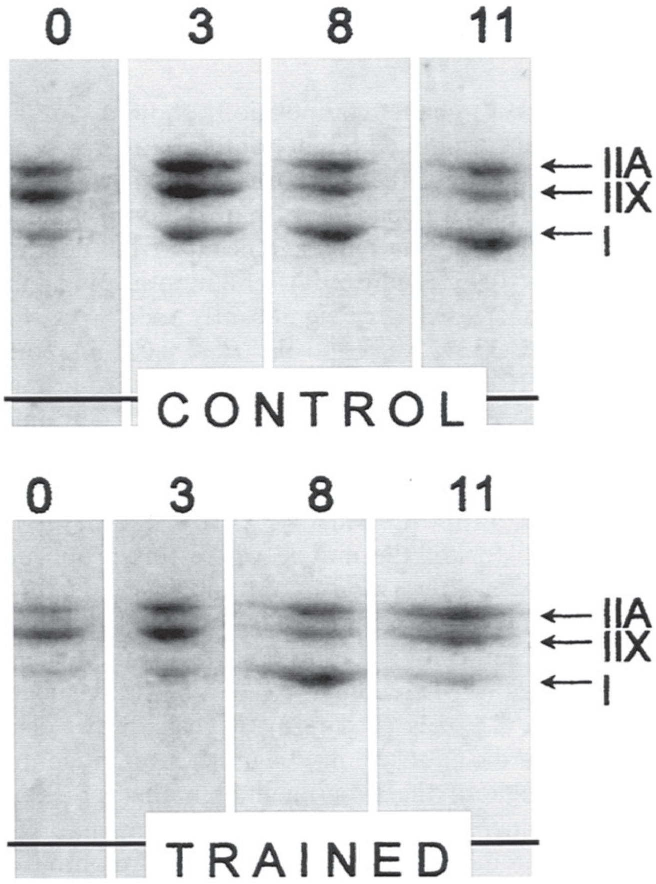

Fig 13.17 Eight percent sodium dodecyl polyacrilamide gel electrophoresis of muscle samples from the *M. gluteus medius* of a control horse (upper row) and a trained horse (bottom row) throughout an experiment to investigate the effects of prolonged endurance exercise training and detraining program. 0, pre-training; 3 and 8, after 3 and 8 months of training; 11, after a further 3 months of detraining. More details of the experiment in Serrano and Rivero (2000). The three myosin heavy chain isoforms are identified as I, IIA and IIX. Note the effect of training on the relative densities of the I and IIX bands, indicating a fiber type transition in the order IIX → IIA → I.

influenced by the absolute activity of anaerobic enzymes expressed within muscle fibers (Booth & Baldwin, 1996). In experimental animals training is known to increase the sensitivity of glucose uptake across the sarcolemma via increased GLUT-4 expression (Rodnick et al., 1992). In horses, moderate-intensity exercise training increases middle gluteal muscle GLUT-4 protein content, but this change is not reflected by increased sarcolemmal glucose transport in post exercise muscle samples (McCutcheon et al., 2002). Finally, the transfer of FFAs from the vascular to the intracellular compartment is also enhanced with endurance training, and is promoted by increased extracellular (interstitial) albumin concentration (Heilig & Pette, 1988).

Physiological adaptations and buffering capacity

Training results in increased motor unit action potential amplitude indicative of recruitment of larger motor units and synchronization when analyzed by quantitative electromyography (Wijnberg et al., 2008). An increase of muscle force as a result of training can be, among others, the result of increased muscle fiber hypertrophy and/or motor unit synchronization (Gabriel et al., 2006). Thus, the significant increase in motor unit potential amplitude seen after training (Winjberg et al., 2008) is most likely the result of an increase in muscle fiber size, recruitment of larger (type II) motor units, and increased synchronization of the muscle fiber action potentials.

Training has significant effects on the electrical and ionic membrane properties of equine skeletal muscle (McCutcheon et al., 1999; Suwannachot et al., 1999, 2001; Rietbroek et al., 2007a). Short-term exercise training of moderate intensity results in an increase in the density of Na^+/K^+-ATPase pumps measured by ouabain binding assays, together with an attenuation in K^+ efflux from working muscles during high-intensity exercise. Although the physiologic implication of these training-induced adaptations is unclear, enhanced ionic control at the sarcolemma may result in myofibers that are better able to respond to the rate of motor neuron discharge (Bottinelli & Reggiani, 2000). Additional responses following physical conditioning include increased SR calcium uptake (Ca^{2+}-ATPase activity) and an attenuation of the exercise-induced decline of calcium uptake (Wilson et al., 1998).

Several studies have reported an increase in buffering capacity of equine skeletal muscle after a few weeks of sprint training (Fox et al., 1987; McCutcheon et al., 1987; Sinha et al., 1991, 1993), and after prolonged (34 weeks) training (McGowan et al., 2002). This increase may be due to 1) increased incorporation of myofiber protein, 2) increased creatine phosphate concentration or 3) higher muscle carnosine concentrations (Hyyppä & Pösö, 1998), although with regard to the latter, no differences in carnosine concentration were found in muscle from either trained or untrained Thoroughbreds (Marlin et al., 1989).

Other training consequences

Training increases the expression of heat shock proteins (Pösö et al., 2002) and splice variants of neuronal nitric oxide synthase (Gondim et al., 2005), which protect muscle cells from exercise-induced oxidative stress. Furthermore, the reported apoptosis that occurs in trained equine skeletal muscle (Boffi et al., 2002) probably promotes the work/recovery/rebound/supercompensation cycle, when unconditioned muscle cells undergo programmed cell death, to be replaced by new, stronger cells. In fact, training attenuates exercise-induced ultrastructural damage in equine skeletal muscle (Kim et al., 2005), probably via a parallel fiber type transition, myofiber hypertrophy or increased satellite cell activation (or perhaps all three).

Overtraining

Overtraining is a syndrome that has been recognized as a cause of poor performance in racehorses over the course of a high intensity and prolonged (more than 4 months) training (Bruin et al., 1994; Tyler et al., 1998; McGowan et al., 2002; Rivero et al., 2008). However clinical signs of overtraining are accompanied by relatively few characteristic changes in skeletal muscle. In the study by Tyler et al. (1998), overtraining caused significant type IIA fiber atrophy (~8%), a decrease in type IIA : IIX mATPase fiber ratio, and increased mitochondrial volume in type I (~16%) and type II (~39%) fibers accompanied by an increase in VO_{2max} (~8%). As a consequence, muscle fibers of overtrained horses are generally highly oxidative (Karlstrom & Essén-Gustavsson, 2002). Additional metabolic adaptation of overtrained muscle includes ATP depletion (Bruin et al., 1994), and reduced resting glycogen concentration (McGowan et al., 2002), though this latter finding may relate to delayed glycogen replenishment seen in normal horses, particularly given that glycogen utilization during exercise itself, is not influenced by overtraining (McGowan et al., 2002).

Detraining

Maintenance of the trained muscle signature during inactivity is more prolonged in horses than other athletic species, lasting

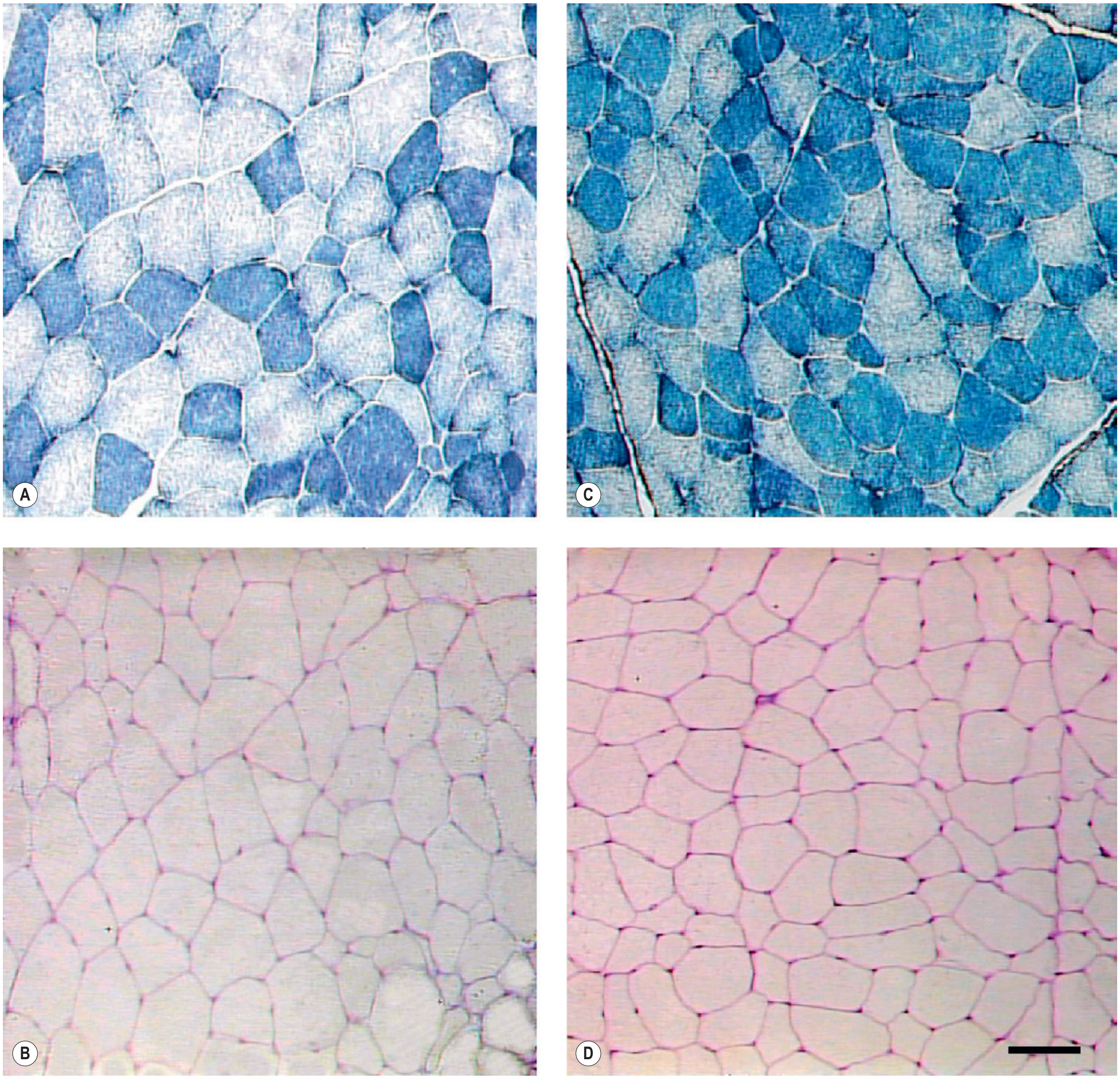

Fig 13.18 Transverse serial sections of muscle biopsy samples from the *M. gluteus medius* from the same horse taken before (A, B) and after (C, D) 9 months of prolonged endurance training. (A, C) Sections are stained with succinate dehydrogenase to demonstrate the oxidative capacity of individual muscle fibers; note the increase in the number of fibers with dark staining after training. (B, D) Sections are stained with the α-amylase PAS to visualize capillaries; note the increased capillary density (e.g. number of capillaries per mm^2) after the training program. Bar = 75 μm.

throughout 5–6 weeks of inactivity (Essén-Gustavsson et al., 1989; Foreman et al., 1990; Tyler et al., 1998) although not beyond 12 weeks (Rivero et al., 1995a; Serrano & Rivero, 2000; Serrano et al., 2000). Researchers have suggested that expression of the MHC-IIX gene constitutes a default setting that may be altered (decreased) by chronic increased contractile activity (e.g. training), and compensated for, by increased expression of MHC-IIA (Goldspink et al., 1992). In line with this hypothesis is the observation that a return to sedentary activity levels following a prolonged endurance training period normalizes the expression of MHC-IIX, via a slow-to-fast fiber type transformation in the order I → IIA → IIX (Fig. 13.17) (Serrano et al., 2000). These detraining-induced changes in MHC phenotype parallel a reversion of the muscle's size and return of the muscle's metabolic and capillary characteristics to pre-training levels (Serrano et al., 2000). In summary, fiber sizes decrease, together with a decline in mitochondrial density, aerobic enzyme activities and glycogen content and normalization of anaerobic enzyme activities.

Possible mechanisms underlying muscular adaptations to training

Skeletal muscle responds to altered functional demands by specific quantitative and/or qualitative alterations in gene expression

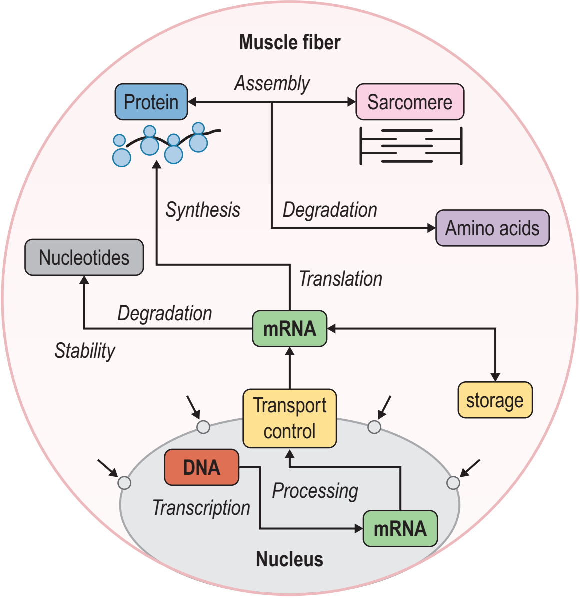

Fig 13.19 Schematic diagram showing different steps in the regulation of gene expression in skeletal muscle associated with increased contractile activity.

Box 13.1 Steps in cascade of events by which exercise and increased neuromuscular activity lead to physiologically relevant changes in the characteristics of skeletal muscle

- Exercise
- Contractile activity
- Messengers and signal transduction pathways
- Regulatory genes
- Structural genes
- Muscle fiber characteristics
- Muscle tissue characteristics

(Fig. 13.19) provided the stimuli are of sufficient magnitude and duration (Pette, 1998). Repeated or persistent elevation of neuromuscular activity (e.g. during exercise and training) induces a series of concerted changes in gene expression, evoking either myofiber hypertrophy or myofiber remodeling, or both (Williams & Neufer, 1996). Myofiber hypertrophy is generally characterized by a coordinated increase in abundance (per fiber) of most protein constituents. To some extent this process includes the selective and transient activation of specific genes immediately following the onset of work overload. The major events, however, underlying muscle hypertrophy involve a general and non-specific augmentation of protein synthesis within cells. Remodeling of myofiber phenotype, with minimal or no hypertrophy, is the typical muscular response to prolonged training in the horse (Serrano et al., 2000). During this type of adaptation, myofibers undergo striking reorganization, with selective activation and repression of many genes, and switching between different myofibrillar isoproteins occurring in a graded and orderly sequential manner (Pette, 1998). These changes occur in parallel, but not simultaneously over time, and correspond to the changes observed in enzymatic profiles, cytosolic proteins and membrane receptors and transporters.

The complexity and pleiotropic nature of the physical and metabolic stimuli presented to myofibers during contraction that ultimately results in altered gene regulation were reviewed by Williams and Neufer (1996). Acetylcholine released from motor neurons and other signaling molecules of neural origin, bind to cell surface receptors on myofibers, triggering intracellular events that may be linked to altered gene expression (Box 13.1). Additional signals are probably derived from contraction-induced mechanical stress perturbing the sarcolemma and extracellular matrix, thus exerting tension via intermediate filaments on the cytoskeleton, organelles and the nucleus (Milner et al., 1999). Changes in the intracellular concentrations of ions and metabolites during repeated muscle contraction are also implicated in the activation of signaling pathways (Booth & Baldwin, 1996). These signals include intracellular calcium, hydrogen ions produced during anaerobic exercise, the marked reduction in phosphorylation potential of the adenylate system (ATP/ADP_{free}), a depletion of the redox state (NADH/NAD) and hypoxia. Among all these factors, an imbalance between energy requirement and energy supply is possibly the most important signal that triggers appropriate adjustment of contractile and metabolic protein expression (Green et al., 1992). Finally, recent years have seen significant advances in our understanding of the signaling mechanism by which the information contained in specific action potential patterns alters transcription within muscle fiber nuclei (Yan et al., 2001). For example, Ras-mitogen-activated protein kinase (Murgia et al., 2000) and calcineurin (Serrano et al., 2001) signaling are implicated in the α-motor neuron induction of slow muscle fiber phenotype, but not muscle growth. Conversely, a protein kinase β-dependent and rapamycin-sensitive pathway controls myofiber growth but not fiber type specification (Pallafacchina et al., 2002).

Specific genes known to undergo altered expression following contractile activity include those encoding sarcomeric and cytosolic proteins and enzymes of the glycolytic pathway, TCA cycle, the electron transport chain and fat oxidation (Williams & Neufer, 1996). Additionally, signals inducing the expression of proteins derived from mitochondrial genes are coordinated with the activation of the various nuclear genes that encode mitochondrial proteins.

The factors that promote angiogenesis in skeletal muscle in response to training have not been clarified although they may be related to a chronic increase in muscle capillary blood flow and the corresponding endothelial shear stress, as well as increased capillary wall tension (Hudlicka et al., 1992). Hudlicka and colleagues speculated that endothelial stress might disturb the luminal surface, resulting in the release of bound proteases that damage the basement membrane and contribute to an increase in basic fibroblast growth factor release (Hudlicka et al., 1992). Subsequently, growth factors may enhance vascular growth and satellite cell proliferation (Morrow et al., 1990). Still unclear, however, is the influence of training intensity and duration on neovascularization and the mechanisms that underlie the increase seen in intramuscular substrates in response to long-term endurance training. These latter adaptations may be related to either 1) increased glucose and FFA availability (via GLUT-4 and albumin respectively), 2) a lower utilization of these substrates for energy production or 3) possible artifacts imposed by experimental design (e.g. they may be a reflection of increased dietary intake of soluble starches and fat from a parallel change in diet in horses in training (Snow & Valberg, 1994)).

Implications of training-induced changes to the physiologic response to exercise

The main physiologic consequence of increased muscle mass in response to training is to produce a muscle with a greater peak force capacity, because force output is proportional to total cross-sectional area of the fiber mass recruited (Bottinelli & Reggiani, 2000). At slow speeds, this adaptation has an impact on gait, causing a marked reduction of both stance time and stride duration (Rivero et al., 2001). This adaptation significantly affects the performance of show jumpers via enhanced power output from the hindquarters (Rivero & Letelier, 2000). Furthermore, because increased power output results in a greater ability to accelerate and may increase stride length, these training adaptations (strength rather than endurance) may be important for racehorses competing over short distances (Snow & Valberg, 1994). However enhanced power through training comes with the cost of a corresponding decline in aerobic potential, because the increased mass of recruited fibers and concomitant rise in ATP utilization occur simultaneously with a relative inability of oxygen to diffuse into the larger fibers (Essén-Gustavsson et al., 1989).

From a physiologic standpoint, remodeling of myofiber phenotype with minimal or with no hypertrophy in response to training, produces a muscle that is much more resistant to fatigue but with decreased maximal shortening velocity: the former corresponding to each myofiber's increased oxidative capacity, and the latter, to the increased expression of slow MHC and other contractile protein isoforms (Rome et al., 1990). In a similar but reciprocal fashion to that described for strength training, some conventional training programs of young racehorses produce a decrease in the size of type II fibers (Ronéus et al., 1993) and a corresponding decline of both speed and force of contraction (Valberg, 1996). Clearly a balance must be acquired at a level deemed most appropriate for the intended use of the horse (see below).

Following endurance training, exercise at submaximal intensity is facilitated by optimal delivery of oxygen and blood borne substrates, early activation of oxidative metabolism with low utilization of endogenous carbohydrates and increased reliance on fat oxidation as an energy source. The increased oxidative capacity observed in skeletal muscle after training occurs concurrently with increased maximum oxygen uptake (Tyler et al., 1998) and a significant reduction in the net rate of muscle glycogenolysis and anaerobic metabolism (Geor et al., 1999). As a consequence, in the trained state the speed at which a horse begins to accumulate lactate increases gradually (e.g. there is a delay in the onset of lactate accumulation and ATP depletion; Ronéus et al., 1994; Valberg, 1996; Rivero, 1997). This is accompanied by enhanced muscle buffering capacity and more efficient excitation–contraction coupling. Hence collectively, endurance may be enhanced by a wide variety of related factors that delay the onset of fatigue during anaerobic exercise and, although relative sparing of muscle glycogen underlies the delay in fatigue onset during this type of exercise in the trained state, it is likely that all the metabolic adaptations summarized above combine to increase endurance.

Although controversial then, it is clear from extensive scientific literature that equine skeletal muscle has considerable potential to adapt during training, and overall, that these adaptations have important functional implications affecting stamina, strength and speed (Table 13.2). Ideally therefore, conditioning programs of athletic horses should promote characteristics that optimize equilibrium between these physiological traits (Snow & Valberg, 1994; Rivero & Piercy, 2008). While interpreting Table 13.2, first note that certain changes occur together, whereas others occur independently. For example reduced intrinsic muscle shortening velocity occurs together with increased endurance capacity following IIX → IIA fiber transition, whereas increased aerobic muscle enzyme activities are never associated with decreased mitochondrial volume. Second, note that certain changes precede others: for instance, aerobic metabolic adaptation occurs prior to any structural adaptation. Thus significant increases in muscle glycogen concentration occur after only 10 consecutive days of training (Geor et al., 1999), whilst a significant degree of type II–type I fiber type conversion needs much longer (8 months; Serrano et al., 2000). Third, adaptations are cumulative and dose-dependent, but there is an upper limit above which further adaptations do not occur, even when the stimulus continues (Tyler et al., 1998). Most relevant training adaptations then, occur in the first 3–4 months: prolonging training beyond this period, although improving aerobic capacity, reduces anaerobic capacity and has no effect on strength. Simultaneously, the risk of overtraining increases. Finally, certain adaptations to training are reversible, tending to return to the pre-training situation when the stimulus is stopped.

Table 13.2 **Summary of main muscular adaptations to training reported in horses and their functional significance for endurance, strength and speed**

Muscular adaptations	Physiological traits		
	Stamina	Strength	Speed
Morphological adaptations			
Muscle fiber hypertrophy	−	+++	+
Muscle fiber atrophy	+	−−−	−
Increased number of capillaries	+++	nc	nc
Increased mitochondrial volume	+++	nc	nc
Increased myonuclear density	nc	+++	nc
Metabolic adaptations			
Increased aerobic muscle enzyme activities	+++	nc	nc
Increased glucose and fatty acid transport	+++	nc	
Increased muscle (glycogen) and its sparing during exercise	+++	nc	nc
Increased muscle (triglycerides)	+++	nc	nc
Decreased post-exercise muscle (lactate)	+++	nc	nc
Increased anaerobic muscle enzymes	nc	nc	+++
Decreased anaerobic muscle enzymes	nc	nc	−−−
Increased muscle (high-energy phosphate)	nc	nc	+++
Increased muscle buffering capacity	+	nc	+++
Contractile adaptations			
Unidirectional IIX→IIA→I fiber type (MyHC isoform) transition	+	nc	−−−
Bidirectional IIX→IIA←I fiber type (MyHC isoform) transition	+	nc	−−−
Increase of IIA:IIX fiber type (MyHC isoform) ratio	+	nc	−−−
Increase of I:IIA fiber type (MyHC isoform) ratio	+	nc	−−−
Increase of IIA:I fiber type (MyHC isoform) ratio	−	nc	+++

The symbols +++ and −−− indicate primary implication (positive and negative, respectively) towards the particular characteristic; + and −, secondary implication (positive and negative, respectively); nc: no contribution to the particular characteristic.

As stated earlier, the response of equine muscle to training depends on two sets of factors: 1) the basal status of the muscle, (determined by the breed, age, sex and level of fitness of the horse) and 2) the stimulus applied (e.g. type, intensity, duration, frequency and volume of the training exercise). Unfortunately, little is known about the relative influence of most of these factors. For example, only a few studies compare muscular adaptations that occur with different training programs. Of these, two studies (with contradictory results), examine the influence of different exercise intensity (Sinha et al., 1993; Eaton et al., 1999), and only one study has examined the combined influence of intensity and duration (Gansen et al., 1999). This latter study concluded that low intensity exercise (~50% of V4) for long duration (45 min) was, after 6 weeks, more effective in improving aerobic capacity exercise than high-intensity exercise (~100% of V_4) of moderate duration (25 min). Recent years, however, have seen the publication of several experimental studies with well-documented exercise protocols (Table 13.3). From these it seems that moderate to high intensity (~80–100% of VO_{2max}) exercise of short duration (5–10 min) improves both stamina and strength in racehorses following 12–16 weeks of training (Tyler et al., 1998; Miyata et al., 1999), whereas anaerobic capacity, can only be increased in the short to mid term (up to 16 weeks), by introducing supramaximal intensity exercise (~100–150% of either VO_{2max} or V_4) of short (2 min) to moderate (15 min) duration (Rivero et al., 2002; Yamano et al., 2002; Eto et al., 2004). Interestingly, adaptation occurs more readily in younger (~2 year old) than in mature racehorses, e.g. muscular adaptations compatible with a combination of improved stamina, strength and speed were reported in young Thoroughbreds following exercise of high (~100% of VO_{2max}) to very high (~165% of VO_{2max}) intensity and short duration or distance (1.6–5.3 min; 1 600–3 600 m) 5 days/week for 16 weeks (Yamano et al., 2002).

In general though, it seems clear that improved stamina through enhanced aerobic capacity is the most common response of equine skeletal muscle to training, regardless of either the basal status of the muscle or the training-exercise program. Given that many equestrian disciplines, including Thoroughbred racing, are largely aerobic in nature, this underlies the likely benefit of training to the equine athlete.

Tendons and ligaments

Introduction

A great proportion of locomotor injuries in equine athletes involve the flexor tendons, accessory ligaments and the suspensory ligament. The injuries occur both in training and during athletic competition, resulting in significant wastage, with consequent financial and welfare implications (Rossdale et al., 1985; Williams et al., 2001).

The extent of clinical pathological change can range from a minor disruption of a small number of fibrils to complete catastrophic rupture of the tendon. However, the last event is unlikely to occur without preceding preclinical injury and changes to the matrix at a molecular and ultrastructural level occur before clinical injury is evident, making tendon damage from frequent cumulative microtrauma into the most frequent cause for tendon injury (Kannus & Josza, 1991; Selvanetti et al., 1997).

Table 13.3 Physiological implications of muscular adaptations in various training programs scientifically evaluated in horses

Horses		Conditioning parameters				Functional significance			Reference
Breed	**Age**	**Intensity**	**Duration (distance)**	**Frequency**	**Volume**	**Stamina**	**Strength**	**Speed**	
Thoroughbred	4–8 years	~55% VO_{2max}	60 min (~13–14 km)	Daily	10 days	+	Ni	–	Geor et al., 1999
Thoroughbred	2–9 years	~80% VO_{2max}	3 min (1500 m) × 2	6 days/week	6 weeks	+	Ni	–	Sinha et al., 1993
Thoroughbred	5–7 years	~80–100% VO_{2max}	5 min (× 2)	5 days/week	12 weeks	Ne	Ni	++	Eto et al., 2004
Thoroughbred	2–3 years	~100–165% VO_{2max}	1.6–5.3 min (1600–3200 m)	5 days/week	16 weeks	++	+	–	Miyata et al., 1999
Thoroughbred	2 years	~100–165% VO_{2max}	1.6–5.3 min (1600–3200 m)	5 days/week	16 weeks	++	+	+	Yamano et al., 2002
Standardbred	3–5 years	~60–100% VO_{2max}	6–12.5 min (~3–9 km)	5 days/week	16 weeks	++	++	Ne	Tyler et al., 1998
					32 weeks	++	+	–	
Standardbred	2 years	~100–140% V_4	15 min	2nd day	5 weeks	+	–	+	Rivero et al., 2002
		~65% V_4	60–90 min	2nd day					
Arab	8.6 years	~80% V_4	50–80 min (~10–20 km)	3 days/week	12 weeks	+	+++	–	D'Angelis et al., 2005
Andalusian	~4 years	~25–30% V_4	45–60 min	5 days/week	12 weeks	+	+	–	Serrano et al., 2000
		~50–60% V_4	75–120 min		32 weeks	+++	+	–	

Intensity is expressed as a fraction of either VO_{2max} (velocity at maximal aerobic capacity) or V_4 (velocity inducing a blood lactate concentration of 4 mmol/L). The symbols + and – indicate that either the muscular adaptations to training had a positive or negative effect respectively towards the particular characteristic; the number of symbols is proportional to the magnitude of the adaptation; Ne, no effect; Ni, not investigated.

Lesions in the superficial digital flexor tendon (SDFT) of the horse are very similar to injuries seen in the human Achilles tendon, in the quadriceps tendons of jumping athletes and also the degenerative changes occurring in the rotator cuff of the shoulder. Thus, the horse may provide a natural model of tendon degeneration from which the underlying biological mechanisms and pathological processes of a number of tendon and ligament lesions, resulting from both exercise and aging, may be elucidated.

Recovery from tendon injury is protracted and incomplete; once injured, the tendon is permanently compromised to a greater or lesser extent (Watkins, 1999). Treatments are numerous and, although recent cell-based therapies have shown encouraging results (Smith, 2008), not one approach thus far has resulted in completely restoring the functional capacity of an injured tendon. Rehabilitation is thought to be one of the most important components of the treatment regimen. Consequently, an appreciation of the mechanisms involved in the response of normal tendon to physical training could have implications for developing rehabilitation strategies in the management of tendon injuries.

In most competition- and racehorses there is a high predisposition to injury in the SDFT and, to some extent, the suspensory ligament of the forelimb. In dressage horses many injuries in the suspensory ligament of the hind limb are seen. In addition to biomechanical predisposition resulting from individual conformation, external mechanical influences such as track surface contribute to injury risk. In some racetracks in Japan a change in track surface has led to a great increase in tendon injury, while reducing the influence of bone fractures.

The methods used in training to condition tendons are for the most part based on a traditional empirical approach. Trainers often describe the effect of training as 'hardening' the tendons, yet changes do not appear to be related to biological events within the tendon structure. The response of tendons to load and thus to training may also differ between specific tendons that have different biological functions (Birch et al., 1997a; Goodman et al., 2004). The incidence of injury being related to particular tendons suggests that the predisposition is associated with a specific function. The extensor tendons, together with the deep digital flexor tendons (DDFT) have, in general, a low incidence of failure in equine athletes (apart from the navicular area of the DDFT that has received much attention in recent years because of the advent of sophisticated diagnostic methods such as high-field magnetic resonance imaging (MRI) and contrast-enhanced computed tomography (CECT) (Dyson & Murray, 2007; Puchalski et al., 2007), whereas the SDFT and the suspensory ligament have a very high incidence of injury.

With exercise, and particularly elite athletic performance, the different functional requirements will result in the need for changes in the composition and structure of tendons. It is this relationship and the mechanisms controlling it that are important in conditioning horses for peak performance while minimizing injury risk. In the following part first a brief overview of structure and function of tendons will be given with special attention to the reaction of tendons to mechanical challenge. After that, sections will follow on the response of tendon tissue in juvenile and older horses to imposed exercise.

Tendon composition and structure

Tendons consist of a relatively small cellular fraction and a correspondingly large extracellular matrix (ECM), which is composed of densely packed and hierarchically arranged collagen filaments, embedded in a hydrophilic, proteoglycan rich matrix that provides tendons with characteristic viscoelastic properties (Goodship et al., 1994). Collagen is the main component of the ECM (60–85% of the dry mass of a tendon), of which type I is predominantly present, accounting for 95% of the total collagen content (von der Mark, 1981; Williams et al., 1980). Collagen type III represents 3% of total collagen and minimal concentrations of several other types can be found (Riley, 2004). The basic structural unit of collagen is tropocollagen, a triple-helix of polypeptide chains. Five tropocollagen molecules pack together forming collagen microfibrils, which are organized into the larger structural units of the tendon: fibrils, fibers, sub-fascicles (primary fiber bundle), fascicles (secondary fiber bundles), tertiary fiber bundles and the tendon itself (Kastelic et al., 1978; Wang, 2006) (Fig. 13.20).

In the relaxed state the fascicles show a planar wave form or 'crimp', which can be well demonstrated using plane polarized light microscopy (Gathercole & Keller, 1991). It is the crimp that, by flattening out, causes the initial, nonlinear load/deformation behavior of the tendon. Intra- and interfibril collagen cross-links can be formed after enzymatic transformation, such as hydroxylysylpyridinoline (HP) and lysylpyridinoline (LP) cross-links or via non-enzymatic glycation (NEG), of which pentosidine cross-links are the best-known examples. Cross-linking is essential for the stability of collagen fibrils and HP cross-links contribute significantly to the biomechanical properties of a tendon (Parry, 1988; Tsuzaki et al., 1993). The level of NEG products is closely related to the remodeling rate of tendon tissue. NEG products are formed in a time-dependent fashion via the so-called Maillard reaction (Sell et al., 1991; Vlassara et al., 1994). In metabolically active tissues they are broken down in the process of tissue turnover and thus remain at a constant level. However, in tissues with a very low turnover rate they will accumulate and can therefore be used as an estimate of tissue age (Verzijl et al., 2000).

The major non-collagenous constituents of tendons are water (~65% of wet weight) and proteoglycans (PGs, ~1% of dry weight). PGs are composed of a core protein to which one or more sulphated glycosaminoglycans (GAGs) are covalently attached. The strongly negatively charged and therefore hydrophilic GAGs attract water molecules and the collagen network prevents the tissue from expanding beyond its limits, thus giving the tissue an intrinsic tension and its characteristic viscoelastic properties (Scott, 1995). Besides this direct effect PGs are also known to have an effect on fibrillogenesis and matrix architecture (Iozzo, 1998), thus indirectly influencing tensile strength (Garg et al., 1989). The content and types of proteoglycans vary between biomechanically differently loaded areas within the SDFT (Micklethwaite et al., 1999).

Fibroblast-like cells account for 90–95% of all cells in tendons. They have been histologically classified as tenoblasts and tenocytes and are important for the production, organization and maintenance of the extracellular matrix (Kannus, 2000). Tenoblasts are immature, ovoid to spindle-shaped tendon cells, with a high metabolic activity. As they mature, tenoblasts transform into tenocytes with a more flattened, slender appearance. Tenocytes show a lower metabolic activity, due to their lower nucleus-to-cytoplasm ratio, than tenoblasts (Kannus, 2000). Tenocytes are able to adjust their shape and metabolic activity with respect to the production of extracellular matrix components (Robertson, 1994). Different types of loading (compression, tension) elicit different types of metabolic response (Arnoczky et al., 2007; Gillard et al., 1979). The whole tendon is surrounded by the paratenon, a layer of loose connective tissue that allows movement of the tendon in relation to the surrounding tissues. The tendon itself is encapsulated in a fine connective tissue sheath called epitenon that contains vascular, lymphatic and nerve supplies to the tendon. This layer penetrates deep into the tendon as the endotenon covering the tertiary fiber bundles (Kastelic et al., 1978). Tendons can be covered by a synovial sheath in areas where the mechanical loading is not parallel to the longitudinal axis of the tendon (Jozsa & Kannus, 1997).

Blood vessels enter tendons at three main sites: the so-called intrinsic system at both the myotendinous junction and the osteotendinous insertion and the extrinsic system via the paratenon or the vincula within synovial sheaths (Carr & Norris, 1989). The ratio of blood supply from these sources differs between different tendons, but the extrinsic route is usually the most important,

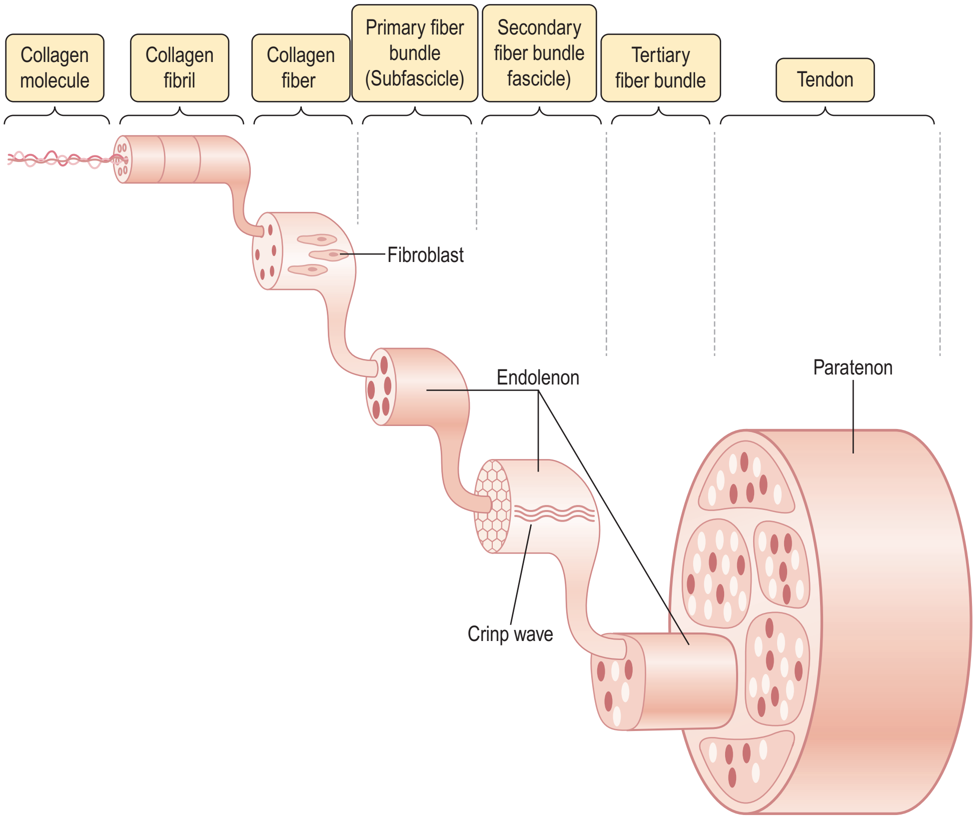

Fig 13.20 Schematic diagram representing the hierarchical structure of tendon.
Modified from Wang et al. (2006).

especially in areas distal from the myotendinous junction and close to the insertion on the bone (Carr & Norris, 1989). The blood supply of tendons, which is already scarce, decreases further with increasing age and mechanical loading (Astrom, 2000).

Tendon biomechanics

During the stance phase of the stride cycle flexor tendons are loaded under tensile stress with loads that may attain easily two times body weight, depending on the gait (Schryver et al., 1978). The tendons are able to store much of the kinetic energy when they are loaded during the first half of the stance phase as elastic energy and release it during the second half of the stance phase where it aids in propulsion. In fact, flexor tendons act basically as energy saving elastic springs, while the main function of the flexor muscles is to damp this spring-like action (Wilson et al., 2001). This energy saving role of tendons is also utilized in other species and is perhaps most evident in the kangaroo, which is able to increase speed without an associated increased oxygen uptake (Morgan et al., 1978), by utilizing the large Achilles tendons as springs.

Optimization for this role results in very low failure safety margins compared with other less mass-critical structures of the musculoskeletal system; consequently, at peak performance levels, functional strains are close to failure strains (Fig. 13.21). Functional tensile strains in equine flexor tendons have been recorded *in vivo*. Tensile strains measured were approximately 3% at the walk, 6–8% at the trot and 12–16% at the gallop (Stephens et al., 1989). Laboratory testing showed that the SDFT of horses will rupture at a level of 12–16% in the Thoroughbred (Wilson, 1991) and at approximately 12.5% in the Warmblood (Riemersma & Schamhardt, 1985).

The relationship between load (stress) and deformation (strain) of elastic structures, such as flexor tendons can be graphically depicted in a so-called stress–strain curve (Fig. 13.22) (Jozsa & Kannus, 1997). This curve has four distinct regions. The initial concave portion of the curve (toe region) (I) represents the straightening of the crimp wave, where minor loading results in a considerable elongation until about 3% strain (Evans & Barbenel, 1975). Beyond this point, tendons deform in a linear fashion as a result of sliding of collagen molecules and fibrils and the fibers become arranged in a more parallel fashion. If the strains do not exceed 4–5% the tendon behaves in an elastic fashion and changes are still completely reversible. The gradient of this almost linearly elastic part of the curve (II) represents the tensile stiffness or elastic modulus (EM) of the tendon (EM = Δstress/Δstrain). In the third region (III) higher strains, up to 8%, will result in dissociation of fibrils due to interfibrillar bond failure, which causes a plastic deformation and microscopic failure (Evans & Barbenel, 1975; Jozsa & Kannus, 1997). With further increasing strains larger tendon bundles start to fail and macroscopic failure occurs (region IV) (Jozsa & Kannus, 1997). The strain at which each phase occurs differs in functionally distinct tendons; tendons with a spring-like function experience higher strains before plastic deformation occurs.

Cyclical loading of a tendon, to a level not reaching yield, in a materials testing machine over a period of time shows two phenomena that are relevant to the effects of exercise in the short term. First, as shown in Figure 13.23, there is a shift of the load–deformation curve to the right with each successive loading cycle until eventually a steady state is reached. This is known as 'preconditioning' and, although it is a feature seen in laboratory testing of tendon; it may have *in vivo* relevance in relation to 'warming up' prior to peak athletic performance. Secondly, as illustrated, the plot of loading followed by unloading of the tendon forms a loop, starting and finishing at the same point. The loop, termed hysteresis, is formed as a result of the elastic recoverability of the tendon being less than

Fig 13.21 Flexor tendons are heavily loaded during high-level equestrian activities.

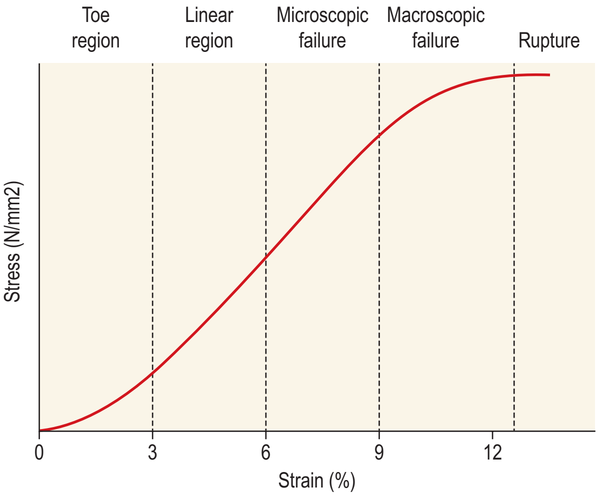

Fig 13.22 Stress–strain curve; the relationship between stress generated by a certain force applied to a tendon and the resulting elongation (strain).

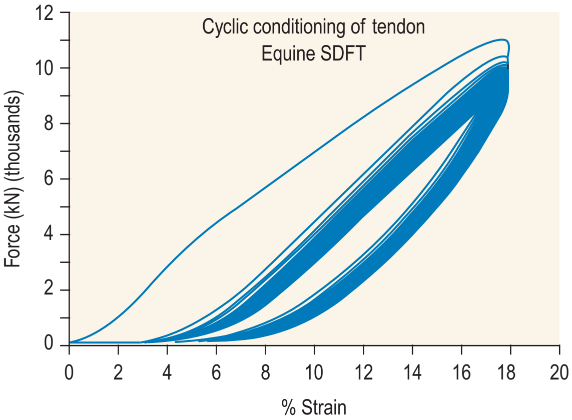

Fig 13.23 Cyclical loading of a tendon within the elastic range. After the first cycle, the tendon will be longer at zero force than originally. In the following cycles this phenomenon repeats, but to a much smaller extent until a steady state is reached. This is called preconditioning. The loops are open because of hysteresis: more energy is required to stretch the tendon (left arm of the loop) than is released when relaxing (right arm). The deficit is dissipated as heat.

100%. The area of the loop represents loss of energy, largely in the form of heat, which occurs during stretch and release of the tendon. It has been shown that the internal temperature of the SDFT may rise to 45–47°C during 7–10 min of peak performance (Wilson & Goodship, 1994). Although this level and duration of hyperthermia would normally result in the death of most cell types, tenocytes within the inner core of the SDFT are able to withstand much higher temperatures than most other fibroblast-like cells (Birch et al., 1997b). It is possible, however, that hyperthermia, although being not lethal for these cells, still plays a role in the initiation of degenerative processes as often seen in the core region of the SDFT.

It is clear that the biomechanical characteristics of the tendon are determined by tendon composition and ultra-structure, as outlined above. As long as the tissue is homogeneous, deformation (strain) will occur evenly. Riemersma and Schamhardt (1985) showed that the strain at different levels of the SDFT is uniform, despite differences in cross-sectional area. As a function of both age and exercise changes in matrix composition and associated functional properties occur. Furthermore tendon injury will lead to significant local changes in tissue properties and thus in non-homogeneous biomechanical behavior.

Effects of exercise

Tendon tissue is responsive to loading, giving the biomechanical environment an important role in the determination of tendon composition and structure. This is best shown by the regional differences in molecular composition of the SDFT. The mid-metacarpal area, which is exclusively subjected to tensional loads, has a high collagen content and typically has a resident population of slender, elongated tenocytes, whereas the area that wraps around the fetlock and sustains compressive loads in addition to tensile forces, contains relatively less collagen, more glycosaminoglycans and rounded tenocytes, taking a more chondrocyte-like appearance (Lin et al., 2005a). Also, the content of cartilage oligomeric matrix protein (COMP) is higher in this region. Cells in tensional regions of tendons thus synthesize predominantly collagen, whereas cells in regions of tendons that wrap around bone produce collagen type II and other matrix components typical of the fibrocartilaginous matrix seen in these areas of compression. Interestingly, this appears to be a dynamic and reversible process. In a study where the compression region of the deep digital flexor tendon was released from compression and subjected to tensile forces, the nature changed from fibrocartilaginous to fibrous type I collagen (Gillard et al., 1979).

The horse is a precocial animal that loads its musculoskeletal system within a few hours after birth and will remain doing so throughout its life. This, together with the responsiveness of tendon tissue to loading, makes it difficult, if not impossible, to discriminate between the effects of growth, maturation and eventually ageing, and exercise, especially with respect to the energy-storing tendons and ligaments that are the subject of most studies, as they sustain by far most injuries and in fact are the only ones that are clinically relevant. However, there have been a number of studies focusing specifically at ageing or the effect of well-controlled exercise protocols that have increased our insight in the complex interaction of the equine tendon with its biomechanical environment.

The effects of ageing on tendon tissue

During embryonic development the collagen fibrils of the tendon that are formed are small in size (diameter approximately 40 nm) and all have a more or less similar appearance. This is called a unimodal distribution. During maturation this distribution changes into a bimodal one through the development of larger size fibrils (diameter up to 250 nm). Although there may be differences in the timing of this process between precocial species, such as the horse, and altricial species, such as the rat and man, this appears to be a universal mechanism that has been demonstrated in all mammals that have been examined (Parry et al., 1978) and is thought to be an adaptation to biomechanical challenges in the postnatal environment. The fibril distribution pattern can be quantified in terms of collagen fibril index and mass average diameter (Flint et al., 1984) and has been shown to reach mature levels in the Thoroughbred by 2 years of age (Patterson-Kane et al., 1997b). The changes in fibril profile may be related to changing GAG or COMP levels. Levels of these molecules change during development (Cherdchutham et al., 1999) and both have been implicated in the regulation of fibrillogenesis (Parry et al., 1982; Smith et al., 2002). In fact, all biochemical components, including collagen and DNA as a measure for cellularity, have been shown to change significantly during early life, also in the absence of specific exercise regimens (Cherdchutham et al., 1999). A study using material from horses aged 0, 5, 12 and 36 months showed that changes in matrix composition occur fastest in the early juvenile period. Interestingly, the study also showed that, in contrast to articular cartilage, tendon tissue is not biochemically 'blank' (e.g. homogeneous) with respect to region (tension or compression) at birth, possibly due to intrauterine movements (Lin et al., 2005b). In another study it was shown that the levels of the gap junction proteins Connexin 43 and 32 (Cx43; Cx32) were significantly higher in fetal tendons than in tendons from other age classes (Stanley et al., 2007). Gap junctions play a role in intracellular communication, which may correlate with synthetic responsiveness that is known to be highest in very young animals. Cartilage oligomeric matrix protein (COMP) seems to be of specific interest with respect to its sensitivity regarding biomechanical loading. In the tensile regions of tendons levels rise from birth to peak at around 2 years of age, after which they decline. However, in the compression region of the tendon COMP levels plateau at about 5–7 years of age after their initial increase and remain stable after that (Smith et al., 1999). In a single case of a foal with a fractured limb, COMP levels were shown to have increased dramatically in the sound limb that was loaded more than normal, but not in the unloaded fractured limb that was immobilized in a cast (Smith et al., 1997).

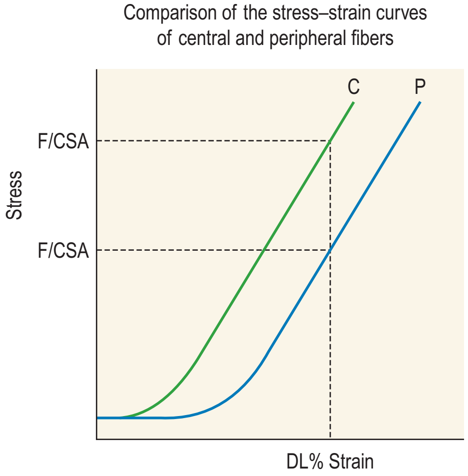

Fig 13.24 A load/deformation plot of collagen fibers from central and peripheral regions of the superficial; digital flexor tendon in an old horse, illustrating the effect of a lower toe limit strain on the greater increase in stress with extension experienced by the central fibers.

Reproduced from Wilmink et al. (1992).

There are also changes in crimp angle with age and these depend on the location within the tendon. In older horses, particularly with some history of exercise, the crimp characteristics were significantly different between peripheral and central core regions of the tendon. In older horses, a reduction in crimp angle in the core region can be observed that makes stress increase at a greater rate than in peripheral fibers (Wilmink et al., 1992) (Fig. 13.24). This seems to be a naturally occurring phenomenon, as similar age-related changes have been observed in wild horses subjected to 'natural' levels of exercise (Patterson-Kane et al., 1997a) and might be a (partial) explanation for the higher incidence of central core lesions than of peripheral lesions in the equine SDFT. In an *in vitro* study using tendon explants, Dudhia et al. (2007) showed that tissue from older individuals (10–30 years) was more susceptible to weakening by cyclical loading than specimens from younger individuals. This effect was possibly due to increased MMP activity and may be related to the age-related changes alluded to above.

The effects of exercise on tendon tissue

There seem to be three major factors that determine the effect of exercise on tendons. These are the type of tendon, the age at which the exercise is given and the level of background exercise.

An increase in biomechanical loading in the form of the imposition of an exercise regimen will elicit an adaptive response in most musculoskeletal tissues, resulting in increased tissue mass and related strength. This general principle seems to apply to ligaments and extensor tendons (Woo et al., 1982, 1987; Newton et al., 1995), but not or to a much less extent to flexor tendons (Birch et al., 1999), probably because a substantial increase in the mass of energy-storing tendons will increase the stiffness of the structure and hence hamper its energy conservation function (Smith & Goodship, 2008). If substantial changes in cross-sectional area (CSA) of the SDFT are seen, this is the case in (very) young animals, which seem to be more adaptive than mature individuals. Some degree of exercise seems to be necessary for the proper functioning of tendons, as there is growing evidence that stress deprivation may be as

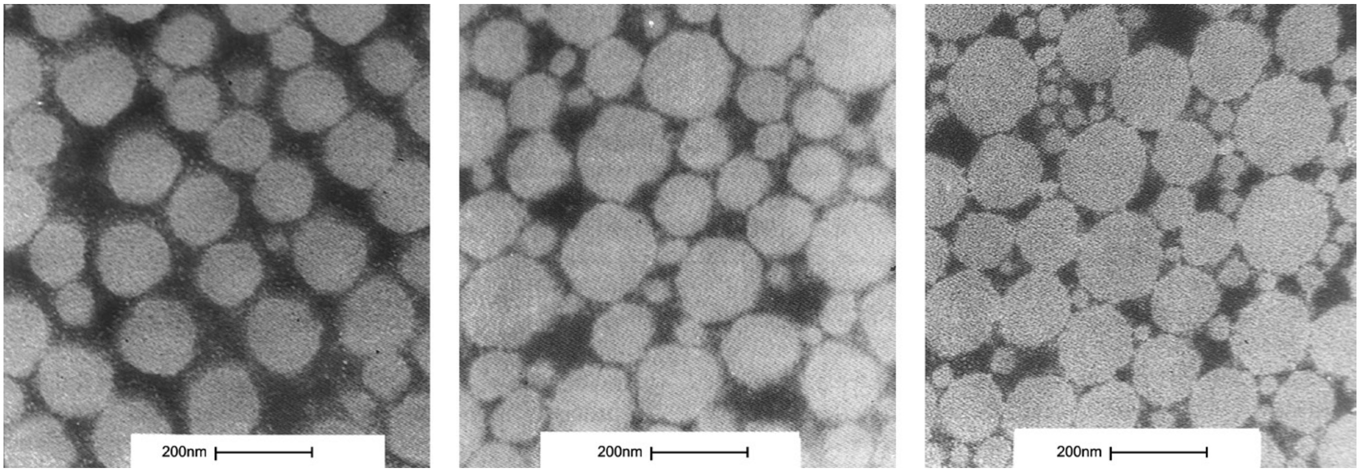

Fig 13.25 (A) Electron micrograph of biopsy from a foal in the pasture group at age 2 months. Note the predominance of thick fibrils. (B) Electron micrograph of peripheral sample from the same foal as in Fig. 13.25B after euthanasia at age 5 months. There is an increase in small-diameter fibrils. (C) Electron micrograph of biopsy from a foal in the pasture group after euthanasia at age 11 months. The number of small fibrils has further increased. This appeared to be not the case in both other groups, indicating that additional exercise did not lead to full restoration of the normal situation.

Reproduced from Cherdchutham et al. (2001b).

deleterious for tendon function as overloading (Arnoczky et al., 2007). In the case of young animals, the amount of this background exercise may be an important factor determining the effect of the exercise regimen.

The largest exercise effect on SDFT CSA has been measured in the EXOC study that has been referred to earlier (van Weeren & Barneveld, 1999a). In this study pasture exercise was compared to box rest and box rest with additional sprint exercise in 0–5 month-old foals. The CSA of the SDFT of foals kept at pasture was significantly greater (by a mean of almost 50%) than of the confined foals and of the foals that were confined and sprinted for a few minutes per day (Cherdchutham et al., 2001a). This means that the background loading as provided by free pasture exercise is an important factor in tendon development in the juvenile animal. This conclusion was supported by a study on collagen fibril characteristics in the same foals. The change from a unimodal to a bimodal fibril diameter distribution was most advanced at age 5 months in the pastured foals and least in the box-rested foals. Additional exercise from 5–11 months led to only partial recovery (Cherdchutham et al., 2001b) (Fig. 13.25).

Further support came from a study in which Thoroughbred foals were exercised on a treadmill from age 2 to 15 months where there was a greater rate of increase in SDFT CSA in the trained animals compared to the controls, but no significant difference at the end of the study due to high variance (Kasashima et al., 2002). Biochemically, COMP was significantly increased in the positional CDET, but not in the energy-storing SDFT. Other matrix components and mechanical properties were not significantly changed (Kasashima et al., 2008). In that study foals did not have continuous access to pasture and the exercise effect was against a background of 'partial' confinement.

In the GERA study that has been mentioned earlier (Rogers et al., 2008a,b) there was no difference in SDFT CSA between the trained CONDEX and the untrained (but pasture exercised) PASTEX animals after an experimental period lasting from age 3 weeks to age 18 months, although there was a trend ($p = 0.058$) towards a larger CSA in the CONDEX group (Moffat et al., 2008).

Whereas there are no data on the effects of exercise on tendons of old horses, various experiments have investigated the exercise effect on tendon characteristics of young-mature horses, often 2-year-old Thoroughbreds.

In the MUGES study alluded to earlier (Firth et al., 2004a) CSA of both the SDFT and the Common Digital Extensor Tendon (CDET) were increased in the trained horses compared to the controls (by 8 and 16% respectively). In the SDFT (but not the CDET) this increase in size was accompanied by a decrease in tissue density. Because no evidence of pathology could be detected, this response was seen as adaptive. There were no changes in mechanical properties of the tendon (maximal load and stress at failure) (Firth et al., 2004b).

In the long-term Bristol study young Thoroughbreds were exercised for 18 months on a treadmill and compared to controls undergoing a much less intensive exercise regimen. There were no differences in collagen content or CSA of the SDFT, but there was a distinct difference in collagen fibril diameter parameters with collagen fibril mass average diameter in the central core region of the trained animals lower than in the control horses (Patterson-Kane et al., 1997c). By determining the level of glycosylation it was evident that the collagen was not newly formed, but a degradation of larger fibrils. Further, mean collagen crimp angle and crimp length were less in the exercised group (Patterson-Kane et al., 1997d, 1998). In contrast to the findings in the SDFT, no exercise-related changes in collagen mass average diameter or collagen fibril index were found in the CDET of these same horses. This observation supported the concept of the functionally distinct nature of the CDET and SDFT, resulting in fundamentally different responses to high-speed exercise (Edwards et al., 2005). It was initially suggested that the changes in the SDFT might not be adaptive in nature, but more indicative of micro-trauma and thus detrimental to tendon function (Birch et al., 1998). In later work the same research group performed detailed biomechanical and biochemical analyses of both CDET and SDFT tissue specimens from animals pertaining to the long-term Bristol study in which no signs of degeneration were found. They concluded that high-intensity long-term exercise on skeletally mature individuals results in changes that suggest accelerated aging in the SDFT and adaptation in the CDET (Birch et al., 2008).

Conclusion

The adaptive response of tendon tissue to exercise is limited. It is clear that the possibility to exercise is crucial to young foals, as lack of exercise in juvenile animals may lead to the development of biomechanically inferior tendons, but little seems to be gained by imposing additional training above a baseline of free pasture exercise. The time window in early life in which the constitution of tendons can be influenced by exercise is short. Already at an age of 11 months the juvenile tendon has biomechanical properties that are similar to those of mature animals (Cherdchutham et al., 2001). This supports the opinion that early competition at young age is not detrimental to horses (Smith et al., 1999). In young-mature animals the adaptive response of flexor tendons is minimal. In the MUGES study a small increase in CSA was observed, but together with a decrease in tissue density and without improvement of biomechanical characteristics. Further, the division line between adaptive response, if any, and degenerative effects is extremely thin. This can be explained by the facts that flexor tendons are known to operate very close to their physiological limit during strenuous athletic activity and that, as energy-storing structures, flexor tendons cannot adapt by a simple increase in size (and thus strength) as other tendons and ligaments and most other tissues of the musculoskeletal system would do. The accurate determination of the delicate balance between the training load that is needed for an optimal preparation of the horse for competition and the load that can be sustained by the SDFT and suspensory ligament, as perhaps the most vulnerable structures of the equine musculoskeletal system, will remain the best prevention against tendon injury and the greatest challenge for the trainer. This endeavor would be greatly facilitated if suitable biomarkers or hyper-sensitive quantitative ultrasonographic techniques would become available that would permit the timely detection of imminent tendon injury.

General conclusion

The musculoskeletal system is the organ system that generates locomotion and is, therefore, together with the cardiovascular and respiratory systems, likely to be influenced by the exercise regimen an individual is subjected to. The actual response of the system is complex, however, and depends on the type of tissue and in some cases even on the specific structure involved. Age is a crucial factor, as exercise may have a different effect on the young, growing animal than in the mature individual. There is enough evidence now to state that physical exercise in young individuals is pivotal for correct development of the musculoskeletal system, which is of great importance for those tissues known not to remodel or to show minimal remodeling at adult age (and related to this have a very limited healing capacity after injury), such as articular cartilage and possibly also tendons (van Weeren et al., 2010; Rogers et al., 2012). However, there is evidence that also in bone, a tissue that is known to respond to exercise and to retain its healing ability throughout life, exercise-induced structural changes may be retained even long after the cessation of exercise (Karlsson, 2007), possibly because of an effect on the underlying collagen skeleton.

Taking the need for exercise for either correct development (in the young animal) or for adequate maintenance of the musculoskeletal system (in the mature individual) as a fact, the question becomes, what would the optimal exercise load be? It has been shown that the amount of voluntary exercise in foals raised with 24 h/day access to pasture is surprisingly similar to what has been observed in foals from entirely free living populations (Kurvers et al., 2006). This, together with the fact that in the EXOC study mentioned earlier the pasture exercised foals developed much better than the foals in the other exercise groups, which were deprived of exercise or were subjected to a combination of box rest with bouts of high-intensity exercise, makes it safe to proclaim that, based on present-day knowledge, free exercise for 24 h/day is the baseline or gold standard for growing foals. This does not mean, however, that this exercise level is by definition optimal for raising all foals, irrespective of future use. There is now evidence that the development of the musculoskeletal system can be manipulated beyond the effects produced by ‘natural’ exercise through the imposition of additional exercise in the young animal. In the case of articular cartilage such intervention led to advancement (and earlier cessation) of the natural process of functional adaptation (van Weeren et al., 2008). No immediate clinical effects were seen in that study, which led to the conclusion that the imposed exercise level was safe (Rogers et al., 2008a). However, the long-term effect on morbidity in the later athletic career could not be established due to low numbers (Rogers et al., 2008b). Later work strongly suggests an overall positive influence of early exercise: epidemiological data from Thoroughbreds have shown that horses in training or racing as 2-year-olds had better musculoskeletal health throughout life than horses starting their career later (Tanner et al., 2013).

In the mature horse attention has focused on the adaptive response provoked by exercise and the thin borderline between these adaptive responses and early damage. No work has been done on the establishment of a baseline workload needed for optimal maintenance of the musculoskeletal system. It is the question whether this lack of interest is justified given the increasing insight that lack of exercise may have an adverse effect on some structures in mature individuals (Arnoczky et al., 2007) and the deleterious effect of a combination of exercise restriction and bouts of heavy, high-intensity loading, an exercise regimen that is all too common for many sports and leisure horses.

It can be concluded that exercise is a must for both the correct development and maintenance of the musculoskeletal system. Restriction of space and of time spent on them means that many horses kept under modern management conditions most probably exercise too little rather than too much. Apart from a severe impact on well-being, this situation is likely to also affect musculoskeletal morbidity rates. Meticulous monitoring and administration of workload and wastage due to illness or injury in the relevant equestrian disciplines in large cohorts of horses over prolonged periods of time and adequate epidemiological processing of these data is the way forward to establish optimal training and conditioning protocols for sport horses.

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CHAPTER 14

Performance in equestrian sports

Hilary M. Clayton, P. René van Weeren

Introduction

The use of horses for different occupations resulted in selective breeding to produce different morphological types in accordance with specific intended uses. Massive draught horses could haul heavy guns and carry medieval knights with their cumbersome and bulky armor, whereas slender, more agile Arabians and Thoroughbreds displayed greater speed and endurance. Today, horses compete is a diverse range of sports each requiring specific athletic talents. For sprinting sports the prime requirements are rapid acceleration and the ability to generate a high maximum speed. Middle distance racing and endurance racing call for stamina to maintain submaximal speed over a longer distance. Other sports depend on different degrees of technical skills, visual acuity, fast reflexes or esthetics of movement.

Over the past half-century, breeders have produced performance horses with highly specialized athletic abilities, such as elegant gaits and efficient jumping technique. Consequently, today's sport horses can truly be described as 'equine athletes', which emphasizes the importance of their locomotor apparatus. This chapter will consider the mechanical factors involved in different types of equine athletic performance under the general headings of racing sports, sport horses and Western sports.

Racing sports

Racing encompasses a broad spectrum of sports that occur over distances from as short as 200 m to greater than 160 km. The common denominator in all these sports is that the winner maintains the highest average speed over the distance of the race. In sprinters, generation of high stride rates is of prime importance. Stride length assumes greater significance for horses racing over middle distances. Economy of movement and energy efficiency are prime considerations in endurance racing competitors.

Speed

Speed is the determining factor in racing, and is also a desirable characteristic in many other sports. Horses change speed by altering the spatial and temporal relationships between the limbs to produce different gaits and to vary the extension within a gait. Each horse has an optimal speed within a gait at which the metabolic cost is minimized; slower and faster speeds both result in a higher metabolic cost (Hoyt & Taylor, 1981). It has been suggested that transitions between gaits may be triggered by energetic cost (Hoyt & Taylor, 1981) or musculoskeletal forces (Farley & Taylor, 1991). Whatever the reason, horses naturally select particular speeds at which to make transitions between gaits.

Within any gait, speed is the product of stride length and stride frequency. In sprinting races, a high stride frequency is the prime requirement; the ability to take longer strides becomes increasingly important as the distance of the race increases (Deuel & Park, 1990). Stride length has been reported to show a rapid and fairly linear increase with speed, whereas stride frequency increased more slowly and in a non-linear manner (Dušek et al., 1970; Leach & Cymbaluk, 1986). In Thoroughbreds galloping at 13.7–19.8 m/s which is approaching maximal speed, Seder and Vickery (2003) reported a linear increases in stride length and stride frequency.

Stride length

Stride length increases with effective limb length. The forelimbs are generally considered to rotate around a point close to the tuber spinae scapulae and the attachment of serratus ventralis, though the precise point of rotation may vary between individuals. The hind limbs rotate around the hip joint in the symmetrical gaits (walk, trot, pace) and around the lumbosacral joint in the asymmetrical gaits (canter, gallop). The advantage of moving the rotation point to the lumbosacral joint is that it increases the effective limb length (Fig. 14.1). Interestingly, a necropsy study showed that 32% of Thoroughbreds had maximal range of motion in flexion–extension at the joint between the fifth and sixth lumbar vertebrae rather than at the lumbosacral joint, and 8% had evidence of sacralization of the sixth lumbar vertebra (Stubbs et al., 2006). Moving the effective lumbosacral articulation more cranially might confer an advantage in terms of further lengthening the hind limb. In the symmetrical gaits, particularly the walk, lateral bending of the vertebral column may enhance stride length, whereas in the asymmetrical gaits dorsoventral flexion and extension make a larger contribution to stride length (Hildebrand, 1962). In horses, the thoracolumbar spine is fairly rigid to provide support for the large body mass and facilitate transmission of propulsive forces from the hind limbs. The need for spinal stability is a priority in gaits that have a suspension phase, which include the racing trot, pace and gallop. Thus, the need for stabilization predominates and intervertebral motion makes a relatively small contribution to stride length in racehorses with the exception of the lumbosacral joint. This is in contrast to smaller animals, such as cats, that make use of a more flexible thoracolumbar spine to increase stride length. For more information on vertebral kinematics, the reader is referred to the chapter on neck and back movements (Chapter 10).

Stride frequency

Stride frequency describes the rate at which the limbs are protracted and retracted. The ability to cycle the limbs rapidly is favored by having a high percentage of fast-twitch fibers in the extrinsic muscles, which influences both the rapidity with which the limbs

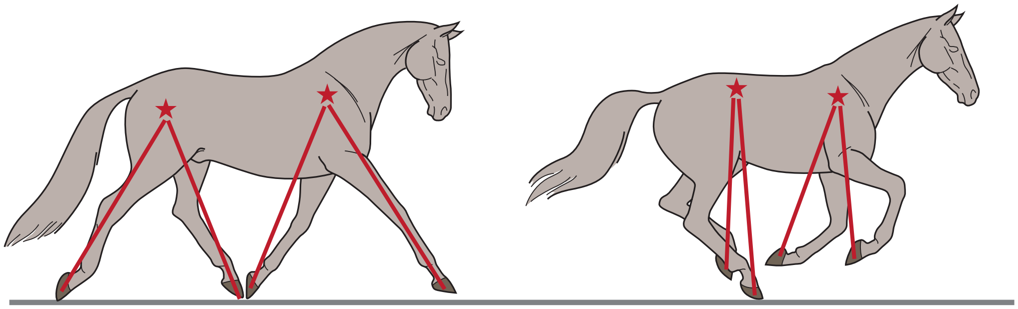

Fig 14.1 Rotation points of the fore and hind limbs are represented by asterisks for the trot (left) and the gallop (right). The forelimb rotates around a point in the upper part of the scapula. The hind limb rotates around the hip joint in trot (left) and around the lumbosacral joint in asymmetrical gaits (right).
Reprinted from The Dynamic Horse with permission of Sport Horse Publications, Mason, MI, USA.

are moved and the ability to generate large forces and impulses during the stance phase. Stance duration is negatively correlated with the diameter of the muscle fibers (Rivero & Clayton, 1996), whereas stride length is positively correlated with the percentages of type I and type IIa muscle fibers, and negatively correlated with the percentage of type IIb muscle fibers in Standardbreds. Stride frequency is positively correlated with the percentage of type IIa muscle fibers (Persson et al., 1991). Stance duration has a negative correlation with the percentage of type IIb muscle fibers (Roneus et al., 1995) that is indicative of an ability to generate high ground reaction forces (GRFs) and so create the necessary impulse over a shorter period of time.

Efficiency of movement

During locomotion, energy is used to move the horse's center of mass and to cycle the limbs back and forth. For sprint races, energy expenditure is relatively unimportant, but as race distance increases beyond the capacity of the anaerobic energy production systems, energetic efficiency has a greater effect on the ability to maintain submaximal speed over a distance. Factors that contribute to locomotor economy include the masses and inertial properties of the limb segments, kinematics, storage and release of elastic strain energy and inter-segmental transfers of kinetic energy (Cavagna et al., 1977).

Segment mass, measured as a percentage of body mass, and its distribution within the segment determine its inertial properties. In horses, heavy muscular tissue is confined to the proximal limb, while the distal limb is composed of less dense tissue including skin, connective tissue, ligament, tendon and bone. This proximal concentration of mass reduces the moment of inertia of the limb and thus facilitates protraction and retraction and reduces the energetic expenditure.

Protraction and retraction of the limbs uses energy and several mechanisms are employed to improve energetic efficiency. The limb is folded during protraction, which brings the distal limb closer to the pivot point, thereby reducing its inertia. The amount of joint flexion and limb folding increase with speed with a consequently higher hoof flight arc (Clayton et al., 2002) (Fig. 14.2). Storage and release of elastic strain energy greatly reduce the metabolic energy requirement (Alexander, 2002). In the first half of the stance phase, the elastic elements are stretched, thereby storing elastic energy. As the body mass rolls over the limb, the elastic tissues recoil, releasing the stored elastic energy, which assists in protracting (e.g. *biceps brachii*) and raising (e.g. superficial digital flexor tendon) the limb. During trotting the fetlock, carpal, elbow and shoulder joints show elastic behavior in the soft tissues that cross these joints (Clayton et al., 1998). The elastic contributions are relatively small at the walk (Clayton et al., 2000) but are much larger during trotting and in cantering and galloping. In the asymmetrical gaits, the elastic lumbodorsal fascia may also contribute to gait efficiency through elastic energy storage and release as the spine flexes and extends (Minetti et al., 1999).

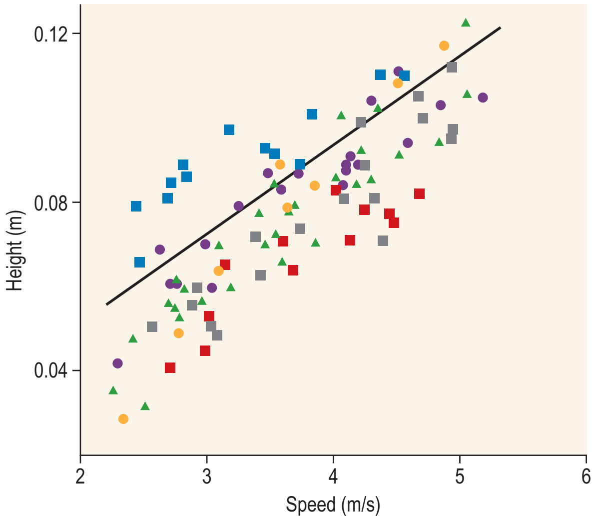

Fig 14.2 Peak height of the hind hoof during the swing phase of the stride in five horses trotting at a range of velocities. Each horse is represented by a different type of data point.
From Clayton et al. (2002).

Quarter Horse racing

The Quarter Horse is the elite equine sprinter and was named for its ability to sprint over a distance of a quarter mile. The most important qualities of a sprinter are rapid acceleration and a high maximal speed. In sprinters speed is more strongly influenced by stride frequency than stride length (Deuel & Lawrence, 1986). This is in contrast to middle distance Thoroughbreds in which speed is altered primarily by changes in stride length (Ratzlaff et al., 1985). Comparing Quarter Horses and Thoroughbreds galloping at 15 m/s, the stride length of the Quarter Horses is shorter by 1.0–2.0 m (Deuel & Lawrence, 1986), with a correspondingly higher stride frequency. The stride variables of 2-year-old Quarter Horse fillies galloping at a mean speed of 13.3 m/s are shown in Table 14.1.

Stride variables

There is no significant covariance between stride frequency and stride length in galloping Quarter Horses, so these variables are regarded as independent factors within the time domain and space domain (Deuel & Lawrence, 1986). As speed increases, stride frequency is increased by shortening the single support periods of the trailing hind limb and leading forelimb, and the duration of the suspension. Linear regression analysis of the data predicts that at 14.9 m/s, overlap between the leading hind limb and trailing forelimb approaches zero. Interestingly, at approximately this speed, two of four horses in the study showed strides with an extended suspension (i.e. a period of suspension between lift-off of the leading hind limb and ground contact of the trailing forelimb) of 4.0–8.0 ms duration (Deuel & Lawrence, 1986). At a constant stride frequency, stride length is adjusted by increasing the distances between footfalls of the trailing and leading forelimbs and between the leading forelimb and the trailing hind limb. In Quarter Horse foals there is a significant correlation between stride length and mass (Leach & Cymbaluk, 1986). Small foals prefer to change speed by adjusting stride length, whereas foals with larger dimensions prefer to adjust their stride frequency.

Sidedness

Two-year-old Quarter Horse fillies show a leading limb preference; approximately twice as many strides were recorded on the right lead versus the left lead in spite of the horses being cued for the left and right leads an equal number of times. The horses either picked up the right lead during the transition or changed from the left to the right lead (Deuel & Lawrence, 1987a). Both speed and stride length were significantly longer on the left lead than the right lead, but stride frequency did not differ between the two leads. The trailing forelimb had a longer stance duration and a shorter period of overlap with the leading forelimb on the left lead, which was interpreted as a sign of an increased reliance on the right forelimb for support. The hind limbs, however, did not show any linear or temporal asymmetries between the left and right leads.

Effect of urging

The effect of urging by the rider was studied by having the rider use a whip on the shoulder of the leading forelimb in rhythm with the stride. Use of the whip did not change the speed, but the horses maintained their speed with a reduced stride length and a higher stride frequency during urging. Also, the stance duration of the forelimbs was reduced (Deuel & Lawrence, 1987b).

Table 14.1 Mean values for stride variables of galloping Quarter Horses (QH) and Thoroughbreds (TB)

Speed (m/s)	Stride length (m)	Stride frequency (strides/s)	Breed
13.3	5.06	2.62	QH
6.6	3.63	1.82	TB
9.9	4.89	2.02	TB
13.8	6.18	2.23	TB
15.8	6.66	2.37	TB
19.8	7.77	2.55	TB

Data for Quarter Horses from Deuel and Lawrence (1986) and data for Thoroughbreds are from Ischii et al. (1989) and Seder and Vickery (2003).

Thoroughbred racing

Thoroughbreds race over short to middle distances, mostly in the range of one to two miles, though shorter and longer races exist. Over the shorter distances, the requirements for acceleration and speed are similar to those for Quarter Horse racing, but as the distance increases stamina assumes more importance. In this breed high maximal speeds are achieved primarily as a result of having a long stride length (Leach et al., 1987). Top class Thoroughbreds galloping at racing speed have had their stride lengths measured at 7.38 m for Secretariat and 6.66 m for Riva Ridge (Pratt & O'Connor, 1976). However, individual horses vary in terms of their preference to increase stride length or stride frequency as they approach top speed. In general, for Thoroughbreds galloping at submaximal speeds, stride length tends to show a decreased rate of increase whereas stride frequency tends to show an increased rate of increase (Yamanobe et al., 1992). Stride lengths and stride frequencies for Thoroughbreds galloping at a range of speeds are shown in Table 14.1 (Ishii et al., 1989).

Stride variables

A study of part-Thoroughbred horses galloping on a variety of surfaces (sand, turf, woodchips, dirt) showed a linear relationship between stride length and speed, with stride length increasing from about 3.5 m at 6 m/s to around 7.5 m at 19 m/s. At the same time, stride duration decreased from 580 ms at 6 m/s to 440 ms at 19 m/s. The reduction in stride frequency was achieved through a large reduction in the swing phase from 200 to 100 ms, and a smaller reduction in the stance phase from 400 to 350 ms (Hellander et al., 1983).

Stride length at the gallop comprises the sum of four inter-limb distances: the hind step, the diagonal step, the fore step and the suspension distance (Fig. 14.3). Alterations in stride length are associated with greater changes in the diagonal distance and the suspension distance than in the hind and fore steps (Ishii et al., 1989). The suspension distance shows the greatest increase at moderate speeds but has a tendency to level off as maximal speed is approached, whereas the diagonal step shows an increasing rate of increase at higher speeds. Lengthening of the diagonal step is a consequence of an increased propulsive force from the hind limbs but there may be an associated increase in forelimb braking force, which, in turn, limits the suspension distance (Yamanobe et al., 1992).

The temporal variables for the gallop stride include periods of single support when one limb only is in the stance phase, periods of overlap when two or more limbs are in the stance phase simultaneously and one or more suspension phases when the horse is airborne. Duration of the suspension phase is highly correlated with stride duration. For Thoroughbreds galloping at 15 m/s, the suspension phase occupies 28% of stride duration (Leach et al., 1987).

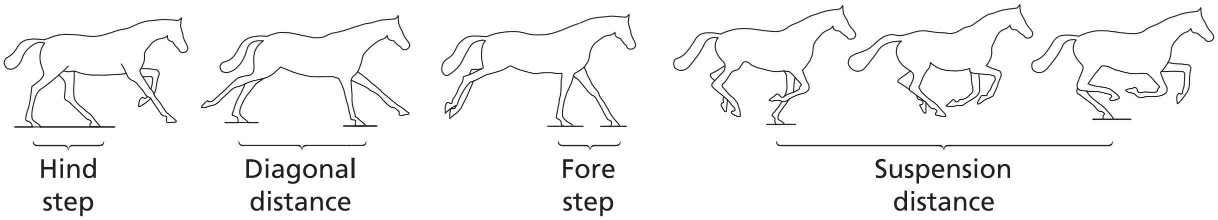

Fig 14.3 Interlimb distances in the gallop. The sum of the interlimb distances is the stride length.

The stance phase durations of the four limbs differ significantly from each other, with the leading hind limb and trailing forelimb having shorter stance durations than the contralateral limbs. Overlap is longest between the two hind limbs, shortest between the two forelimbs, and of intermediate duration between the leading hind-trailing forelimb pair. As galloping speed increases there is a marked reduction in all the overlap durations, with overlap between the leading hind and trailing forelimbs decreasing linearly down to about 50 ms (Hellander et al., 1983). Comparison between the extended canter of horses trained for dressage with horses trained for racing reveals that, at the same speed, there is no difference in stride length or stride frequency, but the racehorses had significantly shorter stance durations and overlap times (Clayton, 1993), which may be a consequence of race training. Following 8 weeks of high-intensity training on a treadmill, the stance duration of galloping Thoroughbreds was reduced by 8–20% (Corley & Goodship, 1994). These changes can be ascribed to greater muscular strength; the ability to generate higher ground reaction forces allows the necessary impulses to be created during a shorter stance phase, and the greater forces project the horse into a prolonged suspension phase. Race training also results in increases in stride duration and stride length (Leach et al., 1987).

The advanced placements (time between footfalls) change in such a manner that, at faster galloping speeds, the hind limbs act more in unison with each other while becoming more dissociated from the forelimbs. Thus the rhythm becomes more like a rabbit hop. As the advanced placement between the leading hind and the trailing forelimbs increases, the distance between placements of these limbs also increases. Dissociation of the actions of the hind limbs and forelimbs causes a greater reliance on spinal flexion and extension. Thoroughbreds traveling at speeds greater than 13.5 m/s may show a short extended suspension between lift-off of the leading hind limb and contact of the trailing forelimb. A third suspension, between lift-off of the trailing forelimb and contact of the leading forelimb, has also been recorded occasionally. The percentage of Thoroughbreds showing multiple suspension phases increases with speed from 27% of horses at 15.5 m/s, to 50% at 17.0 m/s, and 70% at 19.5 m/s. The duration of these suspension phases also tends to increase with speed (Seder & Vickery, 2003).

Head and neck motion

The head and neck, which comprise approximately 10% of body weight, move in synchrony with the limbs. The neck is actively extended and lowered during the hind limb stance phases with the head reaching its lowest point during the propulsive phase of the leading hind limb (Bramble, 1984). This movement may counteract the tendency of the forequarters to rise as a result of hind limb propulsion (Pratt, 1983). Elevation of the head and neck begins as the trailing forelimb contacts the ground, continues through the forelimb stance phases and peaks at lift-off of the leading forelimb.

Lead changes

Horses normally use a transverse gallop in which the leading limb is on the same side of the body for the fore and hind limb pairs. A lead change involves a reversal in the order of placement of the contralateral limb pairs, and Thoroughbreds normally change leads several times during a race. The most common strategy is to use the inside lead through the turns, and the opposite lead in the straightaways. Racehorses usually initiate the lead change with the forelimbs. During the forelimb swing phase the leading forelimb abbreviates the cranial part of its swing phase and is placed early to become the new trailing forelimb. The limb that was the trailing forelimb increases its swing phase duration substantially to become the new leading forelimb. The hind limbs then change their lead in a similar manner during their next swing phase. For one stride (the stride in which the forelimb lead is changed) the sequence of limb placements follows a rotary sequence. Sometimes the hind limb lead is not changed until several strides later, in which case the rotary sequence of limb placements is maintained during the intervening strides; this is also known as being disunited or on a crossed lead.

Acceleration

During acceleration, the initial increase in speed is due to a rapid increase in stride frequency accompanied by a relatively slow increase in stride length (Hiraga et al., 1994). Stride frequency peaks within a few strides after leaving the starting gate, whereas stride length requires 25–30 strides to reach its maximal value. The diagonal distance increases relatively rapidly to reach maximal length within the first few strides. The airborne distance increases linearly after the first few strides until the 20th stride. Forelimb step length and the hind limb step length tend to level off after the 20th stride. Hind step length is very short in the initial strides during which the horses use a half bound before establishing a leading limb for the hind limb pair. The majority of horses use a rotary sequence of limb placements (crossed lead) during the initial acceleration before establishing the normal transverse sequence (Kai & Kubo, 1993; Hiraga et al., 1994). Horses tend to hold their breath for 3–4 s immediately after leaving the starting gate after which they settle into a breathing rhythm that is synchronized with the stride cycle (Kai & Kubo, 1993).

Ground reaction forces

Vertical ground reaction forces have been studied at racing speed in horses galloping round a 0.8-km track with well-banked turns and wearing instrumented shoes on all four feet (Ratzlaff et al., 1987). On the straightaway the greatest vertical force was exerted by the leading forelimb, followed by the leading hind limb, trailing hind limb and trailing forelimb. On the banked turns, the greatest vertical force was exerted on the leading forelimb, followed by the trailing forelimb, leading hind limb and trailing hind limb. It is not surprising, therefore, that the majority of racing injuries occur in the leading limbs, especially the leading forelimb.

Limb kinetics

An early modeling study indicated that each forelimb would support 170% body weight when galloping at 14 m/s (Kingsbury et al., 1978). Subsequent modeling studies, however, have estimated widely different forces in the superficial and deep digital flexor tendons (Brown et al., 2003; Swanstrom et al., 2005b). A detailed musculoskeletal model for dynamic simulation of the Thoroughbred forelimb during the stance phase when galloping at 18 m/s (Swanstrom et al., 2005a) indicated peak vertical ground reaction force of 210% body weight combined with longitudinal forces of 30% body weight (braking) and 63% body weight (propulsion). This model also predicted palmar flexion angles of 148° for the distal interphalangeal joint and 169° for the proximal interphalangeal joint during the first one third of stance and 262° for the metacarpophlangeal joint just before midstance. Angular ranges of motion for these joints were 50° (distal interphalangeal joint), 16° (proximal interphalangeal joint) and 54° (metacarpophalangeal joint). Peak strains in the superficial digital flexor tendon (4.9%) and suspensory ligament (8.5%) occurred prior to midstance, whereas strains in the deep digital flexor tendon (2.8%) and the accessory ligament of the superficial digital flexor tendon (8.8%) peaked around midstance. The accessory ligament of the deep digital flexor tendon had peak strain of 7.1% around the start of breakover. Transection of the accessory ligament of the superficial digital flexor tendon, which is used to treat superficial digital flexor tendonitis, resulted in increased force and strain in other soft tissues, increases in metacarpophalangeal joint extension and distal interphalangeal joint flexion, and a reduction in ground reaction force (Swanstrom et al., 2005a).

Fatigue

Fatigue implies a decrement in performance shown by reductions in stride frequency and running speed. Stride length may increase or decrease depending on the horse. The absolute duration of both the stance and suspension phases of the stride increases, with suspension occupying a greater percentage of stride duration. Footfall of the leading hind is followed more closely by that of the trailing forelimb, and overlap between these two limbs increases during fatigue (Leach & Sprigings, 1979). Since the stride and respiratory cycles are synchronized in galloping horses, it has been suggested that the changes in limb coordination associated with fatigue may be related to the respiratory demands. Prolongation of the suspension phase increases the duration of the inspiratory phase of the respiratory cycle, which may be advantageous as the horse becomes fatigued (Leach & Sprigings, 1979).

Injury

Analysis of racetrack patrol videos (Ueda et al., 1993) has shown that breakdown injuries often occur immediately after a lead change (47% cases), use of the whip (38% cases) or an oblique movement of the horse across the track (21% cases).

Training

An important consideration in Thoroughbred training is the need to stimulate skeletal adaptation without causing injury to the bones and joints. It has been suggested that the training regime should incorporate short sprints on a relatively frequent basis (every 3–6 days) to stimulate bone adaptation, especially with regard to the prevention of bucked shins (Moyer & Fisher, 1991). However, the distance of the sprints must be limited because horses that accumulate extensive distances at high speeds are more likely to suffer a fatal skeletal injury (Estberg et al., 1995). Many complete fractures of the long bones are preceded by incomplete fractures (Stover et al., 1992) indicating that they are a consequence of repeated limb trauma during training and racing.

Track surface

Material properties of the track surface affect both performance and lameness. On a harder surface there is a reduction in stride duration, whereas on a more compliant surface stride duration increases (Fredricson et al., 1983). This offers at least a partial explanation for the fact that faster race times are recorded on firmer track surfaces. However, there is a price to pay in terms of soundness. The incidence of lameness in Thoroughbreds that are in race training increases with the hardness of the track surface (Cheney et al., 1973). One of the factors that affect hardness is the composition and depth of the cushion. Hardness is reduced as the cushion gets deeper, but if the cushion depth is too deep (greater than 10 cm), the footing becomes insecure. Surface moisture content tends to vary, whereas the moisture content of the compacted cushion is more constant (Clanton et al., 1991). There also tended to be more compaction around the starting chutes than in other areas of the track. Next to the rail, track surface was softer than the surface toward the middle of the track.

Dynamic properties of the track, such as hardness, rebound, deceleration rate, rebound rate and penetration, can be assessed with a track-testing instrument. Accelerometers have been attached to the hoof wall for dynamic testing of the track surface (Barrey et al., 1991; Ratzlaff et al., 2005). Lower peak acceleration of the hoof, which increases locomotor efficiency by allowing a smoother transition from braking to propulsion, is achieved by having a deeper cushion or by reducing the dry density of the cushion (Ratzlaff et al., 2005). Hoof-mounted accelerometers (Ratzlaff et al., 2005) indicate wide variations in acceleration from stride to stride on the same surface.

Track surface composition and characteristics have a profound effect on the loading conditions of the horse's limb, with the shear strength of the granular material being particularly influential. Therefore, selection of soil for structure may be more important than the addition of soil amendments that alter damping characteristics (Reiser et al., 2001). Many racing surfaces are a composite of sand, rubber granules and fibers coated with a wax. Horses trained and raced more slowly when the surface reached a temperature of 43-46 degrees at which the lower molecular weight components of the wax melt (Peterson et al., 2010). In one study, a synthetic racing surface was shown to have lower peak accelerations, mean vibrations and peak ground reaction forces than turf or dirt surface (Setterbo et al., 2009). Track maintenance also affects the mechanical properties of the track (Peterson & McIlwraith, 2008).

Standardbred racing

Racing Standardbreds are divided into two groups according to the gait they perform during racing. The tendency to trot, in which the diagonally opposite limb pairs move together, or to pace, in which the lateral pair of limbs move together, has been shown to be genetically determined (Andersson et al., 2012). The offspring of pacers almost always pace, whereas about 20% of the offspring of trotters are pacers (Cothran et al., 1987).

Trotters

Stride variables

A good trotter should have a high maximal speed with a stride frequency in excess of 2.4 strides/s and a stride length greater than 5.45 m. It has been suggested that trotters achieve a high racing speed by selecting an optimal stride length then accelerating to the wire by increasing their stride frequency (Barrey et al., 1995).

Different studies vary in their findings regarding the relationship between speed, stride length and stride frequency. Barrey et al. (1995) found that both stride length and stride frequency increase linearly with speed, whereas Drevemo et al. (1980a) found speed to be moderately correlated with stride length but not correlated with stride duration. The latter study also found a close correlation between stride duration and swing duration. Swing duration, which occupied about 75% stride, had much more effect on overall stride duration than stance duration, which occupied only about 25% of stride. The treadmill study of Weeren et al. (1993) also found that stride length contributes more than stride frequency to an increase in speed, with the swing duration remaining constant at all speeds.

The temporal and linear stride variables of 30 Standardbreds trotting on a racetrack were studied using a camera car driven parallel to the horse as a pacemaker (Drevemo et al., 1980a). With the pacemaker car moving at 12 m/s, the actual speed of the individual strides varied from 11.3 to 12.4 m/s. The values of the stride variables are shown in Table 14.2. There was very little intra-individual variation (Drevemo et al., 1980b; Kobluk et al., 1989), indicating that each horse has a stable locomotion pattern that is repeated regularly with only minor deviations. The variation between individuals was two to three times greater than that within horses. Depending on the variable being studied, the coefficients of variation were of the order of 8–12%, though the variability within horses was about 60% less than that between horses.

Table 14.2 **Mean values for stride variables of Standardbred trotters and pacers**

Speed (m/s) – gait	Stride length (m)	Stride duration (ms)	Suspension (ms)
12.0 – trot	5.45	455.0	99.0
14.2 – trot	5.65	396.8	n/a
11.5 – pace	5.57	485.0	148.6
12.0 – pace	5.57	465.9	141.2
13.1 – pace	6.04	460.0	135.3
14.0 – pace	6.28	448.4*	133.4

*In the original paper the stride duration is given as 499.4 ms, and the stride frequency is 2.23 strides/s. Apparently, the value for the stride duration is a typographical error.

Data for trotters moving at 12.0 m/s from Drevemo et al. (1980a and 1980b) and at 14.2 m/s from Barrey et al. (1995). Data for pacers from Wilson et al. (1988b).

Good trotters show a short stance phase duration, especially in the forelimbs (Bayer, 1973). The stance phase has been subdivided at the instant when the metacarpus is vertical in the forelimbs or when the hoof is vertically beneath the hip joint in the hind limbs (Drevemo et al., 1980a). The early part was named the restraint phase and the later part was named the propulsion phase. Although the names suggest that these terms define functional phases of the stride, it should be noted that they are defined kinematically and so the implied functional relationship to the longitudinal ground reaction forces is an approximation only. Using this definition, the restraint phase accounts for the initial 40–45% stance, and is slightly longer in the hind limbs than in the forelimbs. The propulsive phase is significantly longer in the right hind than in the other limbs, which has been interpreted as an indication of sidedness. The duration of the forelimb propulsive phase is negatively correlated with speed.

Diagonal dissociation is a term that encompasses the dissociation of the diagonal pair at contact with the ground (diagonal advanced placement) and at lift-off (diagonal advanced completion). Dissociation of the movements of the diagonal pair of limbs results in a short period of single support between the periods of bipedal support and periods of suspension. Duration of the diagonal dissociation is significantly longer at lift-off than at contact, with the forelimb acting in advance of the hind limb both at contact and lift-off in the majority of horses. For a given diagonal, the duration of the dissociation at contact and lift-off are highly correlated. When the forelimb precedes the hind limb, diagonal advanced placement is inversely correlated with the distance between the diagonal limb pair during bipedal support (diagonal length). When the hind limb precedes the forelimb, the diagonal advanced placement is directly correlated with the diagonal distance (Drevemo et al., 1980b). About 25% of trotters showed highly significant differences between the left and right diagonal dissociations.

The mean duration of diagonal limb support at a speed of 12 m/s was 99 ms, with highly significant differences between the left and right diagonals in four out of 30 horses. Diagonal length, which is the distance between the diagonal limb pair during their stance phase, had a high coefficient of variation on the right diagonal, and the values for the left and right diagonals differed significantly in five out of 30 horses. The mean duration of the suspension phase was 99 ms, with 66% of the horses showing no significant difference between the left and right sides. The left and right suspensions were strongly correlated with the length and duration of the left and right hind steps, respectively. There was also a moderate correlation between suspension and stride duration (Drevemo et al., 1980b).

For Standardbreds trotting on a treadmill, the swing phase trajectories of the fore hooves are quite different from those of the hind hooves. The fore hooves are lifted higher but show less lateral deviation than the hind hooves in which the limbs swing wide to avoid interference. The hoof movements as seen in the frontal plane seem to be characteristic of the individual animal (Weeren et al., 1993). Drevemo et al. (1987) analyzed temporal kinematic variables in ten Standardbreds trotting at 4 m/s on a treadmill at the ages of 8, 12 and 18 months. After scaling the data to height at the withers, a decrease in relative stride length was found.

Reproducibility of gait

The kinematic stride variables of trotting Standardbreds show good reproducibility in the short term during both overground (Drevemo et al., 1980c) and treadmill (Weeren et al., 1993) locomotion. A 5-month training period did not result in any significant changes in temporal parameters, but other aspects of the stride kinematics did change. In the forelimb there was more flexion of the elbow, more overextension of the carpus and a decrease in fetlock flexion after training. In the hind limb there was an increase in overextension of the fetlock (Weeren et al., 1993). A longer training period of 3 years was associated with significant increases in stride length, stride duration and swing duration. The increase in stride duration resulted almost exclusively from the longer swing duration (Drevemo et al., 1980c).

Ground reaction forces

The peak vertical ground reaction force in the forelimb of a Standardbred trotting at a relatively slow speed of 8 m/s was 99% body weight and occurred around 50% stance. The braking longitudinal force had a maximal value of 6.4% body weight at 15% stance, while the propulsive component peaked at 75% stance with a value of 9.2% body weight. The forelimb longitudinal force changed from braking to propulsive around 40–50% stance (Quddus et al., 1978; Chateau et al., 2009).

Sidedness

By definition the trot is a symmetrical gait, which implies that the movements of the left and right limbs are out of phase by 50%, with the left and right steps being equally spaced in time. In the 30 horses studied by Drevemo et al. (1980b), the kinematic variables for the entire group were symmetrical on the left and right sides. However, many individuals showed left–right asymmetries when trotting at high speeds, especially in the hind limbs. Six of 30 horses had significant asymmetries between the fore steps, while 12 out of 30 horses had significant asymmetries between the hind steps (Drevemo et al., 1980b). Some individuals had such marked asymmetries that, rather than trotting, they showed a transitional type of gait with a galloping motion of the hind limbs, which is known as the traquenard. The asymmetries detected at racing speed by slow motion analysis are often not apparent during a clinical examination when the horse trots at a slower speed. Detection is important, though, because an asymmetrical gait is thought to be associated with poor performance (Dalin et al., 1985) and the development of locomotor pathology (Rooney, 1969).

Even 8-month-old Standardbreds that have not yet been trained show some differences between the kinematics of the left and right limbs (Drevemo et al., 1987). The fact that asymmetries are present at such a young age is strong evidence for congenital laterality or sidedness. Furthermore, when the same horses were re-evaluated at 18 months of age the differences between the left and right sides were even more pronounced in horses that had been trained, but not in those that were not trained in the interim.

An asymmetric appearance of the hindquarters has been associated with poor racing performance (Dalin et al., 1985). Five hundred Standardbreds in race training were evaluated for symmetry in the height of their tubera sacrale. The left tuber sacrale was lower than the right one in nine horses, and the right tuber sacrale was lower than the left one in 30 horses. The asymmetric horses had significantly larger body size than the 461 horses that did not show asymmetry. The asymmetric horses had lower total earnings, a lower number of races per horse and fewer good racing records. It was concluded that horses in which the height of the tubera sacrale is asymmetrical are less likely to become successful racehorses.

Effect of track design

Lameness is a common problem in racing horses, and gait asymmetries that arise due to defects in the geometrical design of the racetrack were identified as a predisposing factor. Dalin et al. (1973) showed that when horses trot on a track with under-banked semi-circular turns the gait becomes asymmetrical at high speeds with the horses changing to a galloping motion in the hind limbs. To overcome the tendency to slip sideways on the turns, the horse leans into the turns and places the feet at an angle, using friction against the track surface to overcome the centrifugal force. The left limbs are adducted and placed on the ground closer to the horse's midline, which is associated with a lateral landing of the left hooves and medial deviation of the fetlock throughout the stance phase. Thermographic evaluation revealed that, after the horses performed at speed around inadequately banked turns, the left fore fetlock became warmer than the right one.

The traditional racetrack design of two straights joined by under-banked semi-circular turns is obviously not optimal for either performance or soundness of the horses. Fredricson et al. (1975) made suggestions for improving the geometric design of racetracks. They recommended the use of wide sweeping turns to reduce the horse's tendency to slide outwards and to facilitate adequate banking; on tighter turns the amount of banking required is so great that the surface material cannot be stabilized. Only the inner half of the track needs to be banked sufficiently for maximal speed; the middle and outer lanes can be less steeply banked to accommodate moderate and slow speed training. It has also been observed that gait asymmetries are most prevalent as the horse enters and leaves the turns. Therefore, the intercalation of a transitional curve between the true curve and the straight is highly recommended (Fredricson et al., 1975).

Conformation of trotters

A study relating conformation to performance in Standardbred trotters (Magnusson, 1985) showed that traits associated with superior racing performance included height at the withers and large girth circumference around the point of the withers, which was indicative of prominent withers and a large area for attachment of the locomotor muscles. In contrast, girth circumference at the lowest point of the back had a negative correlation with performance. Outward rotation of the limb axes, which is typically regarded as a conformational fault, had a positive effect on racing ability. Conformational features that had a negative influence on performance included tied in at the knees and hocks, narrow hooves and greater width/circumference of the forelimbs. Overall it was concluded that the better performing horse was a lightweight, gracile type with tall withers, with open angles at the shoulder and stifle joints and normal-sized hooves.

Pacers

Stride variables

The pace is a symmetrical gait in which the lateral pair of limbs move more or less synchronously. The ability to pace is genetically determined (Andersson et al., 2012). Slow motion studies have shown that ground contact of the hind hoof precedes that of the front hoof (Crawford & Leach, 1984; Wilson et al., 1988a), unlike the racing trot in which the front hoof usually precedes the hind hoof. At racing speed the dissociation is about 30 ms, which represents 7% of stride duration. With this amount of dissociation, the pace can be considered a four-beat gait (Wilson et al., 1988a).

The stride lengths and stride durations of Standardbreds pacing at a range of speeds between 11.5 and 14.0 m/s are shown in Table 14.2. Pacing speed increases primarily as a result of an increase in stride length with minimal change in stride frequency (Wilson et al., 1988b). Lengthening of the stride is a result of covering a greater distance during the suspension phases, without much change in the distance between the lateral pair of limbs during stance. Although the overall stride rate does not show much change with speed, overlap time is reduced and single support time is increased as a consequence of having longer diagonal advanced placements and diagonal advanced completions. These changes in timing create a distinctly four-beat gait. The best discriminators between speeds were stride length and overlap time, while the variables that limited pacing speed were stride rate and suspension time (Wilson et al., 1988b).

At the end of a race, a pacer is moving at a speed close to 15 m/s. When horses with different levels of ability were classified according to their finishing placing, low-order finishers were found to have shorter distances between the lateral pair of limbs during stance, whereas high-order finishers had a greater range of motion in the fore and hind limbs. Comparing the last lap of a race with the preceding lap, speed and stride length were reduced during the last lap for low-order finishers but increased for high-order finishers. At the end of a race, an increase in the amount of overlap expressed as a percentage of the stride was a sign of fatigue.

Sidedness

Although the pace is generally described as a symmetrical gait, many pacers show temporal asymmetries between the left and right sides. Gait variables that show left–right asymmetries include stance duration, suspension, overlap, diagonal dissociation and single support (Crawford & Leach, 1984).

Conformation

Preliminary kinematic data of 2-year-old pacing fillies suggest that a long sloping scapula, substantial development of the brachiocephalicus, a long forearm and an elastic fetlock joint are associated with ergonomic efficiency (Sellett et al., 1981).

Endurance racing

The primary requirement for an endurance horse is economy of movement, but the stride variables that contribute to energetic economy have not yet been evaluated. During a race an endurance horse takes many thousands of strides. Horses that maximize transfers of angular momentum between limb segments reduce their mechanical energy expenditure and so use less metabolic energy to cover a given distance. Prolonged endurance training of 8 months' duration resulted in significant reductions in stride and stance durations in association with an increase in the percentage of Type IIA muscle fibers and a decrease in the percentage of Type IIX muscle fibers, which was interpreted as an indication of more efficient propulsion associated with an increase in muscle fatigue resistance and strength (Rivero et al., 2001).

In one study, stride length increased during the course of an 82 km endurance ride. Compared with pre-race values, stride length at the walk increased to 115% at 41 km and 123% after 82 km. The length of the trot stride increased to 151% at 41 km and 149% after 82 km compared with pre-race values (Lewczuk & Pfeffer, 1998). It was suggested that the increase in stride length was due to warming up during the course of the race. A different study that evaluated the effects of fatigue found that speed decreased from 4.55 to 4.03 m/s during an 80 km race due to a reduction in stride length without any change in temporal variables (Wickler et al., 2006).

This is in contrast to horses exercised to exhaustion at a similar speed (4.5 m/s) on a treadmill with 6% incline, in which the constant speed was maintained using longer stride lengths and shorter stride frequencies (Wickler et al., 2006).

Sport horses

The modern sport horse is elegant in appearance, usually a descendant of draft breeds crossed with hot-blooded Thoroughbreds and Arabians, that has been refined by many generations of selective breeding to produce the Warmblood breeds.

Quality of movement

Sport horses are selected by horsemen, often at a young age, with one of the important selection criteria being visual appraisal of their gait patterns. The definition of 'good gait' or 'good action' is, however, rather subjective (Smythe, 1957), and always leads to discussion between experts (Oliver & Langrish, 1992). Observational gait analysis seems to be a convenient technique to quantify gait (Krebs et al., 1985), but it should be standardized by using a uniform scoring system to improve reliability between judges (Eastlack et al., 1991). Many of the Warmblood registries use such a system to score gait quality (e.g. van Veldhuizen, 1991).

The most important gait for selection of sport horses is the trot (Podhajsky, 1981; Clayton, 1994a). Podhajsky (1981) suggested that the ideal gait and speed to train a horse overground under saddle is the trot at 3.75 m/s, which is between the speeds recorded for the working and medium trot (Clayton, 1994a; Sloet & Clayton, 1999). At a speed of 4.0 m/s horses of all ages move on a treadmill at a comfortable though demanding trot that can be used to evaluate stride characteristics (Back et al., 1994a). The same speed has been used to analyze the gait of Standardbreds and Thoroughbreds (Drevemo et al., 1987; Herring et al., 1992). Standardization of speed is important because many kinematic variables are speed dependent, with the relationship being closer for linear than temporal variables (Galisteo et al., 1998).

Modern kinematic analysis equipment has also been used to assess the quality of movement in elite dressage and showjumping horses during competition (Leach et al., 1984; Deuel & Park, 1990, 1991; Clayton et al., 1995, 1996; Colborne et al., 1995; Burns & Clayton, 1997; Clayton, 1997a; Hodson et al., 1999) and to compare the quality of the overground trot scored by a judge with kinematic variables measured during treadmill locomotion (Back et al., 1994b). In the latter study the judge used a linear scoring system, in which the trot was rated on three criteria: length, strength and suppleness. The measured kinematic variables included forelimb and hind limb stride and swing durations, scapular rotation, forelimb maximal fetlock extension, forelimb maximal retraction, hind limb maximal protraction, maximal stifle flexion and maximal tarsal flexion. The kinematic variables correlated very well with the judged score and allowed the subjective terms used by horsemen to be quantified.

Stride and swing duration

Sport horses with good gaits move with longer stride lengths and a lower stride frequency (Knopfhart, 1966). The lower stride rate and, hence, longer stride duration in horses with a better trot were associated with longer durations of both stance and swing phases in the forelimb (Back et al., 1994b; Morales et al., 1998a, 1998b).

Although the trot is described as a two-beat gait in which the diagonal limb pairs make contact and lift-off simultaneously, slow motion analysis has shown that there is usually a period of dissociation with either the fore or hind hoof making ground contact and lift-off earlier. The time between contact or lift-off of the diagonal limbs is called diagonal dissociation, with the more specific terms diagonal advanced placement (time between fore and hind contact) and diagonal advanced completion (time between fore and hind lift-off) also being used. Positive values are assigned if the hind limb acts in advance of the forelimb, and negative values are assigned if the forelimb acts in advance of the hind limb. A positive dissociation at contact is associated with good movement and a well-balanced horse (Holmström et al., 1994b; Morales et al., 1998a, 1998b). The magnitude of the positive dissociation at contact tends to increase with training due to greater elevation of the forehand as the degree of collection and self-carriage improve (Tans et al., submitted).

Forelimb kinematics

The forelimb has been likened to a pendulum rotating around the proximal scapula, with better moving horses showing more retraction in the forelimbs and more protraction of the hind limbs (Fig. 14.4). To increase stride length, an increased scapular movement is obligatory (Spooner, 1977). Therefore Smythe (1957) and Spooner (1977) both stressed the importance of having enough space between the elbow and the ribs to facilitate the sliding movement of the proximal forelimb over the rib cage.

The spring-like action of the fetlock joint is valued as a method to reduce impact shock (Smythe, 1957; Alexander, 1988; Gray, 1993), to give smoothness of action (Gray, 1993) and to store elastic energy (Clayton et al., 1998). The action of the fetlock contributes to the appearance that the horse moves in a graceful, floating manner (Oliver & Langrish, 1992).

Much of the expression in the trot is judged from the forelimb movements during the swing phase (Fig. 14.5). At the position of maximal forelimb protraction, expressive movers have greater flexion of the elbow and more elevation of the carpus (Fig. 14.5) (Holmström et al., 1994b). This type of movement is indicative of the horse controlling the motion of the distal joints during protraction rather than relying on inertial forces and anatomical constraints to determine the joint position in maximal protraction.

With regard to conformation, a sloping shoulder facilitates forward and upward movement of the limb during the swing phase, so conformation of the shoulder may play a role in gait quality (Holmström et al., 1990). After the limb reaches its maximally protracted position, it is retracted before making ground contact (Fig. 14.6). This period, which is known as the swing phase retraction, has a longer duration in the forelimbs of horses that receive high trot scores (22% of stride duration) than for those with low trot scores (10% of stride duration). The fore hoof trajectory reaches a height of 20–25 cm during midswing in horses with a high gait score, whereas horses with lower gait scores do not raise the hoof as high and the flight arc peaks earlier in the swing phase (Holmström et al., 1994b).

Hind limb kinematics

Better moving sport horses have more protraction of the hind limbs, shown as more forward placement of the hind hoof relative to the tuber coxae as a result of the combined actions of the joints of the hind limb (Holmström et al., 1994b). When horses show a combination of large ranges of hind limb protraction and simultaneous forelimb retraction, the trot has the appearance of greater 'suppleness' in lateral bending of the body, which is one of the visual indicators in horses with a good gait (Back et al., 1994b). Stifle and tarsal joint flexion, which are closely related through the reciprocal apparatus (Weeren, 1990), support protraction with greater flexion being indicative of superior action in the hind limb (Spooner, 1977; Alexander & Trestik, 1989; Oliver & Langrish, 1992; Back et al., 1994b; Morales et al. 1998a, 1998b).

Fig 14.4 A good quality trot is recognized by a long swing phase duration and a long suspension phase with more retraction of the forelimb and more protraction of the hind limb.
Courtesy of Ellen van Leeuwen, The Netherlands.

Fig 14.5 Photograph of 'Mythilus' ridden by Courtney King-Dye performing the trot with good flexion of the elbow joint raising the carpus and giving expression to the forelimb movement.
Courtesy of Jacob Melissen, The Netherlands.

During the stance phase, horses with high gait scores show greater inclination of the pelvis, flexion of the hock and extension of the fetlock joints as the limb accepts weight. This is associated with a significantly larger angular velocity during tarsal flexion between 20 and 55% stance and during tarsal extension between 75 and 85% stance. In the later part of the stance phase, the limb is retracted faster in good movers (Holmström & Drevemo, 1997). Maximal hoof height occurs soon after lift-off in the hind limb and does not differ with gait quality (Holmström et al., 1994b).

Breed differences

Although European Warmblood breeds currently predominate in international dressage competitions, other breeds are competing more frequently. Warmbloods typically have lofty gaits with a long suspension phase, which requires the generation of large vertical ground reaction forces and impulses. Compared with Quarter Horses, Warmbloods have been shown to have higher peak vertical forces normalized to body weight (Back et al., 2007). Comparison

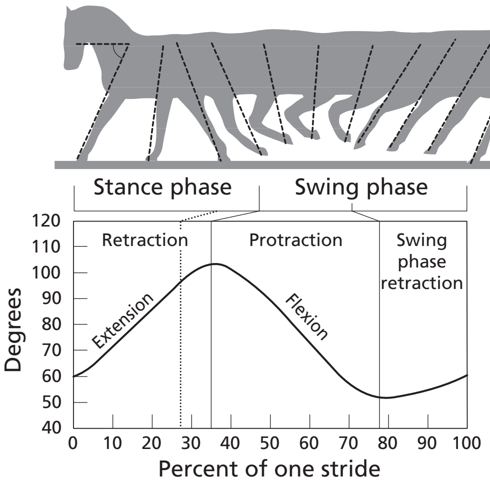

Fig 14.6 Illustration of the relationship between scapular angle to the horizontal and protraction and retraction of the forelimb during one stride.
From Holmström et al. (1994a).

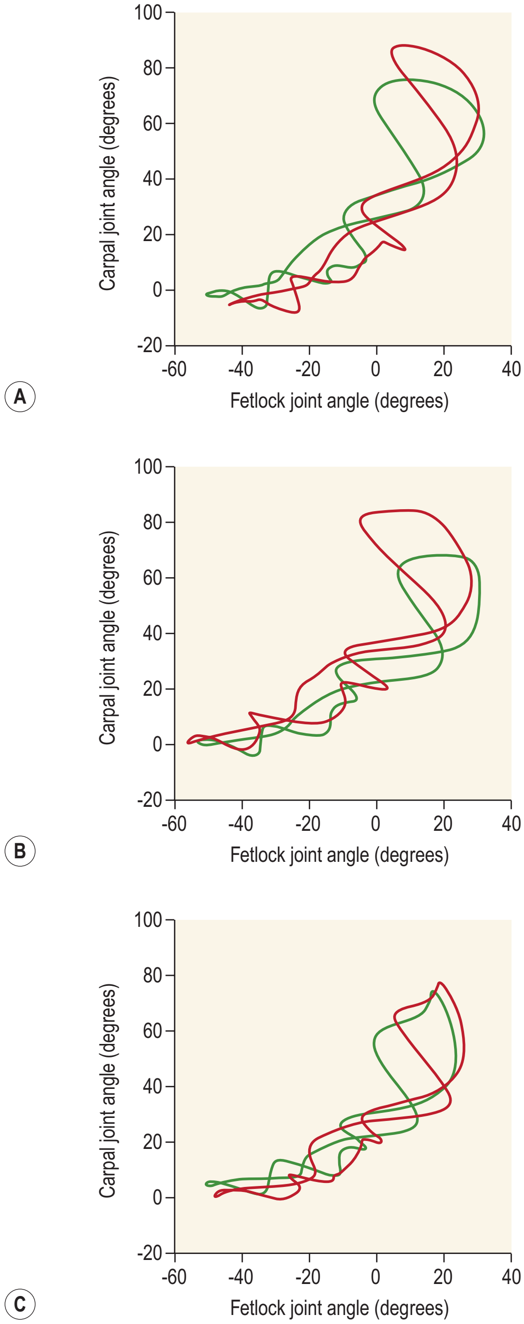

Fig 14.7 Angle–angle diagrams of the carpal and fetlock joints of three horses (A, B, C) as foals (green line) and adults (red line).
From Back et al. (1994a).

of the gaits of Andalusian, Arabian and Angle-Arabian horses showed that Andalusians have more carpal flexion resulting in a larger range of carpal joint motion and also have less forelimb retraction than the other breeds at walk (Galisteo et al., 2001). Cano et al. (2001) found that Andalusians had more flexion in the joints of the forelimb at trot than Arabians or Anglo-Arabians, which accounted for the elevated movements that are characteristic of the breed. Anglo-Arabians had a smaller range of protraction–retraction in both the fore and hind limbs. Tracking length was positive (over-tracking) in Arabians and Anglo-Arabians, but negative (not tracking up) in Andalusians.

Ontogeny of gait

Horse breeders are interested in identifying gait characteristics of young animals that are predictive for future performance, so it is important to know at what age the adult gait characteristics are acquired. Using modern automated kinematic analysis equipment Back et al. (1994a, 1995a) compared the gaits of foals with those of adults using angle–angle diagrams that are indicative of intra-limb coordination (Kobluk et al., 1989; Martinez-del Campo et al., 1991). Plots of carpal angle against fetlock angle (Fig. 14.7) showed that some horses accelerate their carpal joint flexion during the swing phase ('spike' pattern) and some maintain a constant carpal angle during the same period ('straight' pattern), and others demonstrate a smoother rate of carpal flexion ('convex' pattern).

A longitudinal study of 24 Warmblood horses was performed with evaluations at 4, 10, 18 and 26 months of age at walk, trot and canter on the treadmill (Back et al., 1993, 1994a). A treadmill was used to standardize speed, because Dušek (1974) was not able to find any correlations between height and temporal gait variables during overground locomotion when the individuals selected their own, preferred walking or trotting speed. Intra-limb coordination features could be recognized as early as 4 months of age. Variability of kinematic variables was similar throughout the growth period indicating that kinematic patterns are already established at a young age. Remarkable resemblance between angle–angle diagrams recorded in the foal compared with the adult can be observed especially in individuals showing the more typical 'spike' versus 'convex' pattern in the carpal–fetlock kinematics (Fig. 14.7).

There were age-related increases in stride and stance durations (Back et al., 1994a) as a result of increases in limb length and height at the withers (Beck et al., 1981; Vilensky et al., 1990a, 1990b). Swing duration, protraction and retraction angles, and joint angular kinematics were consistent throughout this age range (Back et al., 1994b). Within an individual animal, angle–time and angle–angle graphs for the joints of the fore and hind limbs were remarkably similar both visually and numerically from 4 to 26 months (Fig. 14.7). Each animal appeared to have an inherent and characteristic intra-limb pattern that was retained from foal to adulthood, the 'gait fingerprint'.

Prediction aims to select horses with a good gait quality at an early age and Back et al. (1995b) proved that locomotor variables, including swing duration, maximal protraction–retraction angles, and maximal tarsal flexion, showed a good correlation between 4-month-old foals and adults. Since these kinematic variables are indicative of gait quality (Back et al., 1994b) this explains why astute horse breeders are said to be able to predict future gait performance at a young age (Clayton, 1989a; Grant, 1989).

The inherent patterns of the angle–angle diagrams that are recognized at foal age (Back et al., 1994a) might be related to the future ability to perform gait transitions or piaffe and passage in dressage horses, while in jumping horses it might be related to jumping technique, which has become a more substantial part of selection procedures. Gait analysis can be used to quantify performance, while neural networks might be developed to automate pattern recognition in the data (Holzreiter & Köhle, 1993; Dalin, 1994). In this way, more specific selection criteria for dressage or jumping could be defined and objectively measured. Finally, it should be remembered that horses can be trained to perform well, but for élite performance in competition the mental capacities of rider and horse might be the crucial factor.

Normalization of temporal variables

Temporal gait variables in differently sized animals of the same breed can be made comparable after a transformation based on linear and dynamic similarity principles (Günther, 1975; Alexander, 1984). However, models found in the literature that would compensate for the influence of height on temporal kinematic variables, like trot–gallop transitions (elastic similarity) and Froude numbers (dynamic similarity), showed inconclusive results (Vilensky & Gankiewicz, 1986; Drevemo et al., 1987). The principle of Günther (1975), in which frequencies are related to linear dimensions, showed a decrease in relative stride duration with age, which is in accordance with Back et al. (1994a) that younger animals take relatively longer strides (Fig. 14.8). Back et al. (1995b) hypothesized that, after normalization for differences in conformation, foal and adult kinematics are similar within a certain range (Tables 14.3–14.5).

Differences in height at the withers influence temporal kinematics. Models that compare the kinematics of differently sized animals are those of linear or dynamic similarity.

Linear similarity

Consider a small and a large horse, in which the dimensions of the large one are a simple multiplication of the dimensions of the smaller one. If the forelimb is regarded as a pendulum that moves the body forward at constant horizontal velocity with the same pro-/retraction angles and stance durations, the distance moved during the stance phase will increase almost linearly with height. During the swing phase the limb must move over a greater distance in the same time. If the maximal protraction and retraction angles of the limbs are the same (Back et al., 1994a) and the speed of progression is also the same, the larger animal moves with a longer stride length and a slower stride frequency. Normalization can be achieved by multiplying the quotient of the height at the withers of the larger and smaller horse with, for example, the stride duration of the smaller horse (Günther, 1975).

Dynamic similarity

Forces occurring in a pendular locomotor system are considered dynamically similar when the ratio of kinetic energy ($\frac{1}{2}mv^2$) and potential energy (mgh, where $g = 9.81\ m/s^2$) is the same regardless of horse size. The ratio between these energy variables is known as the Froude number (v^2/gh). When the substitution of $v = h/t$ is used, the Froude number equals h/gt^2. This relationship leads to the following scaling procedure if dynamic similarity conditions are fulfilled: the stride duration of the smaller horse is multiplied by the square root of the quotient of the height at the withers of the larger and the smaller horse (Alexander, 1984).

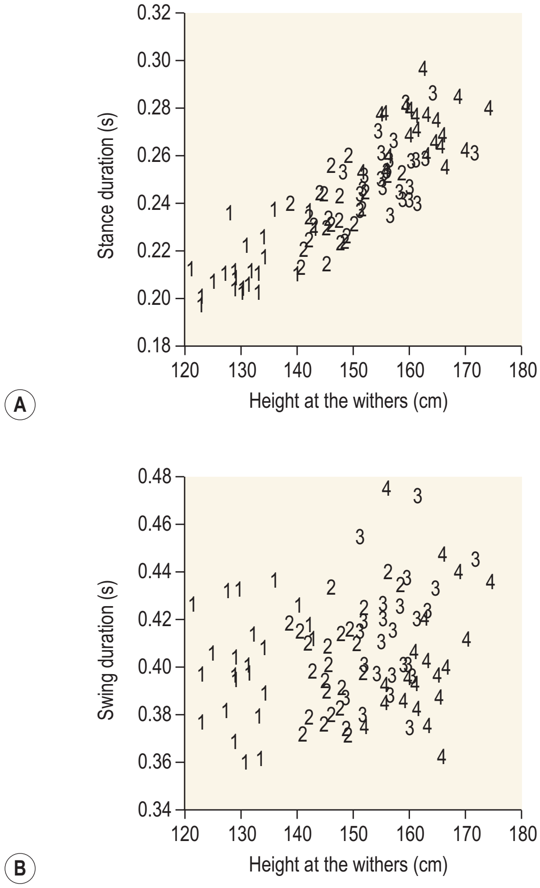

Fig 14.8 Correlation between height at withers and stance duration (A) and height at withers and swing duration (B) recorded at trot in a group of horses at ages 4 months (1), 10 months (2), 18 months (3), and 26 months (4).

From Back et al., (1994a).

Due to the increased limb length in adult horses, the distance the body moves forward over the grounded hoof during the stance phase is longer in adult horses trotting at the same velocity because the body moves forward over a greater distance during the stance phase (Back et al., 1994a). Compensation for the difference in stance duration is achieved by multiplying stance duration by the ratio of the height at the withers, assuming linear similarity. Stride duration of foals became similar to adults after dynamic correction. When using linear similarity principles to correct stride duration, it was found that adult horses took shorter strides than foals (Back et al., 1994a, 1995b; Drevemo et al., 1987).

From the latter study it became clear that as the swing duration at foal age was already similar to that at adult age, but the limbs were less flexed in foals than adults because a shorter distance had to be covered in the same time. This is nicely illustrated in the forelimb, in which the carpal joint showed greater flexion in adult horses. The extension dip in the fetlock joint at the end of the swing phase is more pronounced in adults compared with foals, because mass and speed of the hoof are higher. In the hind limb, the pendular response of tarsal flexion to the increase in limb length is minimal. This fact, together with the remarkably high correlation coefficient, illustrates the 'adult-like' capacities of this joint at foal age.

Coordination

Limb timing and coordination patterns affect many aspects of performance including locomotor efficiency, quickness and esthetics of

Table 14.3 Recorded and predicted temporal kinematics of the forelimb and the hind limb of a group of horses trotting on a treadmill at foal and adult age

Variable	Foal			Adult						
	Mean	Not corrected predicted		Linearly predicted			Dynamically predicted			Recorded mean
		Range	Correlation	Value	Range	Correlation	Value	Range	Correlation	
Forelimb										
Stance duration (%)	34.7	33.4–36.0	0.10	42.9	41.0–44.9	$0.82^{\dagger}$	38.6	37.1–40.1	$0.95^{\dagger}$	40.3*
Stance duration (s)	0.21	0.20–0.22	$0.43^{\dagger}$	0.26	0.25–0.28	$0.89^{\dagger}$	0.24	0.22–0.25	$0.97^{\dagger}$	0.27*
Swing duration (s)	0.40	0.38–0.42	$0.65^{\dagger}$	0.50	0.47–0.53	$0.90^{\dagger}$	0.45	0.42–0.47	$0.97^{\dagger}$	0.40
Stride duration (s)	0.62	0.59–0.65	$0.83^{\dagger}$	0.76	0.72–0.80	$0.86^{\dagger}$	0.68	0.65–0.72	$0.96^{\dagger}$	0.67*
Hind limb										
Stance duration (%)	34.3	32.1–36.5	$0.63^{\dagger}$	42.3	39.7–44.9	$0.92^{\dagger}$	38.1	35.8–40.4	$0.98^{\dagger}$	40.5*
Stance duration (s)	0.21	0.20–0.22	$0.65^{\dagger}$	0.26	0.25–0.27	$0.61^{\dagger}$	0.23	0.22–0.25	$0.66^{\dagger}$	0.27*
Swing duration (s)	0.41	0.38–0.44	$0.77^{\dagger}$	0.50	0.46–0.54	$0.68^{\dagger}$	0.45	0.42–0.49	$0.73^{\dagger}$	0.40
Stride duration (s)	0.62	0.59–0.65	$0.86^{\dagger}$	0.76	0.72–0.80	$0.71^{\dagger}$	0.68	0.65–0.72	$0.80^{\dagger}$	0.67*

☐ recorded adult variable outside the predicted range of foal age.

*, $^{\dagger}p < 0.05$: significant difference and correlation between foal and adult.

Predicted range is based on foal kinematics ± SD.

Data from Back et al. (1995b).

movement. The basic patterns of limb coordination are governed by central pattern generators in the spinal cord that regulate flexion and extension of the joints, which are the basis for stride rate and inter-limb coordination patterns that give rise to the recognizable gaits. Individual horses vary slightly in the synchronization of their limb movements, which can have a marked effect on the esthetics and energetics of sporting performance.

When a new motor skill is learned, the initial attempts are clumsy and inefficient. After a period of practice, efficiency in performing motor tasks improves. In human athletes, muscular activation patterns are modified by practice; champion athletes have a specific temporal and sequential pattern of muscle activation in the execution of their specific skill (Normand et al., 1982). Sustained practice establishes an advanced level of muscular control and economy of effort. Codification that develops as a result of practice is attributed to reorganization of the motor program required to execute the specific task within the central nervous system. These modifications are manifest as inhibition of undesired cocontractions in the antagonistic muscles, contributing to lower overall tension and greater economy of effort. This is an important training consideration, especially in high-intensity sports, such as polo, cutting and eventing, that combine the need for speed and endurance with highly coordinated technical skills. For more information, the reader is referred to the chapters on initiation and coordination of gait.

Effect of training

Prediction of good gait at a young age seems to be possible, but the question remains as to whether good gait also results in good performance when the horse is being ridden. Swedish researchers found that, during ridden exercise, good movers had a longer stride duration compared to poor movers (Holmström et al., 1994b). Furthermore, they calculated that the subjective evaluation of conformation and locomotion accounted for 43% of the variation of their gaits under saddle (Holmström & Philipsson, 1993).

Training is defined as a program of exercise to improve the horse's physical performance in a particular task (Blood & Studdert, 1990). Most of the literature on training involves the effect on physiological parameters and on blood chemistry. This section mainly focuses on the influence of training on kinematics of riding horses. Clayton (1993) found differences in stride variables of the extended canter under a rider between horses trained for dressage and horses trained for racing. These included longer stance durations and longer overlaps between stance phases of different limbs in the dressage horses. The level of training of a dressage horse affects the ability to make a transition directly between walk and trot (Argue & Clayton, 1993a) and between halt and trot (Tans et al., 2009), but not between trot and canter (Argue & Clayton, 1993b). Horses competing at a higher level performed transitions between walk and trot

Table 14.4 Recorded and predicted kinematics of the forelimb of a group of horses trotting on a treadmill at foal and adult age

Forelimb variable	Foal	Adult		Foal–adult correlation
	Recorded	Predicted range	Recorded	
Pro- and retraction (degrees)				
Max protraction	23.0	21.1–24.9	21.5*	0.44†
Max retraction	−21.7	−23.0–20.4	−22.8*	0.03
Range of max pro- and retraction	44.7	42.8–46.6	44.4	0.50†
Scapula (degrees)				
Range of max rotation	15.5	13.8–17.2	$\boxed{17.8^*}$	0.47†
Elbow (degrees)				
At IGC	53.6	50.1–57.1	50.1*	0.12
Max extension relative to IGC	−25.7	−28.7–22.7	−25.6	0.36
Max flexion relative to IGC	30.9	26.6–35.2	34.6*	0.48†
Range of movement	56.6	52.1–61.1	60.2*	0.44†
Carpus (degrees)				
At IGC	4.4	1.8–7.0	6.0	0.03
Max extension relative to IGC	−7.6	−9.9–5.3	−9.0	0.36
Max flexion relative to IGC	70.0	64.9–75.1	$\boxed{81.9^*}$	0.42†
Range of movement	77.5	73.2–81.8	$\boxed{90.8^*}$	0.47†
Fetlock (degrees)				
At IGC	−15.3	−18.4–12.2	−16.8	0.01
Max extension relative to IGC	−36.9	−40.4–33.4	−39.1*	0.37
Max flexion relative to IGC	42.2	37.8–46.6	41.5	0.47†
Range of movement	79.1	73.6–84.6	80.6	0.36

☐ recorded adult variable outside the predicted range at foal age.

*, †$p < 0.05$: significant difference and correlation between foal and adult.

Predicted range is based on foal kinematics ± SD. IGC, initial ground contact.

Data from Back et al. (1995b).

more 'cleanly', that is with fewer support sequences that were not part of the normal pattern for either gait.

Many Warmblood registries have a stallion performance test as part of the process for determines which stallions are accepted for breeding. In Dutch Warmbloods a training period of 70 days has been shown to correlate well with the future performance (Huizinga, 1991). Back et al. (1995a) compared the effects of a 70-day training period with turn out on pasture by evaluating the temporal, angular and segmental kinematics of the fore and hind limbs. In the hind limbs of the trained horses, the same stride duration was achieved with a significantly shorter stance duration after the 70-day period, illustrating the development of 'impulsion' through improvement of muscular strength (Fig. 14.9). Horses pastured for 70 days also decreased their stance percentage, but this was associated with increases in both swing and stride duration (Back et al., 1995a).

Schwarz (1971) analyzed some temporal kinematic variables of Hannoverian stallions walking and trotting overground and found that swing duration expressed as a percentage of total stride duration increased after 1 year of training. Similarly, in Andalusian horses, 10 months of training resulted in an increase in swing duration and a decrease in hind stance percentage (Cano et al., 2000). Corley and Goodship (1994) also reported a decrease in stance duration in cantering Thoroughbreds trained on a treadmill, as did Drevemo et al. (1987) in four young Standardbreds that were trained over a 3-year period. Training changes the relationship between stance and swing durations (Cano et al., 2000) and between stride duration and stride frequency (Muñoz et al., 1997), but the definition and effects of 'training' may differ between studies.

In trained horses the load seems to shift from the forelimbs towards the hind limbs, in which maximal fetlock extension increases, and the horse is said to 'carry itself' (Crossley, 1993). Back et al. (1995a) hypothesized that increased impulsion in trained horses might be visible as increased extension of the tarsal and hind fetlock joints, in contrast to the increased extension of the carpal and fore fetlock joints seen in pastured horses. Interestingly, young Standardbreds that were trained for 5 months showed both

Table 14.5 Recorded and predicted kinematics of the hind limb of a group of horses trotting on a treadmill at foal and adult age

Hind limb variable	Foal	Adult		Foal–adult correlation
	Recorded	Predicted range	Recorded	
Pro- and retraction (degrees)				
Max protraction	18.1	17.1–19.1	$\boxed{21.6^{*}}$	0.28
Max retraction	–29.7	–30.9–28.5	$\boxed{-26.6^{*}}$	$0.48^{\dagger}$
Range of max pro- and retraction	47.8	46.5–49.1	48.1	$0.58^{\dagger}$
Pelvis (degrees)				
Range of max rotation	7.6	5.9–9.3	9.1*	$0.77^{\dagger}$
Hip (degrees)				
At IGC	91.7	87.5–95.9	88.4*	0.07
Max extension relative to IGC	–20.9	–23.4–18.4	–20.6	$0.70^{\dagger}$
Max flexion relative to IGC	2.0	0.9–3.1	2.7*	$0.55^{\dagger}$
Range of movement	22.9	20.9–24.9	23.3	$0.59^{\dagger}$
Stifle (degrees)				
At IGC	15.9	11.7–20.1	12.0*	0.08
Max extension relative to IGC	–0.8	–1.6–0.0	–1.0	0.19
Max flexion relative to IGC	48.4	43.8–53.0	46.3*	$0.48^{\dagger}$
Range of movement	49.2	44.4–54.0	47.3*	$0.55^{\dagger}$
Tarsus (degrees)				
At IGC	21.4	18.0–24.8	$\boxed{16.1^{*}}$	$0.42^{\dagger}$
Stance flexion relative to IGC	9.6	6.8–12.4	10.6*	$0.52^{\dagger}$
Max extension relative to IGC	–6.1	–8.2–4.0	–5.8	0.17
Max flexion relative to IGC	47.3	42.3–52.3	49.7*	$0.65^{\dagger}$
Range of movement	53.4	48.3–58.5	55.4*	$0.70^{\dagger}$
Fetlock				
At IGC	–8.8	–12.9–4.7	$\boxed{-13.5^{*}}$	0.27
Max extension relative to IGC	–37.8	–42.0–33.6	–39.5*	$0.53^{\dagger}$
Max flexion relative to IGC	44.8	38.9–50.7	45.5*	$0.61^{\dagger}$
Range of movement	82.6	75.6–89.6	85.0	$0.56^{\dagger}$

☐ recorded adult variable outside the predicted range at foal age.

*, $^{\dagger}p < 0.05$: significant difference and correlation between foal and adult.

Predicted range is based on foal kinematics ± SD. IGC, initial ground contact.

Data from Back et al. (1995b).

phenomena: increased carpal and fetlock extension in the forelimb and increased tarsal and fetlock extension in the hind limbs (Weeren et al., 1993).

At the beginning of a horse's career under saddle the movement often appears to become 'shorter in front.' For example, Andalusian horses had a shortened stride length after 10 months in training (Cano et al., 2000). After a further period of training, young horses find their balance, and are able to carry a rider 'on the bit.' These changes are accompanied by re-establishment of movement of the proximal limb segments, which is reflected by gradual increases in cranio-caudal movement of the distal segments of the forelimb similar to those of pastured horses (Table 14.6) (Back et al., 1995a). Overall, horses kept at pasture show increases in swing and stride durations, they have a larger range of protraction and retraction and increases in maximal carpal and fetlock extension of the forelimb. They appear to be more on the forehand with a more relaxed type of movement.

A more prolonged period of dressage training teaches horses to move with greater collection and self-carriage. The hind limbs provide more of the forward propulsive force as self-carriage develops. At the same time, the forelimbs show a reduced propulsive force and develop an increased braking force to control balance and

Fig 14.9 'Ravel' ridden by Steffen Peters moves with impulsion and shows a large amount of forelimb retraction and hind limb protraction.
Courtesy of Jacob Melissen, The Netherlands.

Table 14.6 **Maximal cranial and caudal movement in centimeters of the forelimb segments relative to the proximal scapula before and after 70 days in training or 70 days at pasture**

Forelimb segment	Training (n = 12)		Pasture (n = 12)		ANOVA (post-hoc)
	Before	After	Before	After	
Scapula					
Distal	5.1	5.6*	4.7	5.3*	
Humerus					
Proximal	11.4	12.3*	11.1	12.2*	
Distal	22.7	23.6*	22.4	24.0*	
Radius					
Proximal	27.9	29.2*	27.2	29.1*	
Distal	62.1	62.4	61.2	62.7*	†
Metacarpus					
Proximal	75.6	75.1	74.3	76.3*	†(#)
Distal	93.9	92.9	92.2	93.9*	†(#)
Hoof					
Coronet	112.2	111.2	110.3	112.6*	†(#)
Heel	113.5	112.7	11.3	114.2*	†(#)
Toe	116.2	115.8	113.9	116.5*	†(#)

*Indicates that the values before and after 70 days are significantly different ($p < 0.05$) within the training or pasture groups (Student's *t*-test).

†Indicates that the changes in the values over the period of 70 days are significantly different ($p < 0.05$) between the training and pasture groups (ANOVA).

#Indicates the changes in the values over the period of 70 days are also significantly different between the training and pasture groups after a Bonferroni post-hoc test ($p \leq 0.05$).

There was a statistically significant interaction between 'time' (before/after) and 'group' (training/pasture), and between 'segment' (marker no. 1–10), 'time' and 'group' ($p < 0.05$; ANOVA).

Data from Back et al. (1995a).

Table 14.7 Time relative to initial ground contact ($t = 0$) of the maximal protraction of the different segments of the hind limb before and after 70 days in training or 70 days at pasture. Time is expressed as a percentage of total stride duration

Hind limb segment	Training (n = 12)		Pasture (n = 12)		ANOVA (post-hoc)
	Before	After	Before	After	
Femur					
Distal	−1.9	−3.2*	−2.7	−2.9	
Tibia					
Proximal	−2.4	−3.8*	−3.0	−3.5	
Distal	−1.4	−2.4*	−1.6	−1.8	†
Metatarsus					
Proximal	−1.6	−2.5*	−1.7	−1.9	†
Distal	−2.1	−2.8*	−2.1	−2.0	†
Hoof					
Coronet	−2.0	−2.7*	−1.8	−1.9	
Heel	−1.9	−2.6*	−1.8	−1.8	
Toe	−1.8	−2.5*	−1.7	−1.8	

*Indicates that the values before and after 70 days are significantly different ($p < 0.05$) within the training or pasture groups (Student's *t*-test).

†Indicates that the changes in the values over the period of 70 days are significantly different ($p < 0.05$) between the training and pasture groups (ANOVA).

There was a statistically significant interaction between 'time' (before/after) and 'group' (training/pasture), and between 'segment' (marker no. 1–10), 'time' and 'group' ($p < 0.05$; ANOVA).

Data from Back et al. (1995d).

prevent the horse from falling onto the forehand as a result of the increased hind limb propulsion. Consequently, the trained horse does not roll over the forelimbs; instead the forehand is vaulted upwards over the forelimb strut. 'Engagement of the hind quarters', which is one of the primary goals of training the young sport horse (Crossley, 1993), might be visible as an earlier maximal protraction of the hind limb with respect to the retracting ipsilateral forelimb as a consequence of the ability to generate the impulse needed from the hind limbs during a shorter stance time (Fig. 14.9; Table 14.7). At the same time, increased fetlock extension illustrates more weight carrying by the hind limbs (Back et al., 1995a) (Table 14.8). After an initial 10 months of dressage training Andalusian horses had more flexion of the hip and stifle joints at the beginning of stance and at the beginning of swing, which may indicate the development of engagement (Cano et al., 2000).

Table 14.8 Response to the 70 days in training or 70 days at pasture assessed according to the change in maximal fetlock extension of the forelimb and the hind limb

	Forelimb			
	Training (n = 12)		Pasture (n = 12)	
	Decrease	Increase	Decrease	Increase
Hind limb				
Decrease	3	2	1	$\boxed{6}$
Increase	$\boxed{5}$	2	2	3
Total	8	4	3	$9^{\dagger}$

☐ recorded adult variable outside the predicted range at foal age.

†Indicates that the ratio of the number of horses that showed an increased and decreased value after 70 days is significantly different ($p < 0.05$) between the training and pasture groups (Chi square test).

Data from Back et al. (1995d).

Effect of a rider

The presence of a rider affects both the kinematics and the ground reaction forces, with the changes being more pronounced in the forelimbs (Schamhardt et al., 1991; Sloet and Barneveld, 1995; Clayton et al., 1999). When the rider performs a posting trot there are left–right asymmetries in the ground reaction forces, and experienced riders shift part of the weight towards the hind limbs (Schamhardt et al., 1991). Comparing horses trotting at the same speed in hand and with a rider, the peak vertical ground reaction force normalized to the mass of the system (horse or horse plus rider) is lower in both the forelimbs and the hind limbs when horses are ridden. In the forelimbs the mass normalized propulsive force is higher in the second half of stance in ridden horses (Fig. 14.10), and the fetlock joint is more extended between 50 and 70% stance. During walking, the effect of an experienced rider was almost identical to that of a sandbag of equal mass.

Dressage

Dressage is a judged sport in which the quality of the horse's gaits (kinematics) and the horse's innate athleticism (balance,

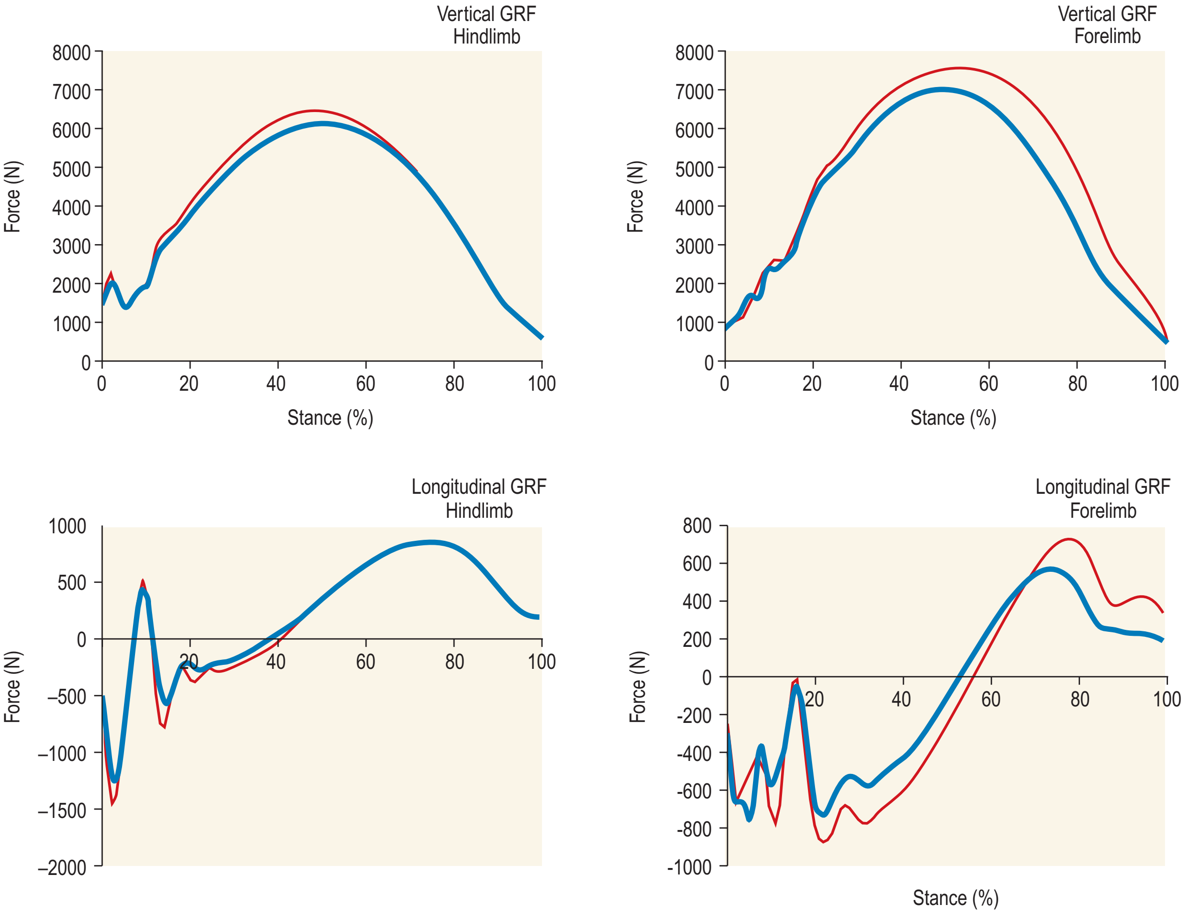

Fig 14.10 Vertical (above) and longitudinal (below) ground reaction forces (GRFs) of the hind limbs (left) and the forelimbs (right) for horses trotting at the same speed in hand (blue line) and with a rider (red line).

coordination) are determinants of competitive success. Since dressage competitions are judged subjectively, the esthetic quality of the gaits and the expressiveness of the movements are important factors in determining competition scores. Estimated heritabilities for dressage in the Dutch Warmblood breed were 0.17 ± 0.05 and genetic correlations between conformation and performance were low to moderate (Koenen et al., 1995). The length of the neck, length and position of the shoulders, shape and length of the croup and muscularity of the haunches had a significant moderate genetic correlation with dressage performance. Due to the low genetic correlations with performance traits, it was concluded that indirect selection for performance based on conformation is of limited value. In Swedish Warmbloods, similar heritabilities for gait traits were found (range 0.09–0.27) and, when combined with estimated heritabilities for competitive dressage performance, they were interpreted as being useful for early genetic evaluation and selection of both mares and stallions for sport performance traits (Wallin et al., 2003). Comparison of gait variables of walk and trot with skeletal conformation measurements in 142 3-year-old horses of three breeds (German, French and Spanish saddle horses) were interpreted as indicating that the gaits of the German horses were more adapted for dressage competition, whereas purebred Spanish horses could be considered as a reference for collected gaits as used in academic dressage (Barrey et al., 2003).

The qualities of rhythm and relaxation are important at all levels of dressage training and as the horse progresses to the more advanced levels, the amount of collection and self carriage must be developed to a higher degree. Collection describes a manner of moving in which the strides become shorter and more elevated, the cycle of hind limb movement is well forward under the horse's body, and the vertebral column is rounded while the forehand is relatively elevated. Horses that are able to carry themselves in this manner are said to move in self-carriage. As the horse becomes more collected, the range of pendular motion of the hind limb is reduced (Holmström & Drevemo, 1997).

Rider effects

The dressage rider strives follow the movements of the horse harmoniously during all the gaits. This is a learned skill that improves with practice. For example, novice riders stabilize their position by gripping with the *adductor* muscles but these muscles become more relaxed as coordination between *rectus abdominis* and *erector spinae* muscles improves (Terada, 2000). Horses ridden by professional riders perform more harmoniously and with a more consistent motion pattern than horses ridden by recreational riders (Peham et al., 2003). Experienced riders maintain an almost vertical trunk position in sitting trot (Schils et al., 1993) and are able to maintain dynamic equilibrium by anticipating the translational movements of the horse, leaning forward slightly by about 5° in late stance in preparation for the push-off into the suspension, then leaning backward by about 5° in preparation for the deceleration of impact (Terada et al., 2006). Movements of the rider's shoulder and elbow joints are synchronized with these forward-backward trunk oscillations, which allow the rider's hand to maintain a consistent position relative to the bit (Terada et al., 2006). The upper and middle trapezius and middle deltoid muscles are active in early stance to

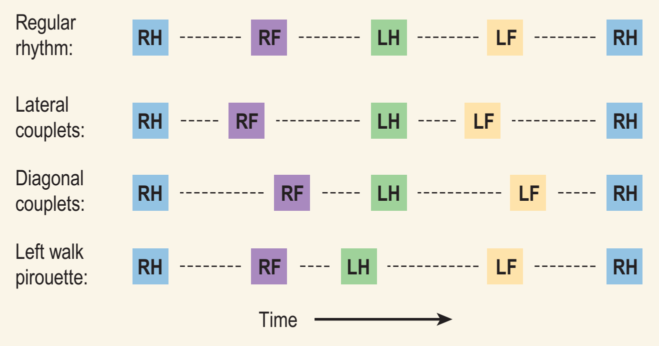

Fig 14.11 Temporal characteristics of a regular walk, a walk with lateral couplets, a walk with diagonal couplets and a half pirouette in walk.

stabilize the rider's neck and shoulder through the impact phase (Terada et al., 2004). At the same time, *biceps brachii* stabilizes the elbow and prevents the forearm descending under the effect of gravity, while the carpal flexors and extensors stabilize the wrist.

It is not only the effect of the horse on the rider that must be taken into consideration; the position and movements of the rider have a dynamic effect on the horse's ground reaction forces (Clayton et al., 1999). For example, in the sitting trot the rider's descent during the stance phase increases the vertical ground reaction force on the horse's forelimbs.

The gaits

The gaits performed in competition are the walk, trot, canter, rein back, passage and piaffe. The walk, trot and canter each have several variations that differ in speed of progression. From slowest to fastest these are the collected, working, medium and extended gaits. Horses are supposed to maintain the same stride frequency (tempo) during the transitions between these gait types. In other words, they should change stride length independently of stride frequency.

The walk

The walk is a four-beat gait with a lateral footfall sequence in which contact of a hind limb is followed by contact of the lateral forelimb: RH, RF, LH, LF. The footfalls should be evenly spaced in time, giving a regular, four-beat rhythm. The limb support sequences alternate between bipedal and tripedal supports (Fig. 14.11). The bipedal supports always consist of a forelimb and a hind limb, which may be a diagonal or a lateral pair. The tripedal supports may be two hind limbs and one forelimb or two forelimbs and one hind limb.

The Fédération Equestre Internationale (FEI) recognizes four types of walk: collected, medium, extended and free. (There is no working walk.) The free walk, in which the horse is allowed freedom to stretch the neck, is only performed in lower levels of competition. The speed, tempo and stride length of the collected, medium and extended walks measured in a group of national level FEI horses are compared in Table 14.9 (Clayton, 1995). Speed of the medium and extended walks was significantly faster than that of the collected walk. Compared with the collected walk, stride length was 23% longer and stride frequency was 8% longer in the extended walk, which agrees with Dušek et al. (1970) who found that increases in speed at all gaits up to a moderate gallop were caused mainly by increasing stride length. However, dressage horses did not fulfill the FEI requirement that the same stride frequency be maintained at all types of walk.

For dressage horses competing in the Seoul Olympics, the mean speed of the extended walk was 1.88 m/s, the stride length was 1.95 m and the stride duration was 1.03 s (Deuel & Park, 1990). These values are similar to the speed of 1.82 m/s achieved with a stride length of 1.93 m and a stride duration of 1.06 s reported by Clayton (1995) in horses of slightly lower caliber. On average, bipedal contact accounted for 61% of stride duration and tripedal contact for 39% of stride duration in the Olympic competitors (Deuel & Park, 1990).

Table 14.9 **Mean values for stride kinematics for the collected, medium and extended walks in dressage horses**

	Collected walk	Medium walk	Extended walk
Speed (m/s)	1.4^{a}	1.7^{b}	1.8^{b}
Stride length (m)	1.57^{a}	1.87^{b}	1.93^{b}
Stride frequency (strides/min)	52^{a}	$55^{a,b}$	56^{b}
Lateral distance (cm)	158^{a}	167^{a}	166^{a}
Tracking distance (cm)	-7^{a}	19^{b}	27^{b}

Different superscripts indicate values that differ significantly ($p < 0.05$).

Data are from Clayton (1995).

Stride length in the walk can be considered as the sum of the lateral distance (distance between the hind hoof and the next placement of the ipsilateral fore hoof) plus the tracking distance (distance between the fore hoof and the next placement of the ipsilateral hind hoof). Changes in stride length at the walk are almost entirely due to adjustments in tracking distance (Table 14.9). Lengthening of the stride is accompanied by a wider arc of limb rotation during the stance phase. The angle between the metapodial bone and the ground is more acute at ground contact and more obtuse at lift-off in the extended walk than in the collected walk, without any change in the carpal or tarsal angle at impact or at lift-off (Clayton, 1995).

Although dressage horses are required to maintain a regular, four-beat rhythm in the walk, only a minority of horses achieve this (Clayton, 1995). When the rhythm becomes irregular, the horses show either lateral couplets (lateral or pacing rhythm), in which there is a shorter time between the lateral footfalls, or they show diagonal couplets (diagonal rhythm), in which there is a shorter time between the diagonal footfalls (Fig. 14.11). Clayton (1995) found that a majority of national level dressage horses showed lateral couplets, with the same footfall pattern being present in all types of walk. The average step durations measured for dressage finalists competing in the Seoul Olympics indicate that they moved with diagonal couplets (Deuel & Park, 1990).

In an investigation of the desirable characteristics of the walk, Biau and Barrey (2004) attached an accelerometer beneath the sternum of young horses (4–6 years old) and experienced horses (7–13 years old). Comparison between the accelerometric data and the scores awarded by dressage judges showed that the horses were rewarded for having a slow, regular and symmetrical pattern of movement with a large amount of dorsoventral displacement.

In highly trained dressage horses, both the collected and extended walk strides have a longer stance duration in the hind limbs than in the forelimbs (Clayton, 1995; Hodson et al., 1999). This may be related to the requirement that highly trained horses move in self-carriage, which implies lightness of the forehand and a greater reliance on the hind limbs for propulsion.

In Andalusian horses, medium to high heritabilities were found for many kinematic parameters of the walk, including stride length and duration, maximal height of the hind hoof, range of forelimb protraction–retraction, hind limb stance duration, and fore and hind limb swing durations (Molina et al., 2008).

Half pirouette at the walk

The half pirouette in collected walk is a half circle in which the forehand moves around the hindquarters. The inside hind limb acts as a pivot point for the movement, but it continues to step in the rhythm of the walk strides. In a study at the Atlanta Olympics (Hodson et al., 1999) the majority (8/11) of the horses completed the half pirouette at walk in three strides; the remaining horses used four strides. This is consistent with the FEI rules, which stipulate three to four strides in a half pirouette. None of the horses maintained a regular four-beat rhythm in the walk pirouette. Instead, the footfall of the inside hind limb occurred relatively early in the stride. Consequently, the time between footfalls of the outside fore and inside hind hooves was short, while the time between footfalls of the inside hind and inside fore hooves was long (Fig. 14.11). This indicates that, to compensate for the lack of forward movement, the horses become more reliant on the inside hind limb to maintain their balance.

The trot

The trot is a two-beat gait in which the diagonal pairs of limbs move more or less synchronously, and the footfalls of the diagonal limb pairs are evenly spaced in time. The diagonal support phases are usually separated by periods of suspension, except in a very slow (jog) trot. Therefore, each stride has two diagonal support phases and two suspensions. In young horses, an accelerometric study showed that judges awarded higher marks to horses showing a slow trot with a large amount of dorsoventral displacement of the trunk (Biau & Barrey, 2004).

Slow motion analysis has shown a slight dissociation between ground contact and lift-off of the diagonal fore and hind limbs. The interval between the fore and hind contacts is known as diagonal dissociation. The value is positive if the hind limb contacts the ground before the forelimb, zero if the diagonal pair contact the ground simultaneously, and negative if the hind limb contacts the ground after the forelimb. Positive diagonal dissociation at contact (Fig. 14.9) is considered a desirable characteristic that is indicative of good balance (Holmström et al., 1995). It occurs in horses that travel with an elevated forehand, which is a characteristic of collection. However, a negative diagonal dissociation does not preclude a horse from being successful in dressage. In the Seoul Olympics, 15% of the extended trot strides that were analyzed had a negative diagonal dissociation at contact (Deuel & Park, 1990).

Four types of trot are performed in competition: collected, working, medium and extended. Table 14.10 shows that speed and stride length differ significantly between each type of trot, and stride frequency is significantly slower in collected than extended trot (Clayton, 1994a), which does not meet the requirements to maintain a constant stride frequency. Deuel and Park (1990) have shown a positive relationship between speed and stride length and a negative relationship between speed and stride duration in a group of top-level competitors. Interestingly, dressage horses that qualified for the individual medal finals in the Seoul Olympics tended to have faster speeds, longer stride lengths and higher stride frequencies in the extended trot than horses that failed to qualify (Deuel & Park, 1990).

Stride length at the trot depends on the diagonal distance (distance between the diagonal pair of limbs during their stance phase) and the tracking distance (distance between the fore hoof and the next contact of the ipsilateral hind hoof). Diagonal distance shows a non-significant increase of 4.0–5.0 cm between working and medium trot, which is probably a consequence of the lengthening of the horse's frame. However, most of the lengthening of the stride is a result of greater over-tracking (46 cm increase from collected to extended trot), which represents the distance covered during the suspension (Clayton, 1994a). The best way to increase over-tracking and, therefore, stride length is to prolong the suspension by pushing-off with a higher vertical velocity. Suspension in the medium and extended trots is twice as long as that of the collected and working trots (Clayton, 1994a).

In the highest scoring dressage horses in the Seoul Olympics the speed of the extended trot was strongly influenced by stride length but not closely related to stride duration (Deuel & Park, 1990). This indicates greater reliance on changes in stride length rather than stride frequency in elite dressage horses. The speed of the extended trot (4.93 m/s) in the national level competitors studied by Clayton (1994a) is similar to the speed recorded in Olympic competitors (4.98 m/s) by Deuel and Park (1990). However the Olympic competitors achieved this speed using a longer stride length (3.79 m versus 3.55 m) and a longer stride duration (0.763 s versus 0.722 s). Therefore, horses of a slightly lower caliber achieve the speed required in the extended trot using shorter, faster strides.

The stance durations of the forelimbs and hind limbs do not differ from each other in any type of trot (Clayton, 1994a), but both the fore and hind stance durations are significantly shorter in extended trot than in collected trot. The angles of the cannon segment to the horizontal are significantly more acute at hoof contact and more obtuse at lift-off in the extended trot than in the collected trot (Clayton, 1994a). The hind cannon consistently has a more acute angle to the ground on its plantar side than the fore cannon throughout the stance phase. The difference ranges from about 10° at hoof contact to 20° at lift-off.

Table 14.10 Mean values for stride kinematics of the collected, working, medium and extended trots in FEI level dressage horses

	Collected trot	Working trot	Medium trot	Extended trot
Speed (m/s)	3.20^{a}	3.61^{b}	4.47^{c}	4.93^{d}
Stride length (m)	2.50^{a}	2.73^{b}	3.26^{c}	3.55^{d}
Stride frequency (strides/min)	77^{a}	$79^{a,b}$	$82^{a,b}$	83^{b}
Diagonal distance (cm)	132^{a}	$132^{a,b}$	$136^{a,b}$	137^{b}
Tracking distance (cm)	-7^{a}	4^{b}	27^{c}	39^{d}
Suspension (ms)	16^{a}	17^{a}	32^{b}	37^{b}

Different superscripts indicate values that differ significantly ($p < 0.05$).

Data from Clayton (1994a).

Fig 14.12 'Salinero' ridden by Anky van Grunsven performing passage and showing elevation of the hooves in midswing.

Courtesy of Jacob Melissen, The Netherlands.

The passage

According the FEI Rules for Dressage, passage is a measured, very collected, elevated and cadenced trot. It is characterized by a pronounced engagement of the hindquarters, a more accentuated flexion of the knees and hocks, and the graceful elasticity of the movement (Anon, 2009). The limbs pause momentarily at their position of maximal elevation (Fig. 14.12), when the toe of the raised forefoot should be level with the middle of the cannon bone of the other supporting forelimb. The toe of the raised hind foot should be slightly above the fetlock joint of the other supporting hind limb (Anon, 2009). None of the horses competing in the individual medal finals at the Barcelona Olympics achieved the required elevation in the forelimbs in passage (Argue, 1994). The diagonal limb pairs move more or less in synchrony in passage but with a pronounced positive diagonal dissociation (Clayton, 1997a; Holmström et al., 1995; Weishaupt et al., 2009), which is longer in the more successful competitors (Clayton, 1997a).

Stride length and speed are significantly reduced from collected trot to passage and from passage to piaffe (Table 14.11). Passage and piaffe have the same stride frequency, which is significantly slower than that of collected trot (Clayton, 1997a).

Kinematic analysis indicated that the stifle and tarsal joints were more flexed at ground contact and the tarsus was also more flexed in midstance in passage compared with collected trot (Holmström et al., 1995). For horses moving on a treadmill, there was more lumbosacral flexion throughout the stride in passage than in collected trot (Weishaupt et al., 2009).

The ground reaction forces in passage resemble those of the collected trot in horses moving overground (Clayton, unpublished). The forelimbs have a higher peak vertical force than the hind limbs. The longitudinal GRF is almost entirely retarding in the forelimbs, and almost entirely propulsive in the hind limbs. The forelimbs have the effect of elevating the forehand, while the hind limbs provide forward and upward propulsion (Fig. 14.13). On a treadmill, passage shows higher vertical impulses than collected trot in the fore and hind limbs without an increase in peak vertical forces. The load shifts from the fore to the hind limb of the diagonal pairs (Weishaupt et al., 2009).

Table 14.11 Mean values for stride kinematics of the collected trot, passage and piaffe in dressage horses competing in the individual medal finals at the Barcelona Olympics

	Collected trot	Passage	Piaffe
Speed (m/s)	3.3^{a}	1.6^{b}	0.2^{c}
Stride length (m)	2.50^{a}	1.75^{b}	0.20^{c}
Stride frequency (strides/min)	71^{a}	55^{b}	55^{b}

Different superscripts indicate values that differ significantly ($p < 0.05$).

Data from Clayton (1997a).

The piaffe

Piaffe (or piaffer) is a highly collected, cadenced, elevated diagonal movement giving the impression of remaining in place. The horse's back is supple and elastic. The hindquarters are lowered; the haunches with active hocks are well engaged, giving great freedom, lightness and mobility to the shoulders and forehand. Each diagonal pair of legs is raised and returned to the ground alternately, with spring and an even cadence (Anon, 2009). As in passage, the limbs pause momentarily at their position of maximal elevation.

Stride duration is longer in piaffe than in collected trot but is similar in piaffe and passage (Clayton, 1997a; Holmström et al., 1995). The rules require piaffe to be performed in place in the Grand Prix test, whereas in the Intermediate II test the horse is allowed to move forward with a stride length of 20 cm (Table 14.11), which is in accordance with the amount of forward progression recorded during Olympic competition (Argue, 1994). Since piaffe has little, if any, forward momentum, horses maintain their balance by increasing the stance durations and overlaps between limbs. Piaffe has longer fore, hind and diagonal stance durations than passage or trot and these are associated with longer overlaps between limbs (Clayton, 1997a). There is always at least one hoof in contact with the ground, so piaffe has no suspension phase (Holmström et al., 1995; Clayton, 1997a). Therefore, piaffe is a stepping gait, rather than a leaping gait, with a gradual transfer of body weight from one diagonal to the other. The amount of overlap between successive diagonal stance phases is, however, shorter in the better-quality piaffe (Clayton, 1997a).

Each horse performs the piaffe with its own, highly individualized coordination pattern and, although the mean value of the diagonal dissociation at contact for piaffe in a group of horses was negative (Argue, 1994; Holmström et al., 1995), the best competitive horses had a positive diagonal dissociation (Clayton, 1997a). Piaffe is a highly collected gait and the collection is associated with more pelvic tilting throughout the stride cycle, greater stifle and tarsal flexion at the start of stance and greater tarsal flexion at midstance compared with passage and collected trot. Horses do not, however, step further underneath themselves in piaffe than in passage or collected trot (Holmström et al., 1995).

A unique feature of piaffe is the GRF profiles (Clayton, unpublished data). The vertical GRF has a smaller amplitude than passage or collected trot and the trace has a flattened profile during the long

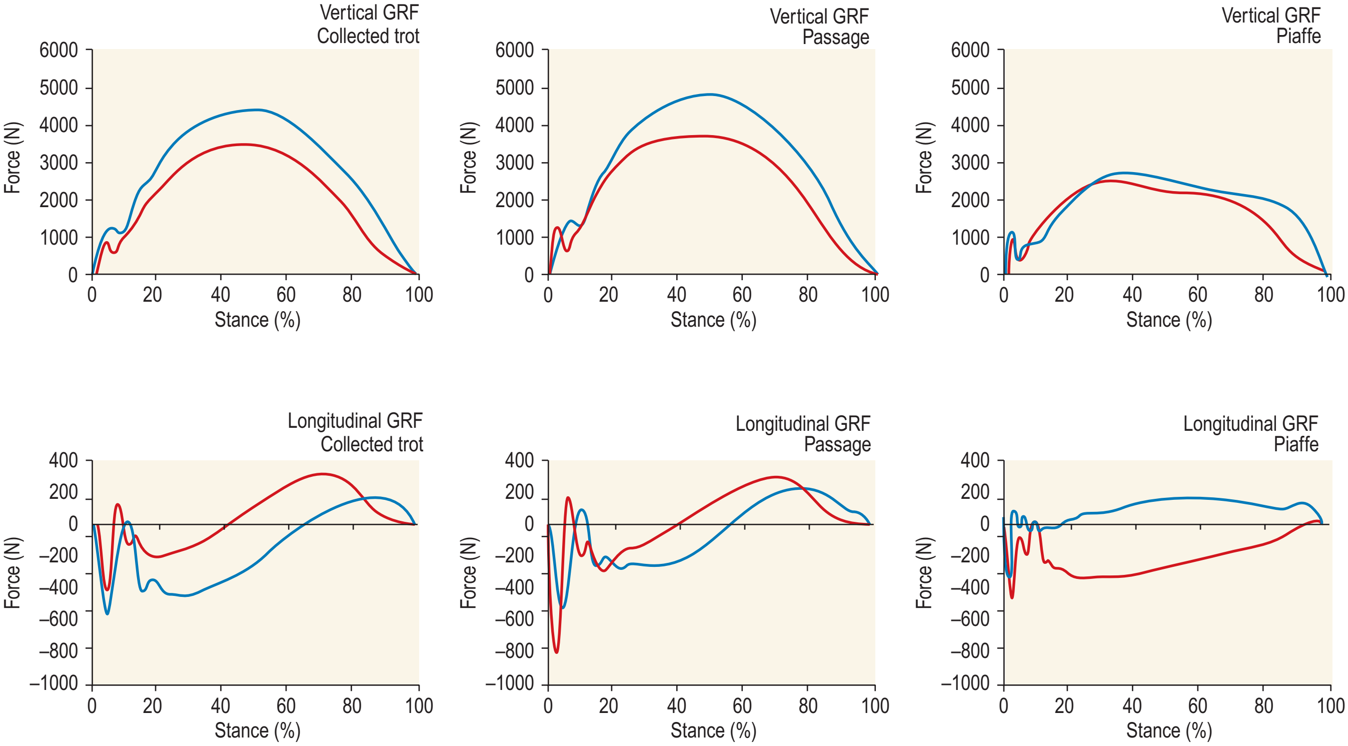

Fig 14.13 Vertical (above) and longitudinal (below) ground reaction forces for collected trot (left), passage (center) and piaffe (right) for the forelimbs (blue line) and hind limbs (red line).

Table 14.12 Stride kinematics of the collected, working, medium and extended canters in FEI level dressage horses

	Collected canter	Working canter	Medium canter	Extended canter
Speed (m/s)	3.27^{a}	3.91^{b}	4.90^{c}	5.97^{d}
Stride length (m)	$2.00^{a,b,c}$	$2.35^{a,d,e}$	$2.94^{b,d,f}$	$3.47^{c,e,f}$
Stride frequency (strides/min)	99^{a}	99^{a}	101^{a}	105^{a}
Suspension (ms)	$0^{a,b}$	$5^{c,d}$	$54^{a,c}$	$87^{b,d}$

Different superscripts indicate values that differ significantly ($p < 0.05$).

Data from Clayton (1994b).

stance phase (Fig. 14.13). The longitudinal force is almost entirely propulsive in the forelimbs and almost entirely braking in the hind limbs (Fig. 14.13), which is the opposite of passage and collected trot.

The canter

The canter is the only asymmetrical gait of dressage horses. It has a transverse sequence of limb placements, so the leading fore and hind limbs are on the same side of the body. Four types of canter are performed in dressage competitions: collected, working medium, and extended, which have significantly different speeds (Clayton, 1994b). The stride frequency is the same for the different types of canter, so changes in speed are accomplished by alterations in stride length (Table 14.12). Stride length increases as a result of a small increase in the distance between the two hind limbs, a small increase in the distance between the two forelimbs, and a large increase in the distance covered during the suspension. The ability to generate a high vertical velocity at the start of the suspension allows the horse to stay airborne longer and to cover a greater distance during the suspension.

For horses competing in the individual medal final at the Seoul Olympic Games, the speed of the extended canter (7.03 m/s) was considerably faster than that recorded in slightly lower-caliber national level competitors (5.97 m/s). The difference was primarily a result of a longer stride length (4.15 m versus 3.47 m), which was combined with a slightly slower stride frequency (101 strides/min in the national level horses versus 105 strides/min in the Olympic competitors). Higher overall competition scores have been recorded for horses with faster speeds and longer stride lengths in the extended canter. No upper limit was detected for optimal stride length (Deuel & Park, 1990). Higher scoring horses also showed shorter periods of ground contact of the limbs, while increasing both the duration and distance covered during the suspension.

The rhythm of the stride differs between the collected and extended canters (Clayton, 1994b). In collected canter, the three footfalls are separated by relatively long intervals but the suspension is relatively short. In extended canter the three footfalls are further

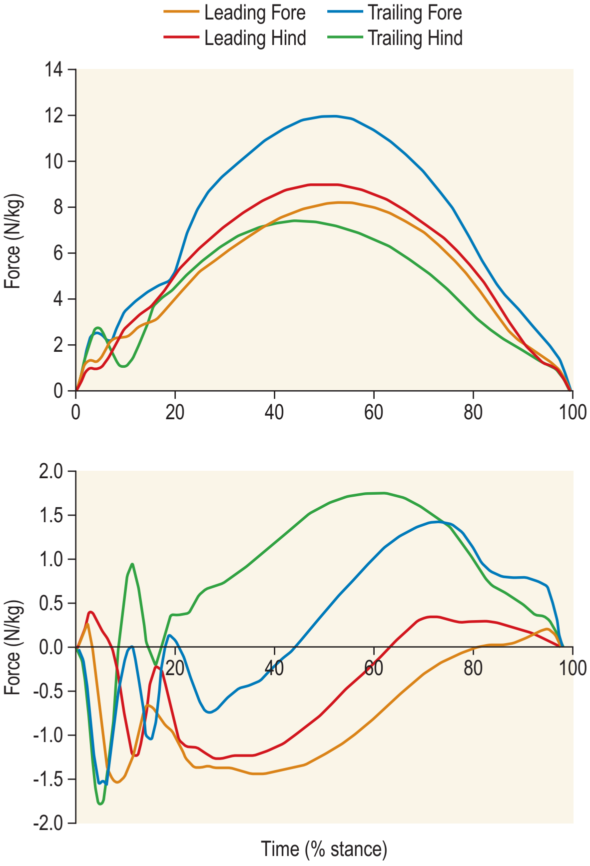

Fig 14.14 Vertical (above) and longitudinal (below) ground reaction forces of the four limbs in the canter.

apart spatially but are more closely grouped temporally and the suspension is longer. The diagonal limb pair (leading hind and trailing fore) do not always make contact with the ground synchronously, though the dissociation is very small and usually only detectable with the aid of slow motion analysis. In the extended canter either the fore or hind limb may contact the ground earlier (Deuel & Park, 1990; Clayton, 1994b).

The ground reaction forces at the canter (Merkens et al., 1993) show marked differences between the trailing and leading limbs (Fig. 14.14). In collected canter the peak vertical ground reaction force is smallest in the trailing hind limb (approximately equal to body weight) and largest in the trailing forelimb (1.5 times body weight). The peak vertical force in the leading hind and leading forelimbs was approximately 1.2 times body weight. With regard to the longitudinal ground reaction force, the trailing hind limb is primarily propulsive; it acts to change the direction of movement of the center of mass from forward and downward to forward and horizontal. The leading hind limb and trailing forelimb (diagonal pair) are principally responsible for supporting the body weight and supplying forward propulsion, with the trailing forelimb having a particularly large propulsive component. The leading forelimb raises the center of mass as the horse moves into the suspension by exerting large vertical and braking forces.

Lead changes at the canter

When a dressage horse performs a flying lead change, the leading hind limb and leading forelimb change during the suspension phase. In high-level competitions, lead changes are performed in series at intervals of four, three, two or one strides. The characteristics of the canter strides during the two tempi (alternate stride) and one tempi (every stride) lead changes are shown in Table 14.13 (Deuel & Park, 1990). During the lead changes, all four limbs have long stance durations and short swing durations, and there is a diagonal dissociation with contact of the leading hind hoof preceding that of the trailing fore hoof by 14.0–24.0 ms.

Table 14.13 **Stride variables for the one tempi and two tempi lead changes**

	One tempi stride	Two tempi strides before change	Two tempi strides after change
Speed (m/s)	3.36	3.65	3.95
Stride length (m)	2.08	2.21	2.44
Hind step TrH–LdH (m)	0.94	0.87	0.88
Diagonal step LdH–TrF (m)	0.97	0.97	0.93
Fore step TrF–LdF (m)	0.80	0.79	0.89
Suspension LdF–TrH (m)	–0.53	–0.47	–0.33
Stride frequency (strides/min)	97	99	97

LdF, leading forelimb; LdH, leading hind limb; TrF, trailing forelimb; TrH, trailing hind limb.

Data from Deuel and Park (1990).

In the two tempi changes (Deuel & Park, 1990), the stride immediately preceding the change (pre-change stride) has a slower speed, shorter stride length and higher stride frequency than the stride following the change (post-change stride). The shorter stride length of the pre-change stride is a result of taking a shorter step between the two forelimbs and covering less distance during the suspension (Table 14.13). In pre-change strides ground contact of the trailing forelimb precedes that of the leading hind limb, whereas in the post-change strides the sequence is reversed.

In the one tempi lead changes, the strides share characteristics of both the pre- and post-change strides in the two tempi changes (Table 14.13). The support sequence varies between horses, reflecting individual differences in technique, but the diagonal dissociation almost always involves placing the leading hind limb before the trailing forelimb. There is a pronounced reliance on overlap between the two hind limbs in the early part of the stride, which is similar to the post-change stride for the two tempi changes. Later in the stride there is a reliance on forelimb overlap. Higher competition scores are associated with a longer time in hind limb support and a shorter time in forelimb support (Deuel & Park, 1990).

The canter pirouette

In the canter pirouette, horses are supposed to maintain the tempo and rhythm of the collected canter strides. However, a study of horses competing in the individual medal finals at the Barcelona Olympics showed that neither the tempo nor the rhythm of the collected canter strides was maintained in the canter pirouette. The tempo was significantly slower in the pirouette strides (68 strides/min) than in the collected canter strides (95 strides/min). The footfalls of the diagonal limb pair were dissociated in the pirouette strides, giving a distinct four-beat rhythm, in contrast

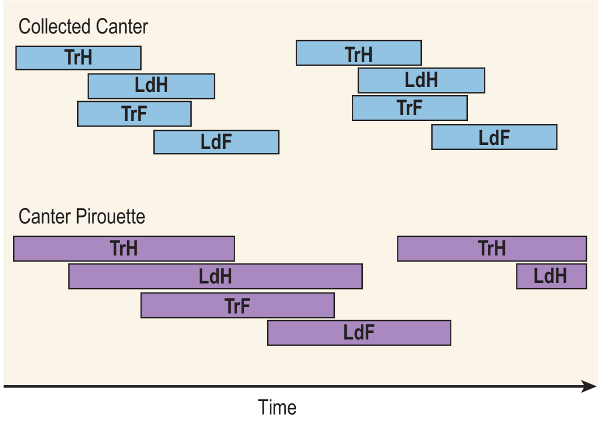

Fig 14.15 Temporal characteristics of the collected canter strides and the canter pirouette strides. The shaded bars represent the stance phases of the limbs. LdF, leading forelimb; LdH, leading hind limb; TrF, trailing forelimb; TrH, trailing hind limb.

to the three-beat rhythm of the canter strides. Also, there was no suspension between successive pirouette strides (Burns & Clayton, 1997).

The lack of forward movement in the pirouette makes it difficult for the horse to maintain its balance. The horse compensates by increasing the limb stance durations and the overlaps between limbs (Fig. 14.15). This was particularly obvious for the inside hind limb, in which the stance duration was greatly prolonged as a means of maintaining the horse's balance in the absence of forward movement (Burns & Clayton, 1997).

The capriole

Knezevic et al. (1987) used high-speed cinematography to describe the capriole in a Lipizzan stallion at the Spanish Riding School in Vienna. This is a movement in which the horse elevates the forehand, then leaps into the air and, at the culmination of the airborne phase, kicks backwards with the hind limbs. At the culmination of the leap, the ventral rump contour was 158 cm above the ground. The hip, stifle and tarsal joints showed extreme extension when the hind limbs were fully stretched behind the horse. Maximal extension of the fetlock and coffin joints occurred about 20 ms later.

Transitions

A study of transitions between the walk and trot classified the transitions into two types (Argue & Clayton, 1993a). Type 1 transitions are those in which all the limb support sequences are typical of the walk or trot. Type 2 transitions include intermediate steps between the two gaits in which the support sequences are not typical of either gait. Type 1 transitions are thought to be more desirable and should be rewarded by judges. The likelihood of performing a type 1 transition may be influenced by the skill of the rider in giving the aids at the appropriate time in the stride.

For the transitions from walk to trot, in a type 1 transition the horse springs from a diagonal support phase in the walk directly into the trot. Type 2 transitions are initiated from either a diagonal or a lateral support phase in the walk. From a diagonal support phase, either the fore or hind hoof is raised, then the opposite diagonal pair is placed for a three-limb support. The original fore or hind limb is lifted, and the horse springs from the remaining diagonal pair into the trot. In the transitions initiated from a lateral support phase, one limb is raised leaving a single supporting limb. The diagonal fore or hind limb is then placed to give a diagonal support phase from which the horse springs into the trot. The ability to perform type 1 transitions from walk to trot is significantly related to level of training; more highly trained horses perform a larger number of type 1 walk–trot transitions (Argue & Clayton, 1993a).

Trot to walk transitions are initiated by placement of the second forelimb during a diagonal support phase at the trot. In type 1 transitions, the horse then proceeds in the walk. In type 2 transitions, the tripedal support phase is followed by lifting of the diagonal pair leaving a forelimb in single support. The diagonal hind limb is then placed, and the horse continues in a normal walk sequence. The frequency of type 1 transitions from trot to walk is significantly related to level of training, with the more highly trained horses showing a higher percentage of type 1 transitions (Argue & Clayton, 1993a).

Transitions between trot and canter are differentiated according to whether the horse initiates the canter from a forelimb or a hind limb (Argue & Clayton, 1993b). Neither type of transition involves limb support sequences that are not typical of the trot or canter. A transition initiated by the forelimb starts with a diagonal support phase in trot. The opposite forelimb is then placed on the ground and it becomes the leading limb as the horse continues in a canter sequence. For the transitions initiated by a hind limb, the forelimb is lifted during the diagonal support phase of the trot. The hind limb that remains on the ground becomes the trailing hind limb. The diagonal pair (leading hind–trailing forelimbs) are then placed on the ground and the horse continues in a canter sequence. The type of trot to canter transition is not related to the horse's level of training.

Two types of transitions were observed between canter and trot. In one type, the horse initiates the change by springing from the diagonal support phase of the canter to the opposite diagonal and then continues in the trot. The other type of transition is initiated from the leading forelimb single support. Instead of proceeding into a suspension, the trailing hind limb is placed on the ground to give a diagonal support phase, from which the horse springs into a suspension and continues in a trot sequence. The type of transition from canter to trot is not related to level of training (Argue & Clayton, 1993b).

A different study (Biau et al., 2002) used an accelerometer attached beneath the sternum to measure dorsoventral and longitudinal acceleration during downward transitions from canter to trot, canter to walk, canter to halt, trot to walk, trot to halt and walk to halt. Wavelet analysis indicated that duration of the transition, and the energy and frequency of the dorsoventral acceleration distinguished between the types of transitions. Dressage training was associated with an increase in the duration of the transition and minimization of the variation in energy and frequency.

Conformation of dressage horses

Elite dressage horses tend to have short necks, which perhaps reduces the leverage of the head and neck and so facilitates collection and self-carriage. In the forelimb, the scapula is sloping and the elbow joint has a large angle. A long humerus, a small hip angle and a long sloping femur are associated with high gait scores. The fore and hind phalanges tend to be long and upright (Holmström et al., 1990).

Jumping

Jumping sports require the horse to raise the center of mass (CM) high enough for all body parts to clear the height and width of an obstacle. The phase of the stride in which the horse jumps is an extended suspension. The pattern of lift-off from the hind limbs and landing on the forelimbs is most easily incorporated into the canter or gallop stride, though horses can also jump from the trot, walk or even the halt.

Terminology

Terminology for the strides during the approach to and departure from a fence for horses jumping at a canter has been described (Clayton, 1989a). The stride in which the jump occurs is the jump stride; its components are the lift-off, jump suspension and landing. The lift-off comprises the stance phases of the two hind limbs immediately preceding the jump. The jump suspension is the airborne phase starting when the last hind limb leaves the ground at lift-off and ending at ground contact of the trailing forelimb during landing. The landing comprises the stance phases of the two forelimbs after the jump suspension. The strides preceding the jump stride are the approach strides and those following the jump stride are the departure strides. Both the approach and departure strides are numbered from the jump outwards (Fig. 14.16).

Jumping mechanics

The approach and lift-off

The path of the horse's CM and the angular momentum of its body during the jump suspension are determined during the lift-off. After the jump suspension begins, these properties cannot be changed until the horse makes contact with another object or with the ground. Therefore, the approach and lift-off are extremely important in determining the outcome of the jump.

The positions of the limb placements on the lift-off side do not differ between a vertical fence and an oxer, or between fences of different heights in the range of 1.10–1.40 m. One study showed that, in 92 of 96 trials, the limb placed closest to the fence on the lift-off side was the leading forelimb in approach stride 1. In the remaining four trials, all of which were over fences, the limb placed closest to the fence was the leading hind limb (Clayton & Barlow, 1989). Fewer knock-downs occurred when there was a larger distance between the trailing forelimb in approach stride 1 and the base of the fence (Deuel & Park, 1991).

The timing and coordination of the limb movements during the approach, jump stride, and departure are shown in Table 14.14. Approach stride 2 and the strides that precede it are fairly typical canter strides performed with an elevated head and neck position. The ability to maintain a high stride frequency during the approach strides is a characteristic of good jumpers (Barrey & Galloux, 1997).

Approach stride 1 is a short, quick stride; both the stride length and stride duration are significantly shorter than in approach stride 2. This stride has a distinctly four-beat rhythm with the leading hind limb contacting the ground before the trailing forelimb. The neck is stretched forward and downward in preparation for lift-off. This action is similar to the 'gather' shown by human jumpers during the transition between the approach and lift-off. The objective of the gather is to lower the CM prior to the lift-off foot contacting the ground. This minimizes the need to overcome a downward movement of the CM before driving the body into the air. It has even been suggested that the amount of lowering during the gather bears a direct relationship to the height jumped. The leading hind limb has a very short stance duration in approach stride 1 and the horse's body does not roll forward over this limb as in a normal stride. The forelimbs are stretched forward at ground contact and, consequently, have a relatively small angle between the palmar aspect of the metacarpus and the ground (Clayton & Barlow, 1991). The forelimbs initiate the upward movement of the forehand, converting forward movement into vertical movement. This involves reducing the horizontal speed, elevating the forehand and rotating the trunk segment into an appropriate position for lift-off. Because the forehand is already starting to move upwards, the leading forelimb is pulled off the ground relatively early, when it is more or less in a vertical position.

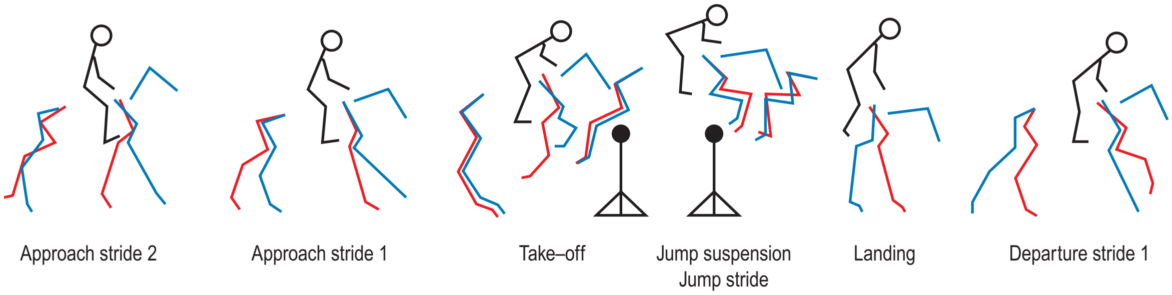

Fig 14.16 Terminology for the strides preceding and following the jump.

Table 14.14 **Stride characteristics of horses jumping a vertical fence 1.55 m high**

	Approach stride 1	Approach stride 2	Jump stride	Departure stride 1
Horizontal speed (m/s)	7.3	6.3	5.9	6.5
Stride length (m)	4.07	2.39	4.87	3.35
Stride frequency (strides/min)	108	157	73	116
Stance TrH (ms)	157	145	197	147
Stance LdH (ms)	179	129	195	171
Stance TrF (ms)	149	188	140	174
Stance LdF (ms)	134	159	176	168

LdF, leading forelimb; LdH, leading hind limb; TrF, trailing forelimb; TrH, trailing hind limb.

Data from Clayton and Barlow (1991).

When a horse jumps a fence that is less than 1 m high, it requires little, if any, elevation of the CM to clear the fence and, consequently, the forces required to jump a small fence are not much greater than those in a canter stride. For example, in jumping a fence 0.8 m high, the combined vertical impulses of the fore and hind limbs increase by only about 8% on the lift-off side and 3% on the landing side. For fences higher than about 1.0 m, the need to elevate the CM increases progressively with the height of the fence, with a consequent increase in the vertical forces at lift-off and landing. A considerable increase in vertical forces has been recorded when the height of the fence was raised from 1.3 to 1.5 m (Fig. 14.17) (Schamhardt et al., 1993), and a vertical force of 3.85 times body weight has been measured in a horse jumping a vertical fence 1.53 m high (Preuschoft, 1989). Both forelimbs exert a large braking impulse that decelerates the forward movement. The trailing forelimb provides a little propulsion in the terminal part of its stance phase, but the leading forelimb provides only a braking force as a result of the early cessation of its stance phase (Schamhardt et al., 1993). The braking action of the forelimbs causes a reduction in horizontal velocity (Clayton & Barlow, 1991) and an upward acceleration of the trunk segment (Barrey & Galloux, 1997). After the forelimbs leave the ground, the head and neck are raised, which helps to establish an advantageous position for optimal power production during the push-off by the hind limbs.

A short suspension intervenes between approach stride 1 and the jump stride. The jump stride is distinguished from the preceding and following strides by the inclusion of the jump suspension, which results in significant increases in stride length and stride duration. At lift-off the hind limbs often contact the ground synchronously and at almost equal distances from the fence. Their functions are to provide upward and forward propulsion, and to reverse the direction of rotation of the trunk segment. Forward rotation of the trunk is necessary for the horse to leave the ground from the hind limbs and land on the forelimbs. Both hind limbs have relatively long stance durations, which allows the generation of large impulses. The two hind limbs show almost identical ground reaction force profiles. The vertical force rises to a plateau, with a peak amplitude around 130% body weight for a horse jumping a vertical fence 1.3 m high. The longitudinal forces are predominantly propulsive (Fig. 14.17) (Schamhardt et al., 1993).

Studies using an accelerometer attached to the thorax beneath the sternum have shown that the action of the hind limbs produces a lower acceleration peak on the trunk segment than the push-off by the forelimbs (Fig. 14.18). However, the inclination of the trunk axis during the hind limb push-off reduces the amplitude registered by the direction-sensitive accelerometer, so the acceleration due to the hind limb action may be underestimated. The hind limb acceleration peak at lift-off is significantly greater for fences with width (oxer, 1.48 g; water jump, 1.74 g) than for those with height only (vertical, 1.27 g) (Barrey & Galloux, 1997). This is because the flight path must be higher and longer when jumping a wider obstacle.

For elite show jumping horses jumping a vertical fence 1.50 m high during an international competition (Bogert et al., 1994), a similar movement pattern was observed in all horses during lift-off. The duration of the lift-off phase averaged 221 ms. At the start of lift-off the trunk was rotating backwards with an angular velocity of 150°/s. The direction of rotation changed almost linearly to 50°/s forward rotation at the start of the jump suspension. During this time the horizontal velocity initially decreased from 4.5 m/s at the start of lift-off to 3.6 m/s, then increased to 6.5 m/s at lift-off. The vertical velocity, which was zero at the start of lift-off, reached a negative value of 1.0 m/s before increasing to 4.0 m/s at lift-off. The initial downward movement of the trunk was a result of the total vertical GRF being less than body weight. The neck rotated downward relative to the trunk throughout lift-off with an almost constant angular velocity.

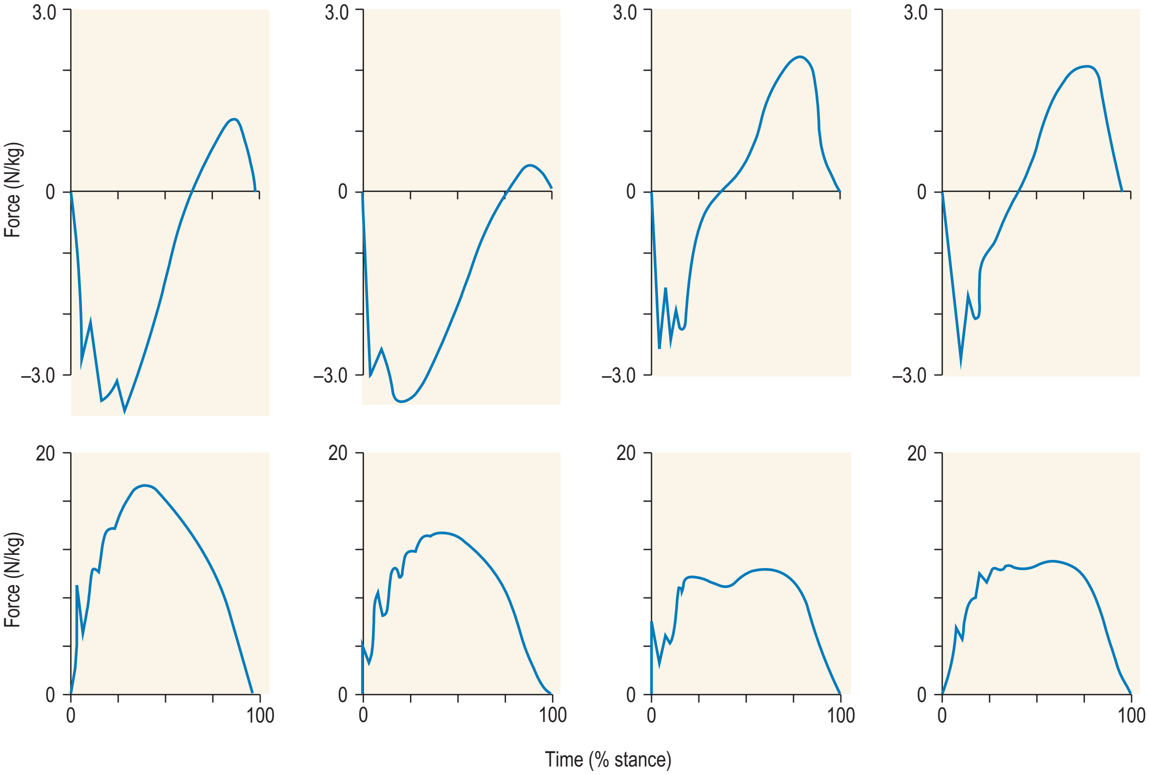

Fig 14.17 Longitudinal (above) and vertical (below) ground reaction forces during the approach and lift-off for a horse jumping a vertical fence 1.1 m high. The traces from left to right represent the trailing forelimb in approach stride 1, the leading forelimb in approach stride 1, the trailing hind limb at lift-off and the leading hind limb at lift-off. Stance durations of the limbs are: trailing forelimb, 0.20 s; leading forelimb 0.18 s; trailing hind limb, 0.21 s; leading hind limb, 0.22 s).

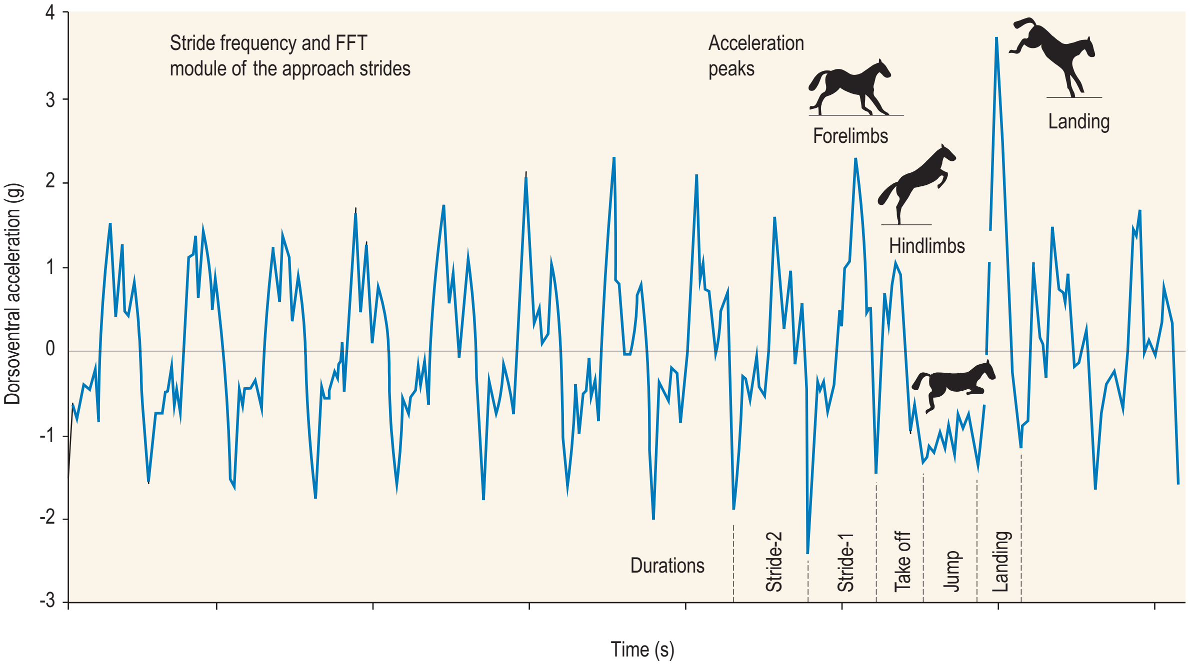

Fig 14.18 Dorsoventral accelerometer recording of the approach, lift-off, jump suspension, landing and departure. FFT, Fast Fourier transformation.
Reprinted from Barrey & Galloux (1997) © EVJ Ltd.

The hip joint extended during the first 152 ms at lift-off, then maintained the same angle until leaving the ground. The stifle and hock joints initially flexed then extended with the transition from flexion to extension occurring earlier in the hock than the stifle. The fetlock showed two phases of extension with a relatively constant angle in the period between. Maximal fetlock extension occurred late in the stance phase after which there was rapid flexion. The total power production by the hind limbs was estimated to be 13 000 J in this study, which represents an average power production of 59 000 W (or about 100 W/kg) during the lift-off phase. These findings indicate that most of the energy required to clear the fence is provided by the hind limbs during lift-off (Bogert et al., 1994). Power production, however, appears to be very dependent on the height of the fence and the speed with which it is approached. In the study by Bogert et al. (1994), fence height was 1.50 m. Dutto et al. (2004) studied horses jumping a much lower fence (0.63 m) which they approached at trot not canter; these authors calculated a power output during hind limb push of only 30 W/kg. When studying horses jumping a 1.15 m obstacle, Bobbert and Santamaría (2005) found a value of 75 W/kg. In the latter study the authors also investigated the contribution of the forelimbs. They calculated that during forelimb push-off total energy first decreased by 3.2 J/kg and then increased again by 4.2 J/ kg. Energy stored in the elastic structures of the limb was calculated to be only 0.4 J/kg in the trailing forelimb and 0.23 J/kg in the leading forelimb. From this observation it was concluded that the forelimbs are not merely used as passive springs, but a considerable amount of energy is first dissipated and then regenerated by muscular power.

Each horse has its own individual jumping technique that is repeatable from jump to jump and produces a characteristic acceleration profile (Barrey & Galloux, 1997). Over a small fence, 0.8 m high, horses with good technique that folded their lower limbs during the jump suspension, and had vertical and longitudinal force profiles that were similar in shape and magnitude to those of a canter stride. However, a horse with poor jumping technique registered considerably higher forces both at lift-off and landing (Schamhardt et al. 1993). The forces used by a poor jumper over a fence 0.8 m high were similar in magnitude to those used by a good jumper over a fence 1.3 m high. It might be expected from these results that horses with poor technique would show earlier signs of wear and tear injuries than horses with good technique. Poor jumpers, even when they clear a fence, tend to have a higher ratio between the acceleration provided during lift-off by the forelimbs and the hind limbs. In other words, they increase the braking action of the forelimbs in approach stride 1 to compensate for a weak acceleration impulse of the hind limbs at lift-off (Barrey & Galloux, 1997).

The jump suspension

The jump stride has a much longer stride length than the approach or departure strides due to the distance covered during the jump suspension. In one study the total distance jumped from lift-off to landing did not differ between a vertical fence and an oxer, but increased significantly with fence height (Clayton & Barlow, 1989). In a different study, the jump distance was longer over an oxer than a vertical fence, with the increase being approximately equal to the spread of the oxer (Deuel & Park, 1991).

After lift-off, the motions of the body and limb segments are coordinated so that the angular velocity of the trunk remains almost constant throughout the jump suspension. All the segments act synergistically with the approximate contributions of the different segments to the angular momentum being 50% from the trunk, 25% from the hind limbs, 2% from the head–neck and 5% from the forelimbs (Galloux & Barrey, 1997). The presence of the rider has virtually no effect on rotation of the horse's body.

As the horse passes over the top of the fence, the forelimbs generally have less clearance than the hind limbs, and clearance by all limbs decreases with fence height (Jelen, 1976). Furthermore, a good horse paired with a good rider shows a smaller discrepancy between the height of the fence and the height of the limbs; in other words horses show less tendency to over-jump with a good rider. Most jumping errors are a result of inappropriate aids from the rider (Lauk et al., 1991). A study of trunk accelerations showed that 87% of jumping faults could be blamed on a forelimb error (Barrey & Galloux, 1997). More faults occur at vertical fences than at oxers or water jumps.

The landing and departure

During landing, the two forelimbs are separated by only a short distance. The metacarpal segment of the trailing forelimb (the first limb to land) is almost vertical when the hoof makes ground contact while the leading forelimb contacts the ground with a more acute angulation (Clayton & Barlow, 1991). The trailing hind limb is usually placed between the previous placements of the two forelimbs, and this characteristic is associated with fewer jumping penalties (Deuel & Park, 1991). The leading hind limb is placed further away from the fence than the forelimbs.

The placements of the leading forelimb and the leading hind limb on the landing side are closer to the last element of an oxer than a vertical at all fence heights, and there is a trend toward landing further from the vertical than the oxer for the other limbs. The limb displacements from the fence on the landing side increase with fence height but this effect becomes less apparent in the later strides as the horse moves away from the fence (Clayton & Barlow, 1991). Therefore, the fewer the strides between fences in a combination, the more important it is to take into account the height and type of the in-going fence in determining the appropriate distance between fences.

During landing the trailing forelimb has a very short stance duration as the horse rapidly rolls forward onto the leading forelimb (Clayton & Barlow, 1991; Deuel & Park, 1991). Horses that have a longer time interval between contact of the two forelimbs are less likely to knock the fence down (Deuel & Park, 1991).

The trailing forelimb has the highest peak vertical forces both at lift-off and at landing (Fig. 14.19) (Schamhardt et al., 1993), which may explain the fact that some horses have a preferred lead for lift-off and landing and habitually switch to this lead one or two strides before the jump. These horses probably have either a subclinical lameness or a marked strength asymmetry between the left and right sides. The high peak vertical forces at landing in the trailing forelimb also translate to higher peak flexor joint moments and hence higher loading of the flexor tendons than in the leading forelimb (Meershoek et al., 2001a). In a study using an inverse dynamics approach Meershoek et al. (2001b) analyzed horses jumping fences of 0.8 , 1.0 m and 1.2 m and calculated peak forces in the suspensory ligament, the deep digital flexor tendon and its check ligament, and the superficial digital flexure tendon, which reached maximum values of 15 500 kN, 13 900 kN and 11 700 kN, respectively. When comparing the recorded values to the maximal load at rupture of these structures, it became clear that the superficial digital flexor tendon is loaded dangerously close to its limit during show jumping, possibly explaining the high incidence of lesions in this structure in jumping horses.

The forelimbs absorb the initial force of landing and this is reflected in the high peak amplitudes of the vertical forces, especially the trailing forelimb in which a vertical force peak of twice body weight has been recorded in a horse jumping a vertical fence 1.3 m high (Schamhardt et al., 1993). This limb makes ground contact with an almost vertical orientation, which is not conducive to generating a braking force. Therefore, the longitudinal force of the trailing forelimb at landing is entirely propulsive, whereas the leading forelimb exerts predominantly a braking force with a smaller propulsive component in its terminal part (Merkens et al., 1991; Schamhardt et al., 1993). The actions of the trunk, hind limbs and head and neck segments play a large role in reversing the direction of rotation of the horse's trunk which is necessary to allow the hind limbs to contact the ground underneath the body mass.

In departure stride 1 the horse regains its balance and the hind limbs re-establish forward movement by generating large propulsive longitudinal forces and impulses, especially in the trailing hind limb (Schamhardt et al., 1993). This stride has a four-beat rhythm

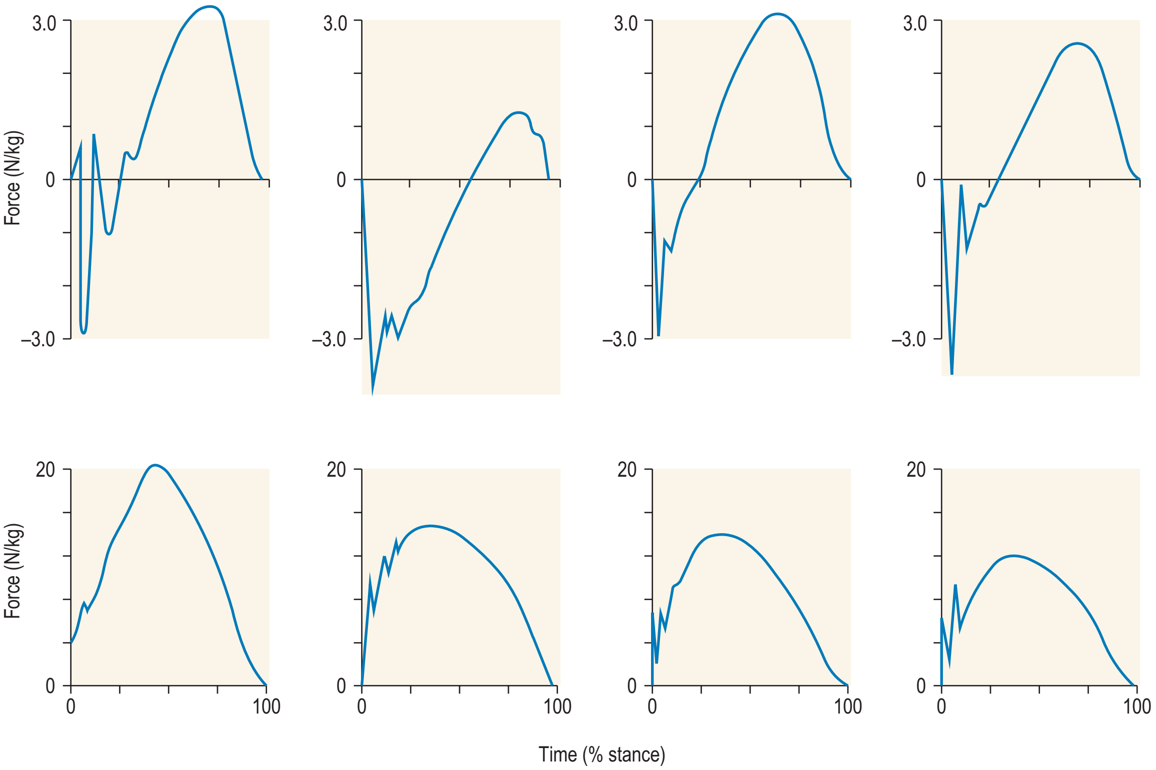

Fig 14.19 Longitudinal (above) and vertical (below) ground reaction forces during the landing and departure for a horse jumping a vertical fence 1.3 m high. The traces from left to right represent the trailing forelimb at landing, the leading forelimb at landing, the trailing hind limb in departure stride 1 and the leading hind limb in departure stride 1. Stance durations of the limbs are: trailing forelimb, 0.19 s; leading forelimb, 0.21 s; trailing hind limb, 0.17 s; leading hind limb, 0.22 s.

with the leading hind limb contacting the ground in advance of the trailing forelimb. The stride length is relatively short (Clayton & Barlow, 1991), and the distance between the two hind limb placements is particularly variable. Sometimes they are placed almost equidistant from the fence, other times they are widely separated. Fewer knock-downs were recorded when the trailing hind limb landed closer to the fence (Deuel & Park, 1991). A study of a two-stride double in which the two fences were separated by a distance of 10.96 m (Hole et al., 2002). The two intermediate strides had similar velocities, but the second intermediate stride had significantly shorter stride length and stride duration. The stride lengths of the two intermediate strides showed low inter-horse variability, but the step lengths were much more variable indicating that different horses achieved similar stride lengths using different combinations of step lengths. Compared with published descriptions of horses jumping a single fence of similar size, the first intermediate stride resembled the first departure stride and the second intermediate stride resembled the final approach stride.

Water jump technique

A study performed during the Barcelona Olympics identified the factors that influence success in clearing a water jump. The vertical velocity and the angle of projection at lift-off were significantly greater, and the horizontal distance between the leading hind limb and the CM at lift-off was significantly shorter, in horses that were successful in clearing the width of the water jump compared with those that failed to clear the entire width (Clayton et al., 1995, 1996; Colborne et al., 1995). The horizontal velocity at lift-off did not influence success, nor did the height of the CM at the start and end of the jump suspension. It was concluded that, to be a successful water jumper, a horse must generate a large vertical velocity during lift-off. Vertical velocity at the start of the jump suspension is highly correlated with trunk angle at lift-off and horizontal distance between the leading hind hoof and the horse's CM at both the start and end of lift-off (Colborne et al., 1995).

Puissance jumping technique

When jumping very high fences body position at lift-off is particularly important. In a study of horses during a puissance competition that started at a height of 1.80 m and ended in the last round at 2.27 m, success was significantly positively correlated with the following variables at lift-off: vertical velocity of CM, height of CM, distance of CM from the fence; and was significantly negatively correlated with the distance of the leading hind limb to the CM (Powers, 2005).

Conformation of jumping horses

The conformational trait that has been linked most consistently to successful jumping performance is height at the withers (Fabiani, 1973; Langlois et al., 1978), which is more important in this equestrian discipline than in dressage. The shoulder is preferably sloping and the fore pastern has been shown to be significantly larger in elite jumping (and dressage) horses compared to other riding horses (Holmström et al., 1990). Also, elite show jumpers have larger tarsal angles than other horses (Holmström et al., 1990). The ratio between the chest girth and wither height tends to be relatively low in good show jumpers, as does the ratio between cannon circumference and wither height (Fabiani, 1973). A long neck is thought to be an advantage for jumping horses, possibly because this feature makes it easier for the horse to maintain balance over the fence (Holmström, 2001). When the horse is viewed from behind, width through the hips and shoulders is desirable (Langlois et al., 1978). The length of the pelvis has a positive correlation with jumping ability and a forward sloping femur also correlates to good jumping performance. The latter feature has the strongest correlation to overall gait quality of all conformational variables (Holmström & Philipsson, 1993). Show jumpers have shorter backs than dressage horses, possibly related to the suppleness required in the dressage horse (Johnston et al., 2004).

Kinematics can, to a certain extent, be seen as a dynamic measure of conformation. In a study relating back kinematics to jumping performance using a relatively simple 4-marker set-up. Cassiat et al. (2004) found significant differences in kinematic patterns between good and poor jumpers when jumping a 1.0 m fence, from which they concluded that criteria based on back kinematics might be developed that could help in selecting talented show jumpers.

The effect of early training on jumping ability and the predictability of jumping performance

Unlike racehorses, peak performance in show jumpers and dressage horses is achieved at a later age (approximately 10–16 years). Therefore, the time lapse between birth and the final evaluation of the athletic capacity of the animal is very long and requires a substantial investment of time and money before it is known whether any financial return can be expected. As a consequence the intergenerational interval is very long and genetic progress through selective breeding is slow. In a long-term study, Santamaría and co-workers investigated two possible ways in which show jumpers might be raised more cost-effectively. Their first research question was whether good predictors for future jumping ability could possibly be found through the analysis of jumping technique at foal age (Santamaría et al., 2005). This would make earlier selection possible. An indication that jumping capacity might be more innate than acquired through specific training came from the work of Fabiani (1973), who reported that jumping ability showed little change after 6 months of jump training. The second question was whether jumping performance could be improved by starting training much earlier than the usual age of 3 years (Santamaría et al., 2006). This was based on the empirical observation that many elite human athletes start their careers as children, which suggests a lasting effect of such early athletic activity.

To answer these questions a cohort of 40 Warmblood foals was selected after weaning at age 6 months and divided into two groups. One group was raised traditionally (free paddock exercise or group housing in open front stalls, depending on the season) until they were broken at age 3; the other group was subjected to a specific jumping training program twice weekly combined with a more general exercise regimen to ensure a sufficient level of physical fitness from 6 months to 3 years of age. At that age all animals were joined in a single group to be broken and to receive a common exercise program to prepare for work under saddle. After a rest period of 6 months, 30 of the now 4-year-olds were trained in a single group as show jumpers for an entire year. This group of 30 horses consisted of 15 animals from each training group; the five worst animals from each exercise group had been culled because of economical constraints.

Kinematic examinations were performed while free jumping at ages 6 months, 4 years and 5 years and also at 5 years with a rider. The outcome parameter for jumping performance was a puissance competition held at the end of the experiment during which horses had to jump fences up to 1.50 m, whereas in the preceding year they had been trained using obstacles with a maximum height of 1.20 m. During the puissance competition performance was characterized as good (faultless), moderate (able to finish the contest but with faults and/or refusals), or bad (unable to finish the competition).

Jumping technique was quite consistent from foal to adult horse (Santamaría et al., 2002, 2004). When the kinematic variables that were consistent over time were related to the outcome of the puissance competition as the main parameter for performance, it appeared that elbow flexion, retraction angle of the hind limbs and inclination of the trunk with respect to the horizontal were among the variables that were related to performance at 5 years of age and could already be identified in the 6-month-old foals (Bobbert et al., 2005; Santamaría et al., 2002, 2004). It was concluded, therefore, that it is indeed possible to use some of the characteristics of the jumping technique exhibited by foals when they are free jumping as predictors for future athletic performance. However, it should be stressed that many other factors influence eventual success of a show jumper beyond jumping technique alone. The kinematic characteristics that were identified are therefore probably of more help in developing an effective culling strategy than in picking out a future top show jumper.

Early training resulted in a less variable and clearly more efficient jumping technique in the 4-year-olds (Fig. 14.20) (Santamaría et al., 2004, 2005). However, when reassessing the effects after a year of common and similar training, no significant difference could be detected anymore between the two former training groups. Also, there was no relation of early training with performance, as measured by the outcome of the puissance competition. Therefore, specific training for jumping at foal age, at least when carried out according to the relatively mild protocol as used in this study, has no measurable long-term effect. It was noted, however, that there was a temporary effect of early training on naïve horses that made them jump more efficiently and thus seemingly better than untrained horses. Early jump training might therefore bias selection events of studbooks, many of which nowadays include free jumping sessions for would-be breeding stock at ages of 3 or 4 years (Santamaría et al., 2006). It should be emphasized that the lack of effect of specific training for jumping does not take away the well-documented beneficial effect of early exercise on the general development of the equine musculoskeletal system (Weeren et al., 2000; Weeren, 2007).

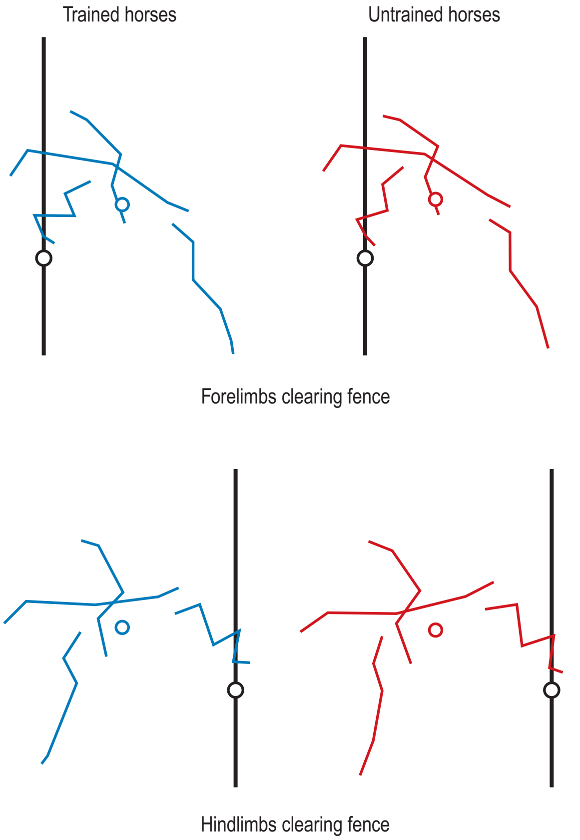

Fig 14.20 Representative schematic drawings of horses from the two training groups clearing a fence under saddle at 4 years of age (i.e. before the common 1-year specific jump training). (A) Clearing the fence with the forelimbs. Left: trained animals; right: untrained animals. The trained animals have their center of gravity closer to the fence and a more flexed elbow joint. (B) Clearing the fence with the hind limbs. Left: untrained animals; right: trained animals. The trained animals exhibit more retroflexion of the hind limbs.

The effect of a rider

In a kinematic study of the effect of a rider on jumping technique, Powers and Harrison (2002) compared the same group of horses jumping a 1.0 m obstacle freely or with a rider. The rider significantly influenced the following variables: vertical velocity at lift-off, height of the CM at lift-off, distance of the CM to the fence at lift-off, maximal height of CM during the suspension phase, position of the CM when passing over the fence, and height of the CM at landing. They concluded that the effect of the rider on the horse was more due to behavioral influences than to the inertial effect of the mass of the rider.

Eventing

The sport of eventing was originally devised as a test of athleticism for cavalry horses, and the name 'the military' is still retained in some languages. Event horses perform three tests: dressage, speed and endurance, and show jumping. Since dressage and show jumping are covered elsewhere in this chapter, this section will focus on studies that are specific to the sport of eventing, especially those describing performance in the speed and endurance phases.

The multi-faceted nature of the sport dictates that event horses must be versatile athletes. They should show relaxation and suppleness in the dressage phase; speed, strength, stamina and athleticism in the endurance phase; and suppleness and coordination in the show jumping phase. A long and energetically efficient galloping stride is an important quality in a potential eventer. More data are needed describing the techniques used to jump different types of cross-country fences.

Dressage performance

In a study at the Barcelona Olympics, performance in the dressage phase was correlated with finishing place. Stride length and speed in the extended canter were positively related to points awarded by the judges for the canter. Horses that failed to complete the entire 3-day event had longer stride lengths and faster speeds in the extended canter during the dressage phase than horses that finished the competition (Deuel, 1995). The author suggested that characteristics of the extended canter that are highly rewarded by the judges have little relation to subsequent galloping and jumping performance, and qualities favored by dressage judges may even predict failure to finish the event.

Speed and endurance performance

Success in the speed and endurance phase is largely dependent on having a ground-covering stride. Recordings made during the steeplechase phase of the 3-day event at the Seoul Olympics (Deuel & Park, 1993) showed an average speed of 12.1 m/s with a stride length of 6.0 m and a stride frequency of 2.0 strides/s. Superior performance in the entire competition was significantly associated with a faster speed and a longer stride length in the steeplechase phase. The score was optimized with a gallop stride frequency between 1.85 and 2.05 strides/s and a speed between 13.0 and 14.3 m/s. Up to 7 m there appeared to be no upper limit for optimal stride length.

In a study of the temporal and linear kinematics of horses jumping a steeplechase fence (1.4 m high, 2.6 m wide at the base) during a young riders' competition (Leach & Ormrod, 1984), the average distance jumped was 5.2 m. The distances of the limbs from the base of the fence on the lift-off side were: trailing forelimb 2.6 m, leading forelimb 2.1 m, trailing hind limb 2.0 m and leading hind limb 2.0 m. Unlike show jumpers, in which the trailing hind limb distance from the fence was between those of the two forelimbs at lift-off, during steeplechasing both hind limbs were placed closer to the fence than the leading forelimb. The forelimb stance durations were approximately 0.13 s, whereas the hind limbs had longer stance durations of around 0.17 s. In a regression analysis the only temporal variable that was a significant predictor of the distance jumped was the overlap between the forelimb stance phases. The longer the forelimbs overlapped, the shorter the horizontal distance jumped. For the linear variables, the distance of the trailing forelimb from the base of the fence was positively related to the distance jumped. When this limb was further from the jump, the horse used a flatter trajectory, which carried it farther across the fence.

Effect of added weight on jumping performance

In the past the competition rules stipulated that event horses had to carry a minimum weight of 75 kg (rider and tack), which represented anything from 10 to 17% of body weight depending on the weight of the horse. It was suggested that this imposed an unsafe burden on small horses. A study was performed (Clayton, 1997b) to compare the landing kinematics of small (maximum height 164 cm) event horses when carrying a 61 kg rider versus carrying the same rider plus an 18 kg weighted saddle pad. The test fence was a table fence with a sloping face that measured 1.1 m high, 1.9 m wide at the base and 1.3 m wide at the top. The results (Table 14.15) showed that with the extra weight the leading forelimb landed closer to the fence, which confirmed the riders' subjective impression that the horses were 'cutting down' during the landing. This was probably a result of failing to generate sufficient impulse during the lift-off to compensate for the extra weight.

During landing both the fetlock and carpal joints of the leading forelimb were significantly more extended with the extra weight as a direct result of the greater force at landing. Since strain of the suspensory ligament and the superficial digital flexor tendon increase with extension of the fetlock, the extra weight may have put the horses at greater risk of suspensory desmitis or superficial digital flexor tendonitis. Stance durations of both hind limbs increased in departure stride 1, which may have been indicative of the use of these limbs to restore the horse's balance by elevating the forehand, which was burdened by the extra weight. As a result of these findings the minimum weight rule for event horses was abolished.

Table 14.15 Temporal and linear kinematic variables for horses jumping a table fence with a 61-kg rider (rider weight) and with a 61-kg rider plus an 18-kg weighted saddle pad (added weight)

	Rider weight	Added weight
Stance duration, TrF at landing (s)	0.18	0.18
Stance duration, LdF at landing (s)	0.21	0.21
Stance duration, TrH in stride D1 (s)	0.19*	0.20*
Stance duration, LdH in stride D1 (s)	0.21*	0.22*
Distance TrF to fence at landing (cm)	173.5	159.3
Distance LdF to fence at landing (cm)	240.4*	222.7*
Maximum carpal angle, TrF at landing (degrees)	191.0	190.0
Maximum fetlock angle, TrF at landing (degrees)	252.9	251.9
Maximum carpal angle, LdF at landing (degrees)	190.7*	193.4*
Maximum fetlock angle, LdF at landing (degrees)	247.4*	250.7*

*Values that differ significantly ($p < 0.05$).

D1, first departure stride; LdF, leading forelimb; LdH, leading hind limb; TrF, trailing forelimb; TrH, trailing hind limb.

Data from Clayton (1997b).

Western sports

Western sports are traditionally associated with skills required of horses and riders in ranching, and are based on breeds such as the Quarter Horse or Australian Stock Horse. The sports usually require a short period of intense exercise, and may require speed and acceleration, strength, stability, or explosive power.

Stability and maneuverability

The qualities of stability and maneuverability are required to different degrees in different sports. Stability is enhanced by lowering the COM and positioning it centrally within the base of support. Maneuverability, on the other hand, is enhanced when the center of mass is high and lies close to the perimeter of the base of support, so that it is easily displaced outside the base of support. An example of a sport based on stability is roping, in which the horse must remain balanced while resisting the forces applied by a roped calf. Cutting demonstrates the need for maneuverability during rapid acceleration, deceleration and turning. Many sports call for a combination of stability and maneuverability.

Reaction time

Reaction time is defined as the time that elapses between an external stimulus and the initial response to that stimulus. It is extremely important in sports that require fast movements and quick reflexes, such as cutting, in which there is an offensive–defensive component and in which the horse must perceive a visual stimulus and respond appropriately within a short space of time.

Reaction time in response to an external stimulus is determined by the sum of the pre-motor time and the motor time. Pre-motor time is dependent on the speed of processing in the central nervous system and speed of conduction along the nerve to the motor end plate. Motor time reflects the speed of muscle contraction, which is dependent on muscle fiber type. The reaction times of human athletes are substantially faster than those of non-athletes (Kroll & Clarkson, 1977). Because nerve conduction velocities do not appear to differ between individuals (Bodine-Rees & Bone, 1976), it has been suggested that the faster reaction time of athletes may be attributed to the superior functioning of the central nervous system. Furthermore, the total reaction time is significantly correlated with pre-motor time but not with motor time (Viitsalo & Komi, 1981). In equine athletes, Clayton (1989b) found that the reaction time of cutting horses in response to a visual stimulus ranged from 110 to 370 ms, and that horses with shorter reaction times had higher competition earnings than those that were less successful in competition.

Western pleasure gaits

Stock types breeds, such as the American Quarter Horse and the American Paint Horse, comprise the majority of horses in North America. One of the popular competitions for these horses is western pleasure classes, in which the horses are required to walk, jog and lope in both directions of the arena. The jog is a type of trot defined as a two-beat diagonal gait that is smooth and ground-covering. The lope is a type of canter defined as a three-beat gait performed with rhythm, forward motion and ease.

Analysis of the temporal gait kinematics of the jog and lope indicated that both gaits were actually performed as four-beat stepping gaits with a lateral sequence of footfalls (Nicodemus & Clayton, 2001). Thus, both gaits had the same footfall sequence as the walk. Furthermore, the lope was performed without suspension and the limb support sequence included a period of quadrupedal support. In 2003, the executive committee of the American Quarter Horse Association made changes to the rules with the intention of encouraging more forward-moving gaits. However, subsequent kinematic analysis (Nicodemus & Booker, 2007) performed during a national caliber show indicated that the speed of the jog was 1.13 ± 0.14 m/s and the speed of the lope was 1.77 ± 0.13 m/s, both of which are slower than the typical speed for the walk to trot transition. It is not surprising that both gaits were again performed with a four-beat rhythm and lateral sequence of limb placements, as in the walk (Table 14.16).

In the jog, the rhythm showed diagonal couplets and stance durations were around 68% of stride duration for the forelimbs and 60% of stride duration for the hind limbs. During each half of the stride, the limb support sequences, starting at contact of a hind limb were as follows: quadrupedal (8.5%); tripedal with two hind limbs (2%); bipedal diagonal (30%); and tripedal with two forelimbs (9.5%).

In the lope, the footfalls occurred as diagonal couplets and the typical footfall sequence was: trailing hind; trailing fore; leading hind; leading fore. There was no period of suspension. The limb support phases, starting with contact of the trailing hind limb were as follows: bipedal diagonal (leading front, trailing hind); unipedal trailing hind; bipeal lateral (trailing hind and trailing fore); tripedal (trailing hind, trailing fore, leading fore); bipedal diagonal; tripedal (leading hind, trailing fore, leading fore); bipedal lateral (leading hind, leading fore); and unipedal leading fore. Thus, the limb support sequence is very different from that of a canter.

Cutting

Cutting horses perform almost independently of the rider; during the judging points are lost if the rider cues the horse. The objective is to sort one calf from a herd and then to prevent it returning to the other calves. The sport evolved from the practical aspects of ranch work, with the first competition taking place around the turn of the century. Since then, there has been increasing interest in cutting as a sport and it is currently one of the most rapidly growing equestrian sports. In competition the horse is judged for 2.5 min during which it usually cuts two or three calves.

Table 14.16 **Speed and stride duration jog and lope of the western pleasure horse**

	Jog	Lope
Speed (m/s)	1.13 ± 0.14	1.77 ± 0.13
Stride length (m)	1.09 ± 0.07	1.27 ± 0.04
Stride duration (s)	0.92 ± 0.03	0.72 ± 0.04

Data from Nicodemus and Clayton (2001).

Cutting is a high-intensity activity in which the horse must have quick reaction times and the ability to turn and accelerate in either direction in response to the unpredictable movements of the calf. Some horses are naturally more talented than others, and 'cow sense' is a highly prized trait. Genetic evaluation of over 3000 horses competing at the World Championship Futurities over a 9-year period yielded a heritability estimate of cutting ability of 19 ± 5% (Ellersieck et al., 1985).

The tactics used to keep the calf separate from the herd are similar to defensive play that blocks the progress of the offensive player in sports such as American football. A study was performed to determine factors that differed between horses with different levels of ability (Clayton, 1989b). A group of cutting horses that were of similar ages, training histories and competitive opportunities, were divided into two groups according to their competitive winnings. The five horses in the 'average' group had won less than $35 000. The seven horses in the 'elite' group had won more than $35 000. The horses worked a mechanical flag rather than a live steer, which allowed the use of a standard test to ensure that all horses performed a similar series of turns and runs in each direction. The mechanical flag is a piece of heavy cloth measuring about 30 cm^2. All the horses had worked with the mechanical flag regularly and frequently during their careers.

Horses in the two groups differed significantly in several ways (Table 14.17). Elite horses had faster reaction times than average horses, which allowed them to respond more quickly when the flag began moving and to stop sooner after the flag stopped moving. The faster reaction times of the elite horses may have some value as a predictor of performance. As a result of their faster reaction times the elite horses were significantly closer to the flag throughout the run and were less likely to overrun the flag when it stopped moving than the average horses. Other features of the performance were that elite horses leaned their shoulders in the direction of the turn before pushing off against the ground, which is a more effective method of turning. The average horses were more likely to move their hooves sideways as the first indication of turning, rather than leaning into the turn and pushing sideways. The elite horses also tended to turn using fewer strides than the average horses though this difference did not reach statistical significance.

In summary, cutting is a high-intensity sport that requires great agility and an inherent 'cow sense'. Successful cutting horses have quick reaction times and an economical turning technique that allows them to follow the calf closely at all times.

Table 14.17 **Comparison of elite and average cutting horses working a mechanical flag**

	Elite horses	Average horses
Reaction time after flag starts moving (ms)	200 ± 66*	282 ± 74*
Time to stop after flag stops moving (ms)	386 ± 108*	492 ± 94*
Distance from flag at start of run (cm)	52 ± 23*	81 ± 32*
Maximal distance from flag during run (cm)	148 ± 28*	221 ± 23*
Distance from flag at end of run (cm)	55 ± 26*	78 ± 32*

*Values that differ significantly ($p < 0.05$).

Values are mean ± SD.

Data from Clayton (1989b).

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CHAPTER 15

Horse–rider interaction

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Introduction

In many countries the role of the horse in society has changed dramatically during the last half century from being used in agriculture and warfare to a companion in sports and leisure. Today considerably fewer people grow up with horses as a daily part of their lives while the general interest in horses grows. The lack of natural training and 'education' of working with horses on a daily basis has led to an increased demand for educational programs in equine care and management from very basic principles to university-level education.

More formalized education increases the demands for knowledge and a natural consequence has been an increase in research. Studies of the horse–rider interaction have included a biomechanical or ethological approach, together with research on health and performance of both horse and rider. Other studies have evaluated training techniques or rehabilitation of rider or horse. In this chapter we focus on the biomechanical approaches to horse–rider performance and, to a limited extent, on horse health.

The biomechanical methods used so far to assess horse–rider interaction comprise kinetic measurements with force plates or a force-measuring treadmill; kinematic measurements using motion analysis or accelerometers; pressure measurements between the saddle and horse's back using electronic pressure mats; rein tension studies; and electromyography. This chapter will begin by describing studies of saddles or other research using saddle mats, then studies of reins and bits. This will lead to a description of the rider's seat and other rider characteristics, including various rider-body factors related to skill, and rider weight. The next part of the chapter devotes itself to concepts used in riding methodology and specifically to the central concept of collection and its definitions.

Saddle

The saddle is an important part of the rider's equipment, making it comfortable to sit on the horse as well as distributing the weight of the rider over a larger area of the horse's back, thus making it more comfortable also for the horse. The idea of distributing weight over a larger area thereby lowering pressure (force over surface area) with the purpose of avoiding pressure injuries to the horse's back is a logical and obvious solution at first sight. However, under closer scrutiny there are some potential problems in this reasoning. Is it always better to have lower pressure, especially if it is more static? Are all tissues equally susceptible to pressure? Does pressure on a certain part of the back, for example behind the 16th thoracic vertebra, limit movement of the back? Many of the questions debated by saddle manufacturers and saddle fitters demand objective standards. In order to construct well-fitting saddles it is essential to know how the rider, saddle and horse interact, and to explain the source of saddle pressure peaks.

The electronic saddle mat

The most obvious way to study the seat in an objective and quantitative way is to use a saddle pressure mat. There are today several brands on the market that can be used for measuring pressure between the horse's back and saddle dynamically. Though this equipment has been available for many years, the first peer-reviewed paper was published in 1994 (Harman, 1994). One reason that relatively few papers have been published might be the difficulties in obtaining good quality, quantitative data using this technology.

There are several problems including relatively poor performance in terms of accuracy and drift. The published papers mainly deal with maxima, local peaks or mean forces, which are a very limited part of the total information registered by the pressure sensitive mats which usually consist of between 256 and 2000 sensors, each sampling at up to several hundred samples per second. The variability between strides makes it useful for the interpretation to calculate a mean stride for each experimental situation, which has not been generally done so far. Mat slip can be an issue and the correct position has to be checked before and after measurement. Placement of the mat relative to both the horse's back and the saddle needs to be defined in a standardized way. In most of the studies to date the mat data has been used and presented in a qualitative or semi-quantitative way. The mats may be difficult to calibrate and the software that handles the data needs further development. There is a need for standardized methods of presenting, analyzing and comparing saddle mat measurements (see also Chapter 2).

The following paragraphs describe studies in which the saddle mat has been used scientifically to study the interaction between the rider, saddle and horse's back. Saddle pressure measurements have also been used to confirm the association between clinical evidence of back pain and pressure peaks acting on the horse's back (Werner et al., 2002; Nyikos et al., 2005; von Peinen et al., 2010) but these studies will not be further elucidated here.

Saddle pressure in the standing horse

De Cocq et al. (2006) calculated a correlation coefficient between total measured force and the weight of 28 different riders, using paired measurements with defined air-pressure inside the panels of the saddle in standing horses. Total force correlated well with the weight of the rider and the results within trials agreed well, but for trials in which the saddle mat was removed and replaced the agreements varied from poor to excellent. The results indicated that

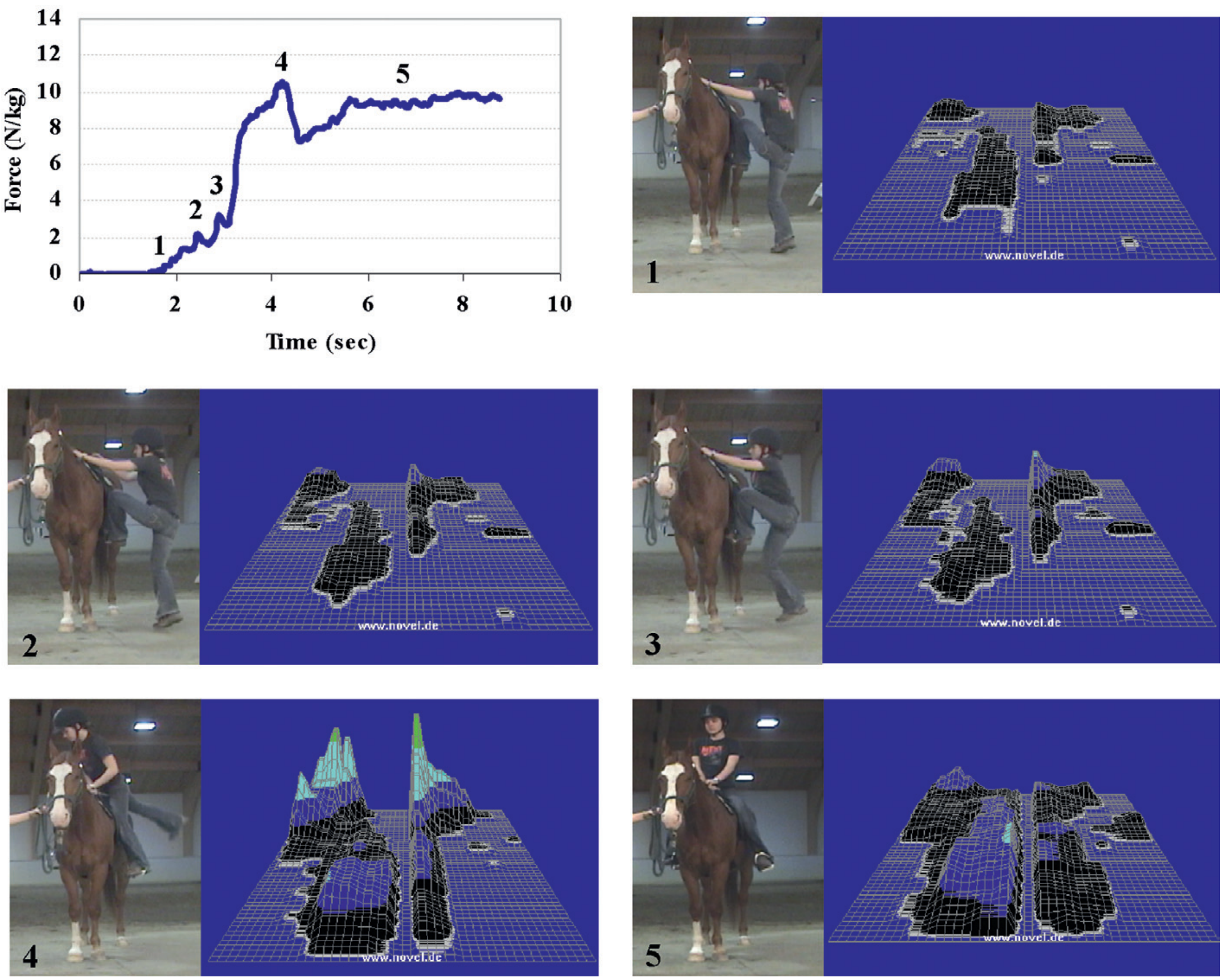

Fig 15.1 Graph showing total force during a typical trial for mounting from the ground. Still photographs and the corresponding maps of pressure distribution under the saddle are shown for the points marked 1–5 on the graph. This sequence shows the most common pattern with a single force peak as the right leg swings upwards. In the pressure maps, the cranial part of the mat is up and the left side is to the left.

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highly standardized conditions were necessary to obtain useful and valid results and that further technical development is necessary. Better results, relative to agreement between different measurement conditions basically measuring the same things, was found in another study using a different type of saddle mat (de Cocq et al., 2009a). Different rider positions were evaluated and the mat registered increased force beneath the saddle in the direction towards which the rider was leaning (de Cocq et al., 2009a). Therefore, the mat could discriminate between rider positions and asymmetrical weighting of the saddle.

A study of forces on the horse's back during mounting showed that the highest forces coincided with the rider's free leg swinging up and over the horse's back. When the rider mounted from the conventional (left) side forces were highest on the right side of the horse's back adjacent to the withers. High forces were also found lower on the left shoulder. Heavier riders yielded higher forces (Geutjens et al., 2008). The use of a mounting block produced a smoother force application and lower peak force (Fig. 15.1). In light of these findings it is recommended that, if possible, the rider should mount without using the stirrup to avoid the asymmetrical loading of the horse's back. If this is not possible, it is recommended to use a mounting block and mount alternately from the left and right sides.

The effect of the saddle on motion of the back

With the use of pressure sensitive saddle mats, the influence of the saddle on the horse's back can be studied while moving at different gaits. However, there is only a weak association between the saddle pressures acting on the back in a standing horse and those exerted during movement (Jeffcott et al., 1999). Total saddle force curves show a characteristic, gait dependent pattern (Pullin, 1996; Jeffcott et al., 1999; Fruehwirth et al., 2004; von Peinen et al., 2009).

Fruehwirth et al. (2004) registered force data from quarters of the saddle mat in horses ridden at walk, trot and right lead canter (12 horses and 12 riders) and found that force patterns were reproducible from stride to stride in each gait and force magnitude increased with speed.

On the contrary, de Cocq et al. (2004) evaluated nine Dutch Warmbloods walking, trotting and cantering on a treadmill in an unloaded condition, wearing a surcingle, a saddle or a saddle plus

75 kg weight. The most marked changes occurred with the addition of extra weight; the horse's back moved through the same range of motion but with more extension and less flexion. Fewer changes were seen when comparing an unweighted saddle with the unsaddled situation. Forelimb retraction increased in walk and trot when the horse had a weighted saddle compared with a saddle, a surcingle or unloaded. Increases in both forelimb retraction and hind limb protraction are mechanisms that counteract back-extension, so the increase in forelimb retraction is likely to counteract over-extension of the back (Jeffcott, 1979).

Saddle types

Early studies using a pressure mat evaluated various saddles qualitatively (Harman, 1994). Werner et al. (2002) studied two types of dressage saddles in 25 horses ridden by the same rider in various gaits. They found differences between saddles and horses and smaller differences with gait. It was suggested that mean pressure >15 kPa and maximal pressure >35 kPa at sitting trot correlated with back pain. Further, patient horses (n = 25) with various degrees of and reasons for back pain were evaluated with an interval of at least 12 weeks, during which time saddlery problems were corrected based on saddle mat data (Mönkemöller, 2005). Qualitatively, improvement was judged to be significant based on distribution and magnitude of pressure.

In a study comparing an English saddle with a side saddle, horses (n = 13) without clinical signs of back-pain were evaluated at walk, trot and canter using a saddle mat and kinematic measurements of back movement both in front of the withers and behind the saddle (4th lumbar vertebra, L4). The results showed asymmetrical loading under the side saddle with the center of pressure located to the right of midline and slightly more caudally than the center of pressure under the English saddle in all gaits. The sidesaddle also influenced back movement. The authors suggested that the two saddle types could be used to change the load distribution on the back of horses with potential back pain and as a training variation (Winkelmayr et al., 2006).

In racehorses (n = 8), no difference was found between saddles with a normal tree, a flexible tree or treeless relative to the stipulated critical pressure on the lower thoracic back at canter and gallop (Latif et al., 2010), which was the main concern. However, loading and peak pressures were relatively high at the withers during cantering and galloping but shifted toward the mid and rear regions while trotting. The authors concluded that the type of tree had no influence on the pressure profile at the rear of the saddle and that the high peak pressures at the rear of the saddle in trot with all saddles may limit back motion. The pressure distribution in trot and gallop was mainly due to jockey position. The high pressure under the rear of the treeless saddle, as well as the saddle with the flexible tree, was directly beneath the rider. With respect to the treed saddle, it was due to an improperly-fitting tree or cushioning.

Saddle fit and saddle pads

The kinematics of horses (n = 21) ridden by one rider on a treadmill at trot with either a well-fitting or ill-fitting saddle (Peham et al., 2004), were documented using three saddles, and two kinematic markers (L4 and right fore hoof). Variability of the motion cycles was calculated as well as the derivates (velocities and accelerations) in the x, y, and z directions. With a rider the variability of velocity and acceleration in the forward direction and acceleration in the transverse direction decreased with a well-fitting saddle compared to an ill-fitting saddle. Meschan (2007) tested differently fitting saddles with a pressure mat and concluded that the load under poorly fitting saddles is distributed over a smaller area than under properly fitting saddles, leading to potentially harmful pressure peaks. Typical pressure profiles for saddles with correct, wide and narrow trees were shown.

Von Peinen et al. (2010) demonstrated that the mean and maximal saddle pressure in walk, trot and canter were larger in 23 horses with clinical evidence of ill-fitting saddles compared to 16 control horses. Pressure was measured at the areas of dry spots (dry non-sweating areas that sustained local ischemia due to high saddle pressure) or acute soreness in the withers area in the horses with the problems and compared to the same areas in the control horses. The results indicated that mean pressure was more repeatable than maximal pressure and was, therefore, a more reliable variable for assessing saddle fit. Similar to the decubitus ulcer probem in people, critical values could be established for different levels of saddle sores in the withers area. Such critical values would help fitting saddles in the future.

In her pioneering work Harman (1994) looked at saddle fit of equine patients and evaluated the effects of 14 different pads on one rider–horse combination, concluding that many pads make the pressure distribution worse compared to using a simple cotton pad. Pullin et al. (1996) evaluated two saddles, two horses and 14 pad-liner combinations. Both static and dynamic measurements and results were evaluated qualitatively. Repeatable differences were seen between the tested pads leading the authors to recommend that dynamic evaluations were more useful, and that static scans without riders should not be used for optimal saddle pad evaluation.

A study of how the fit of a saddle with a tree that was too wide was affected by using a pad made of gel, leather, foam or reindeer fur was undertaken in one rider who rode 18 horses in trot and walk. All pad-saddle combinations were compared to the saddle without pad. In many pad-saddle-horse combinations, maximal overall force increased when using a pad and the pressure differences between adjacent areas of the saddle often did not decrease. The potential benefits of using a pad need careful consideration in horses with back problems (Kotschwar et al., 2010a,b).

Panels and girths

De Cocq et al. (2006) documented that the force beneath the rear part of the panels could be measured more reliably than the force beneath the more forward part of the panels because of the inclination of the horse's back. The sensors measure force applied perpendicular to their surface but shear forces give cross-talk to the measurements, i.e. the forces will not be correctly measured. This means that a larger part of the force is captured in areas of the back that have a more horizontal inclination. As a consequence of the shape of the back on either side of the withers, forces are likely to be underestimated by a larger amount in this area.

Another study examined saddle pressure patterns during riding in trot and canter, comparing traditional and v-system girth strap placement, and wool and synthetic foam panel flocking material (six horses, three riders) (Byström et al., 2010a). Controlling for speed, stride maximum pressures below the hind part of the saddle increased by 7–12% and the area below the saddle with a stride mean pressure >11 kPa increased by 114 cm^2 at trot and 127 cm^2 at canter with foam-filled panels compared with wool-stuffed panels. With the v-system girthing the area with pressure >11 kPa increased by 53 cm^2 and 38 cm^2. It was concluded that both flocking material and girthing are relevant considerations in saddle fitting. In this study, wool performed better than foam as panel flocking material and traditional placement of the girth was better or at least as good compared to the v-system.

Bits and reins

Bits

Clayton and Lee (1984) described the use of a fluoroscopic technique to evaluate bit position, the interactions of the bit with the intra-oral tissues and the effects of rein tension on bit position. This technique was applied in a further study of a variety of bits that varied in shape and mechanical action (Clayton, 1985). It was shown that bilateral rein tension caused the bits to indent the tongue. Horses accepted the bit quietly with minimal intra-oral motion when the bit was adjusted so that there were one or two small wrinkles at the commissures of the lips. When the cheek pieces were adjusted to allow the bit to lie lower on the tongue or when the bit was considerably wider than the distance between the oral commissures the horse could move the bit around more freely within the mouth and tended to show more movements of the tongue that could be interpreted as resistances (Clayton & Lee, 1984). With some bits it was possible to restrict the movements of the mouthpiece, for example, using keepers on a cheek snaffle. For some bits the severity of their action depended on their orientation within the oral cavity, such as the reversible Dr. Bristol bit. In the equestrian literature, when using the double bridle, the bridoon (or bradoon) and the curb are said to have quite different actions, the bradoon lifts and extends the neck while the curb is described as having a leverage effect and powerful action on the bars (Karl, 2008). However, in this study the bradoon of the double bridle moved with the curb, suggesting that the effect of the bradoon and the curb would be somewhat hard to separate within the oral cavity though the horse's sensation likely differs between the actions of the bits (Clayton, 1985).

A further study using lateral-view radiographs (Manfredi et al., 2005b) described the positions of six bits relative to the horse's palate and second premolar teeth with and without 25-N rein tension which is equivalent to peak tension recorded in horses trotting with side reins adjusted to the resting length of the horse's neck (Fig. 15.2) (Manfredi et al., 2005b). Both with and without rein tension, the bits varied in their proximity to the premolars, and angulation of the cannons. Rein tension moved the mouthpiece away from the palate by indenting the horse's tongue. The amount of time spent with the mouth quiet, gently mouthing the bit, opening the mouth, using the tongue to raise the bit between the cheek teeth and displacing the dorsum of the tongue over the bit were measured. The horses' intra-oral behaviors with these six bits were evaluated with a loose rein and with 25 N tension. When rein tension was applied, the time spent with the mouth quiet or gently mouthing the bit decreased and the time spent in the other behaviors increased. The behaviors differed significantly between horses but not between bit types (Manfredi et al., 2010).

It has been suggested that horses are unable to swallow when wearing a bit (Cook, 1999). However, Manfredi et al. (2005a) performed an endoscopic study of horses cantering on a treadmill with tight side reins to maintain poll flexion while wearing a halter, a bitless bridle, a loose ring jointed snaffle and a Myler bit. Swallowing occurred frequently under all four conditions.

Materials, types and sizes of bits are often changed by riders when they think they experience a 'mouth problem' in the horse. Usually the trainer's perception guides the choice and the conclusions about how these act, but scientific evidence to support these ideas is minimal. For example, relative to dressage the difference between the action of a single and double bridle warrants scientific investigation in a larger population of horses. One reason why this is difficult to study is that tension sensors in the reins measure the combined effects of horse and rider and cannot partition the effects between the two. Thus it is not possible to separate variation in a horse's response to a bit from the force applied by the rider or differences in rider technique.

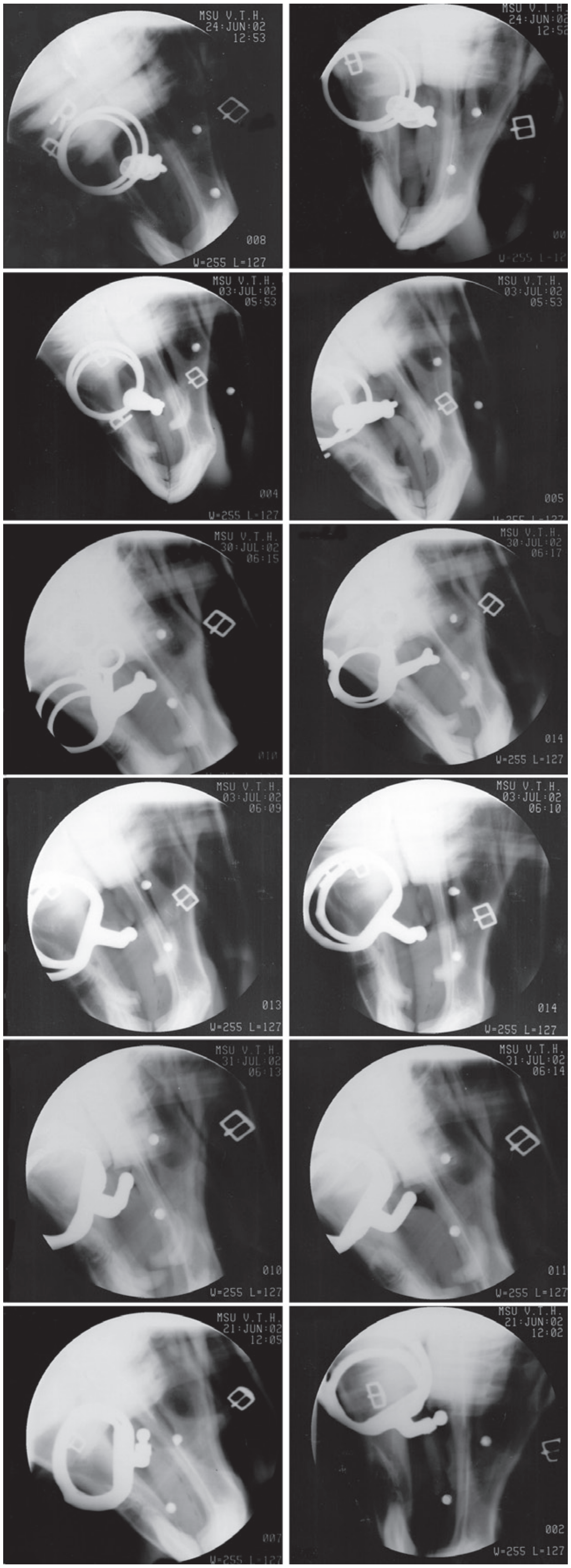

Fig 15.2 Lateral radiographic views of bit positions without rein tension (left panel) and with 25 ± 5 N bilateral rein tension (right). Bits represented from top to bottom are jointed snaffle, KK Ultra, Boucher, Myler low port comfort snaffle, Myler ported barrel, Myler correctional-ported barrel.

Reprinted from Manfredi, J., Clayton, H.M., Rosenstein, D., 2005b. Radiographic study of bit position within the horse's oral cavity. Equine Comp. Exerc. Physiol. 2, 195–201, with permission from Cambridge University Press.

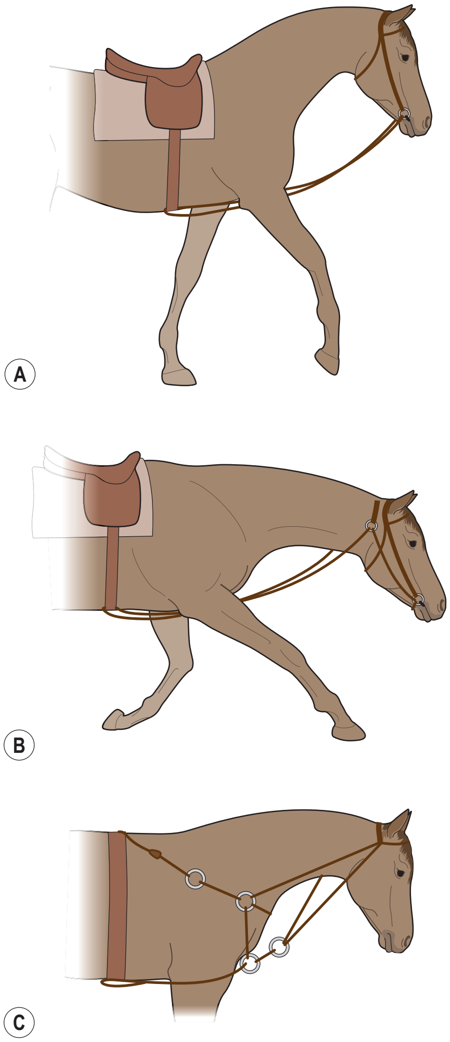

Fig 15.3 The three studied reins. (A) Rubber bands, (B) chambons and (C) back lift.

Reprinted from Biau, S., Couve, O., Lemaire, S., Barrey, E., 2002. The effect of reins on kinetic variables of locomotion. Equine Vet. J. 34 (Suppl.), 359–362, with permission from the Equine Veterinary Journal.

Reins

Auxiliary reins, defined as reins other than simple inelastic reins passing directly from the rider's hand to the bit, differ widely in their popularity among riders. Many see them as coercive, because they most often force the horse's head in a downward direction, with some types being perceived as having a more severe effect. Other trainers use them for a short time as temporary aids to provide better long-term control of the horse's head and neck position (see more on this under collection below). For example, with draw reins the rider can pull the horse's head downwards and backwards to its anatomical limit, whereas upwards movements are restricted by a running martingale in which the reins slide freely through loose rings that are held in place by a neck strap attached to the girth. The rings control the line of action of rein tension and prevent the head of the horse coming above the base of the skull. A few auxiliary reins have been compared (Biau et al., 2002) or evaluated (Roepstorff et al., 2002; Byström et al., 2006; Heleski et al., 2009) but more information is needed to provide a comprehensive picture. In a study of eight saddle horses, normal reins were compared with three types of auxiliary reins (Fig. 15.3), using accelerometers attached at the sternum and sacrum as the horses walked and trotted unridden in a horse walker (Biau et al., 2002). The reins were: 'rubber bands' going from the lowest point of the girth to the bit; a 'Chambon' going from lowest point of the girth through a pulley at the poll area to the bit; and 'back lifts' that were attached to the sides of the girth by a double mechanism, and to the poll. Rubber bands increased propulsion (i.e. the mean acceleration vector used for propulsive work) of the forelimbs at trot. Back lifts increased forelimb propulsion and dorsoventral activity at walk and trot (i.e. the FFT-integrated power spectrum signal of the dorsoventral acceleration signal). Chambons increased hind limb propulsion and forelimb propulsion and hind limb dorsoventral activity at trot. The authors' interpretation was that a Chambon was likely the most effective if the aim was to increase hind limb activity in a long and low position.

Draw reins used alone or in combination with normal reins were compared to normal reins only in horses ridden at trot on sand-covered asphalt over a forceplate (Roepstorff et al., 2002). The body weight was shifted caudally only when draw reins were used with normal reins (Byström et al., 2006). Kinematic analysis of the head angle, measured on the front of the nose relative to the horizontal plane (angles >90° equals nose in front of vertical), was different in all situations. With draw reins alone it was ~97°, combining draw reins with normal reins it was ~109°, while with normal reins it was ~116°. With draw reins forelimb retraction was increased at hoof lift. The hip joint extended more quickly and the hock joint flexed more with both reins compared to normal reins only. The pelvis was more horizontally inclined when draw reins were combined with a normal rein in comparison with draw reins alone, but the hip joint angular pattern was not significantly different between these conditions. It was concluded that the riders were, to a certain extent, able to shift weight towards the hind quarters with the combination of reins. An important finding, though, was that when using the draw rein alone to simulate an overuse of the draw rein, the horse's weight shifted to the fore quarters. So, when used incorrectly draw reins had the opposite effect from that which is intended and the caution to use draw reins with the utmost care (Podhajsky, 1965) seems to be scientifically validated.

Rein tension

From a technical point of view it is quite simple to measure rein forces acting between the hand of the rider and the bit. However, it is important to use appropriate force transducers for dynamic measurements; transducers based on a spring will not provide accurate force data and will underestimate forces when used in a dynamic system. Interpretation of the data can also be problematical due to the inherent variability associated with a pattern of spikes that are characteristic of each gait (Clayton et al., 2005). The mean tension ignores this inherent variability. A more detailed and informative approach measures the forces as minima, maxima and means with standard deviations. The force distribution can be mapped over time and compared between left and right reins. However, the force cannot be partitioned between horse and rider using this method. Some studies have presented forces in weight units (see below), but for the sake of comparison we have here assumed that 1 kg (weight) equals 9.8 N (force).

In pioneering work, it is stated that unexpectedly large rein forces were found, 5–75 N, up to maximal 150 N, on each rein. Most riders, using double bridles, used forces of around 5 N at halt increasing to 20 N at canter (Preuschoft et al., 1995). In further work, different types of riders were compared (Preuschoft et al., 1999). Very low rein tensions were found for western riders, for riders riding only on the curb and at a few dressage stables where forces registered below or just above 20 N, when performing demanding exercises. In other dressage stables, mean forces ranged from 59 to 147 N, without any difference between single and double bridles. Peak force during regular work was below 49 N in driving horses, 98–176 N during dressage training rising to 245 N when slowing down from canter. In trotters moving at high speed, forces up to 392 N were found (Preuschoft et al., 1999).

Cartier d'Yves and Ödberg (2005) studied right rein tension during a dressage test performed by three riders and 30 horses, including riding school horses, leisure horse and professional competition horses. Mean rein tension was approximately 13 N in riding school horses and 9.8 N in leisure horses, with intermediate values in the professional competition horses. Mean rein tension values were not statistically different between groups. Additionally, judge's or rider's subjective evaluation of lightness did not correlate with actual measurements of mean rein tension. Clayton et al. (2003) also report that the rider's perceptions of rein tension differed from the registered forces in one horse. In further work by the same author, one experienced rider rode one horse, chosen because it was known to lean against the bit. Although the rider perceived a constant rein tension, in walk there were regularly occurring spikes with a frequency of 108 per min, in trot 168 spikes per min and in canter 90 spikes per min (Clayton et al., 2005). The maximum values of the rein tension ranged from 4 to 43 N at walk, 19 to 51 N at trot and 21 to 104 N at canter. In this rider, synchronized video analysis showed that peak rein tension occurred during diagonal stance in both trot and canter, which coincided with downward motion of the horse's head.

Rein tension and the steadiness of the hand were evaluated in four horses and nine novice riders (Heleski et al., 2009). Three experimental conditions were studied: running martingales that stabilized the angle of the rein to the horses mouth during riding, elastic rein inserts that yielded if tension exceeded 20 N, which happened very rarely in this study (in 0.6% of the spikes evaluated), and controls without either rein aid. Conflict behaviours of the horse, evaluated using an ethogram, did not differ between experimental conditions. Mean rein tension was highest for the condition with running martingales (4.1 N with a martingale versus 3.5 N for both rein inserts and controls). The authors suggested that carefully fitted running martingales may be advantageous for novice riders on the basis that the head position of the horse was less often judged as unacceptably high. It is suggested by many riders and veterinarians that a somewhat lower head position actually spares the locomotor health of the horse.

The rein tension of three horses, ridden by their own expert rider on a treadmill, was studied at walk, trot and passage (Roepstorff, unpublished). In the vertical head-neck position, data from both reins averaged over four trials, showed that the three horses had different mean low and high values of 11 N and 16 N, 1.5 N and 3.5 N, and 2.7 N and 4.8 N. Mean rein tension increased with increasing collection (as determined by the head and neck position). This is contrary to most riding texts and to the concept that rein contact should be able to be dropped in collection (descente de main) with the horse remaining in the collected movement/position when rein contact is released (Decarpentry, 1949). In walk, trot and passage the mean rein tension was higher in eight of nine comparisons when the head and neck were in the vertical (competition) position compared with positions slightly behind the vertical, with a low neck or with a neck elevated and the bridge of the nose in front of the vertical. On the contrary, all three horses had a much lower mean rein tension when walking with the neck low and forward compared with the competition position. The maximal peaks in walk were found at contralateral hind limb stance and in trot there was one peak in each rein at stance, which agrees with the results found by Clayton et al. (2003, 2011).

In walk and sitting trot, rein tension was generally lower in one of the reins in two of three horse–rider combinations. A typical example from the vertical head–neck position in one of the horses is shown (Fig. 15.4), where the right rein more often has lower tension, while the opposite pattern is seen for the two next bars. This is further evidence of motor laterality, but the data cannot detect whether it comes from the horse, the rider or both. In rising trot the tendency was that the tensions in both reins were higher for the diagonal on which the rider was sitting, compared to the diagonal on which the rider rose.

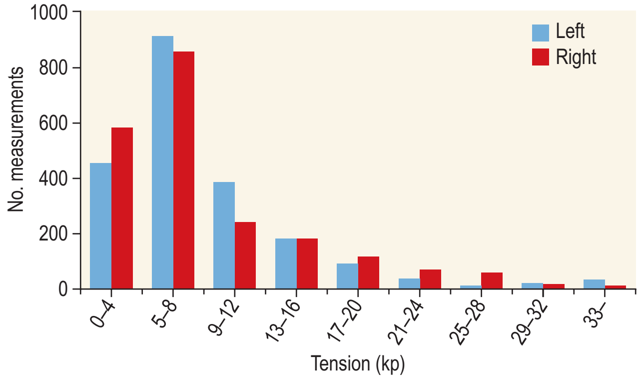

Fig 15.4 Distribution of number of left and right rein force recordings (y) by amount of tension (x) in one horse and rider in sitting trot on a treadmill during a period of 15 s with a sampling frequency of 140 Hz.
From Roepstorff (unpublished).

Kuhnke et al. (2010) studied 11 right-lateralized (right-handed) riders that rode one left-lateralized horse and one right-lateralized horse in walk, trot and canter. There were differences between the sides for the two horses. For example, there was more slackening of the reins of the horse's non-preferred side and taken together the left rein, especially in the left-lateralized horse, had generally higher rein tension. The authors speculated that right-lateralized riders might benefit from riding right-lateralized horses because this seemed to enhance symmetry in the riding.

Warren-Smith et al. (2007) studied one professional, one intermediate and one novice rider on 22 horses performing a simple dressage test under saddle and the same horses being long-reined by a professional handler. Mean rein tension during riding was 7.4 N and during long-reining 10.7 N. Rein tension was highest when halting and higher when turning compared to riding on straight lines. When horses were ridden, tension in the left rein when turning left was higher than the tensions in either rein when turning right, which could be interpreted as evidence of motor laterality in the rider or the horse. The novice rider used more tension for turning. Tension did not differ between bridles and halters. Tensions were higher in ex-racehorses compared to other horses.

In an effort to separate the effects of horse and rider on rein tension, Clayton et al. (2011) studied the tension in side reins made of three materials with different amounts of elasticity and adjusted to three lengths. The materials were inelastic, stiff elastic and, compliant elastic. The rein lengths were neutral (equal to the length of the horse's neck when standing in a relaxed position), long (10 cm longer than neutral) and short (10 cm shorter than neutral). Horses (n = 8) trotted in hand at consistent speed in a straight line wearing a bit and bridle with the three types of side reins being evaluated in random order. Strain gauge transducers (240 Hz) measured rein tension dynamically and the authors reported minimal, maximal and mean rein tension, rate of loading and impulse. Rein tension oscillated in a regular pattern with a peak during each diagonal stance phase. Within each rein type minimal, maximal and mean tension were higher with shorter reins. At neutral or short lengths, minimal tension increased and maximal tension decreased with a more elastic rein. Short, inelastic reins had the highest maximal tension and highest rate of loading. Since the tension variables responded differently to rein elasticity at different lengths, it was recommended that studies of rein tension should report a set of variables representing different aspects of rein tension.

In conclusion, some studies only measured tension when horses were moving straight, others have looked at rein tension during dressage tests and correlated rein tension to various activities or to different head and neck positions. Only a few studies have correlated rein tension to the footfall sequence. It is likely that the situations measured so far are relatively standardized experimental situations and, in real life, much higher forces will be applied in emergency situations or by novice riders. Since some studies presented their results as mean tension there is a need for more information about the tension patterns, minimal and maximal tensions, the evenness of the contact and the rein forces applied during half halts, halts and jumping. It will also be necessary to study horse and rider laterality with respect to rein forces. If the rider/trainer could better analyze the distribution of forces on the horse's mouth, this may lead to a more efficient and humane riding technique. One of the challenges facing researchers is to distinguish between correctly trained sport horses that accept the bridle with a light soft contact and horses that achieve a light contact by dropping the bit and working in a pseudo-collected frame (with the nose behind the vertical, flexion not at the poll but further down the spine, see also further down on collection) (German National Equestrian Federation, p 143).

Basic rider movements

Trot

Of the three basic gaits, trot is the gait at which rider movements have been most extensively studied, particularly the sitting trot, although rising trot has also been evaluated and compared with sitting trot. A number of studies describe aspects of the basic rider movements (Schils et al., 1993; Terada, 2000; Terada et al., 2004, 2006; Peham et al., 2001; Matsuura et al., 2003, 2005; Lovett et al., 2005; Lagarde et al., 2005; de Cocq et al., 2010a; Byström et al., 2009, 2010b; Symes & Ellis 2009; von Peinen et al., 2009) mostly at trot and, to a lesser extent, at walk and canter.

Starting with rider movements at trot, one of the fundamental questions addresses the characteristics of the trot that the rider must react and adapt to. The trot is a regular symmetrical gait with diagonal hoof placement in which each diagonal stance encompasses a braking phase when the horse's limbs are compressed and a propulsive phase when the horse's limbs extend (Farley et al., 1993). The horse keeps its back rigid through strong muscle activity to resist wasteful lateral and rotational movements induced by the diagonal stance (Robert et al., 1998; Faber et al., 2001). Accordingly it can be expected that the movement pattern of the rider will be dominated by the effects of and reactions to the alternating impacts and push-offs. Even in high-level dressage riders riding at collected trot, i.e. rather slowly (~3 m/s), the rider's movements can largely be explained from the vertical and horizontal decelerations and acceleration of the horse's trunk that take place during each diagonal stance (Byström et al., 2009).

Rider movements at sitting trot

The following description of the rider's movement starts at ground contact of one diagonal and ends after the following suspension phase. The description is based on kinematic measurements of seven high-level dressage riders riding at collected trot on a force-measuring treadmill (Byström et al., 2009) unless a different reference is given.

Both the trunk of the horse and the rider's seat reach maximal upwards displacement at the end of the suspension phase. Following diagonal ground contact both horse and rider move downwards. Because the horse descends more quickly than the rider, the vertical distance from the rider's seat to the saddle increases during the first 5% of the stride (Fig. 15.5). The rider is thus little influenced by movements of the horse during the landing phase and the rider therefore continues the movements induced by the preceding push-off.

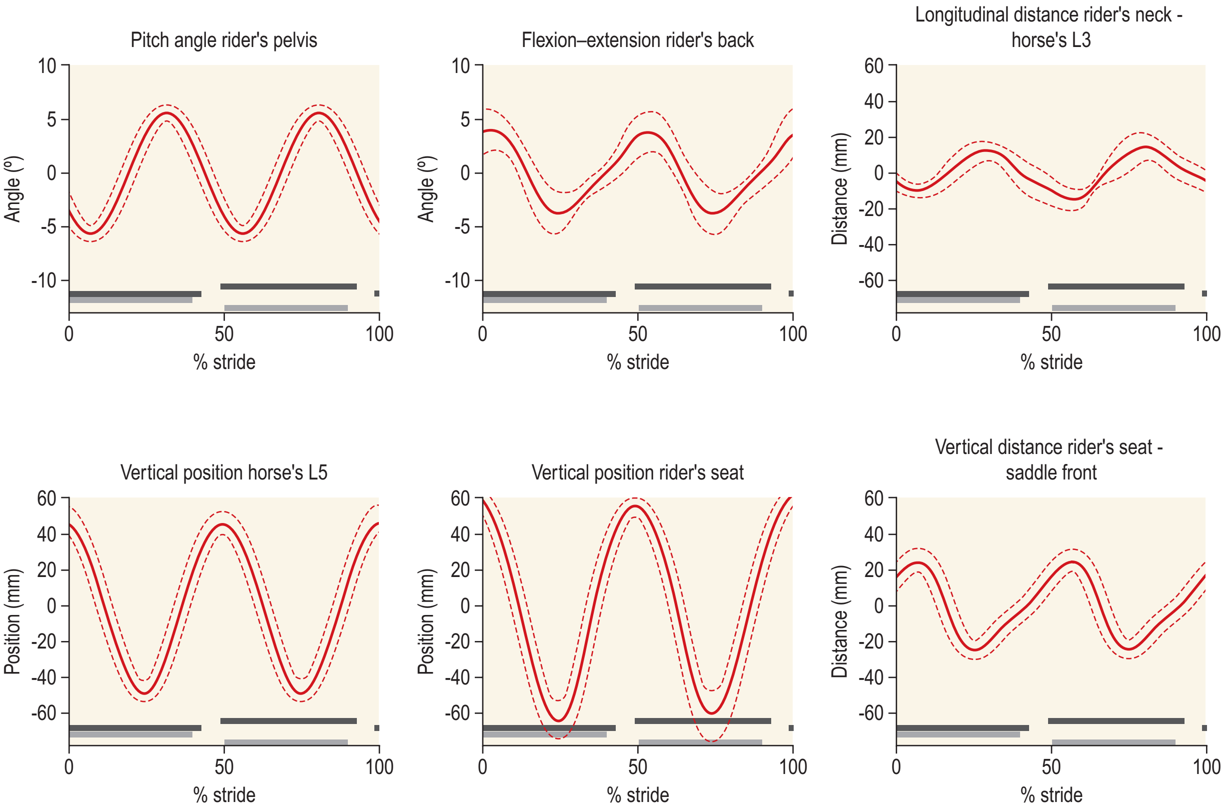

Fig 15.5 Upper row, left to right: rider's pelvic pitch, flexion–extension of the riders back, longitudinal distance from the rider's neck at the C7 vertebra to the horse's L3; lower row, left to right: vertical position of the horse's L5, vertical position of the rider's seat, and vertical distance from the rider's seat to the front of the saddle in seven horses ridden in sitting trot on a treadmill (Byström unpublished). Solid line is mean, dashed lines indicate one standard deviation. On the y axes, zero represents the mean value for the stride with each horse/rider combination curve being adjusted so individual means are zero. For the rider's pelvis, positive pitch represents anterior movement of the upper part of the pelvis relative to the lower part. For the rider's back, flexion is anterior pitch of the upper body relative to the pelvis, i.e. flexion of the lumbar spine. The lower bars show the stance of the left fore, right fore, left hind and right hind (top to bottom).

Shortly after first contact the rider's trunk (hip to shoulder) is tilted maximally backwards as a consequence of both forward motion of the rider's hip and a backward motion of the rider's shoulders, which was interpreted as a feed forward mechanism by which experienced riders anticipate and compensate for the longitudinal deceleration of the horse (Terada et al., 2006). As the rider's seat moves forward in relation to the horse, the rider's neck and feet move backwards. At the same time the rider's pelvis is maximally posteriorly rotated (around the transverse axis), the rider's back and neck are stretched in extension and the rider's legs are also maximally extended (Fig. 15.6).

From 5% stance onwards both vertical and braking ground reaction forces increase rapidly in unridden horses (Barr et al., 1995) and the forwards movement of the horse's center of mass is rapidly decelerated (Buchner et al., 2000). At the same time the distance between rider and horse decreases causing the rider's seat to be pressed against the saddle. Following this the pressure of the saddle against the back of the horse also increases rapidly (Fig. 15.7). The impact forces are now transmitted from the horse to the rider and this has a clear effect on the rider's movements. The rider's pelvis starts to rotate anteriorly, the rider's back extends (hollows) and the rider's neck flexes. The rider's trunk assumes a vertical position (Terada et al., 2006) and the rider's neck moves forwards in relation to the horse. The rider's leg joints flex, the heels are lowered and the feet move laterally and forwards in relation to the rider's hips. As the rider sinks deeper into the saddle the forward movement of the rider's seat eventually ceases at about 16% of the stride after diagonal contact. The rider's seat then starts to move backwards in relation of the horse as midstance is approached.

At midstance both horse and rider reach maximal downwards displacement, the rider sits deepest into the saddle (Byström et al., 2009) (Fig. 15.8) and the pressure of the saddle against the back of the horse is maximal.

During the propulsive phase, the upwards–forwards directed push-off by the horse is transmitted to the rider's seat through the saddle. The rider's seat starts to move out of the saddle as soon as the horse's trunk starts to move upwards (Fig. 15.5) and the pressure of the saddle against the back of the horse then starts to decrease (Fig. 15.7). A little later, at 36% of the stride following ground contact of the diagonal and coinciding approximately with the time of maximal propulsive ground reaction force (Merkens et al., 1993), the rider's seat also starts to move forwards in relation to the horse. As the rider is pushed out of the saddle the rider's trunk tilts forwards due to a combination of relative forwards movement of the shoulders and backwards movement of the hips (Terada et al., 2006). At this time the rider's pelvis rotates posteriorly and the rider's back and neck straighten. The rider's legs extend and the feet move medially and backwards in relation to the hips. These movements then continue into the following suspension phase.

The seat at rising trot

Rising trot is a rather recently invented technique that makes trotting more comfortable for the rider and reduces peak forces on the horse's back (de Cocq et al., 2010). Using this technique, the rider alternately sits on one diagonal pair of limbs and rises on the other.

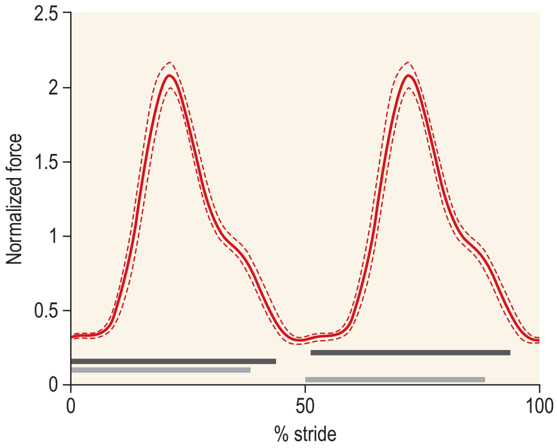

Fig 15.7 The saddle force normalized to rider weight (N/kg) at trot with stance bars in seven horses ridden in sitting trot on a treadmill (Byström unpublished). Solid line is mean, dashed lines indicate one standard deviation. The lower bars show the stance of the left fore, right fore, left hind and right hind (top to bottom).

Fig 15.6 Rider in sitting trot landing on the right diagonal

Photograph courtesy of the Equine Biomechanics Research Team from the Universities of Uppsala, Utrecht and Zürich.

Fig 15.8 Rider in sitting trot at midstance on the left diagonal at midstance.

Courtesy of the Equine Biomechanics Research Team from the Universities of Uppsala, Utrecht and Zürich.

The full stride sequence for rider movements during rising trot has not yet been documented. A preliminary kinematic study of five riders performing rising trot on one horse showed that at first contact of the sitting diagonal the rider's trunk and thigh were more vertical while the shank was angled more backwards compared with the equivalent time on the rising diagonal when the trunk leaned more forward and the thigh was also more angled forward while the shank was closer to the vertical (Lovett et al., 2005). These findings suggest that the rider first leans the trunk forward by flexing the hip joints and simultaneously moves the feet more forward relative to the hip before rising with a forward–upward movement of the seat through extension of the hip joints such that both trunk and thigh position approach the vertical. This interpretation must be, however, considered preliminary and perhaps incomplete as it is based on measurements at diagonal first contacts. It is also possible that there are relatively large variations in rider technique in rising trot.

Saddle pressure measurements of one high-level dressage rider riding at sitting and at rising trot on several different horses showed a tendency towards smaller longitudinal excursion of the center of pressure during rising trot compared to sitting trot (Peham et al., 2009). This means that the rider maintains a more constant position relative to the horse even though the longitudinal displacement of the rider's body is larger at rising trot compared to sitting trot (Matsuura et al., 2005). A preliminary study of 30 riders with a strain gauge between the stirrup and the stirrup leather concluded that the force was higher at rising than sitting trot (van Beek et al., 2008).

One study examined saddle and leg forces using three saddle mat systems between the saddle and the horse in 11 horse–rider combinations of high but not international level, moving in straight line, shoulder-in (when the horse is bent away from the line of travel) and in travers (when the horse is bent towards the line of travel) (de Cocq et al., 2010b). Mean total saddle force was significantly lower when riding straight ahead (671 N) than when riding shoulder-in (707 N) or travers (726 N). Mean inside saddle force was significantly higher when riding travers (468 N) than when riding straight on (425 N) or shoulder-in (413 N). Maximum outside leg force was significantly higher when riding travers (47.2 N) than when riding straight (31.6 N) or shoulder-in (34.2 N). This information enhances the understanding of contemporary rider movement but should be complemented with data on more riders and various dressage riding styles.

Walk

The description is based on kinematic measurements of seven high-level dressage riders riding at collected walk on a force-measuring treadmill (Byström et al., 2010b) unless a different reference is given. As in the trot, it is paramount to know the characteristics of the gait in order to understand rider movement. The walk is a symmetrical gait without a suspension phase. The horse alternates between tripedal and bipedal support, with the limbs functioning as rigid struts to raise the withers or croup from first contact to midstance. This is in contrast to trot, where both withers and croup move downwards during the first half of stance and then upwards in the following propulsion and suspension phase. As the forelimbs of the walking horse move approximately 25% of the stride out of phase in relation to the hind limbs, the withers are raised when the croup is lowered and vice versa. All together this causes the vertical displacement of the saddle area of the horse's back at walk to be about half that of the trot (Matsuura et al., 2003) while rotation of the horse's trunk around the transverse axis (pitch) is almost doubled (Table 15.1) (Byström et al., 2010b). The amplitudes of lateral and longitudinal excursions of the horse's body center of mass, which are necessary for the horse to maintain its balance during the alternating tripedal and bipedal support phases, are approximately equal to the vertical excursion at walk (Buchner et al., 2000). Such displacement can be accomplished through lateral bending and axial rotation of the back and the axial rotation range of motion is almost doubled during walk compared to trot (Faber et al., 2000; Faber et al., 2001). Therefore, extra-sagittal movements constitute a proportionally larger part of the assembled motion pattern of the walk compared to trot, and it is to be expected that the rider's movement pattern will be equally more complex. To gain full understanding of the horse–rider interaction at walk, the rotations of the rider's body segments around the vertical and longitudinal axes must also be considered. However, focusing on sagittal plane movements is a good place to start describing the rider's movements.

Rider movements in the sagittal plane at walk

At walk both the range of vertical displacement of the rider's body (Matsuura et al., 2003) and the rider's seat in relation to the front part of the saddle are smaller than at trot (Table 15.1). Further, the rider's seat moves upwards in relation to the front part of the saddle while moving downwards in relation to L3 of the horse and vice versa (Fig. 15.9). This indicates that the vertical displacement of the rider's seat at walk results mainly from the croup being lowered and raised in relation to the withers rather than true vertical displacement of the rider in relation to horse and saddle. The fact that the rider shows a decreased range of motion for pelvic pitch, back flexion–extension and all head–neck rotations at walk compared

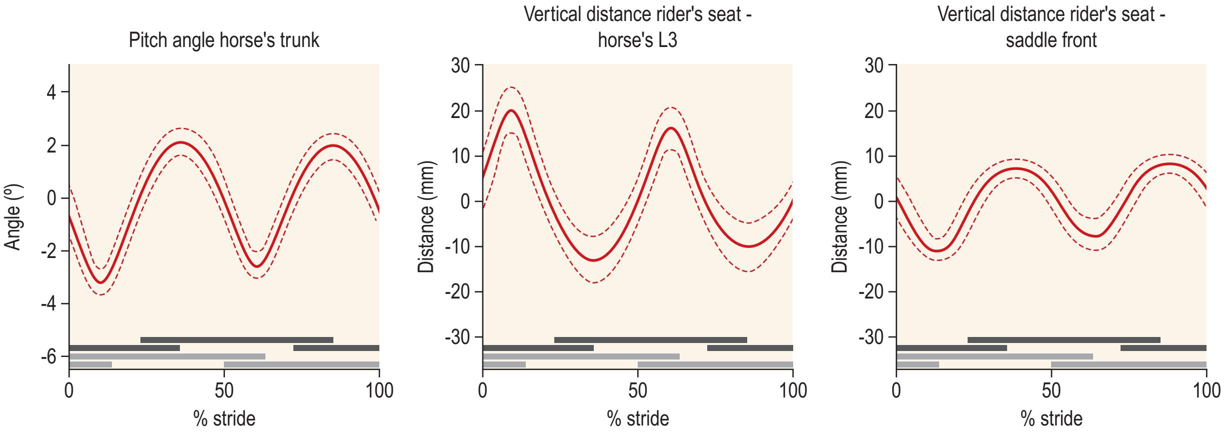

Fig 15.9 Left to right: The horse's trunk pitch angle, the vertical distance between the rider's seat and the horse's third lumbar vertebra (L3) and the vertical distance from the rider's seat to the front of the saddle in seven horses ridden in walk on a treadmill. Solid line is mean, dashed lines indicate one standard deviation. Zero value on the y axis represents mean value for the stride with each horse/rider combination curve being adjusted so individual means are zero. The lower bars show the stance of the left fore, right fore, left hind and right hind (top to bottom).

Data from Byström (unpublished).

Table 15.1 **Stride range of motion in degrees or mm for variables measured in high-level dressage horses and riders (n = 7) during collected walk and trot on a treadmill[#]. Pitch is rotation around a transverse axis, roll is rotation around a longitudinal axis and yaw is rotation around a vertical axis.**

		Walk ROM (°/mm)	Difference trot–walk (%)	Trot ROM (°/mm)
Saddle	Pitch	6.1 ± 0.9	9 ± 13	5.6 ± 0.6
	Roll	8.5 ± 2.7	53 ± 69	7.3 ± 5.2
	Yaw	8.3 ± 1.5	49 ± 33*	5.7 ± 1.0
Rider pelvis	Pitch	9.7 ± 2.0	−28 ± 20*	13.9 ± 2.2
	Roll	5.6 ± 0.6	18 ± 31	5.1 ± 1.1
	Yaw	8.2 ± 1.9	9 ± 31	7.9 ± 2.1
Rider upper body	Pitch	6.0 ± 2.0	−42 ± 14*	10.7 ± 3.4
	Roll	5.0 ± 1.8	12 ± 42	4.9 ± 1.8
	Yaw	5.0 ± 1.3	−6 ± 21	5.5 ± 1.1
Rider head–neck	Pitch	11.0 ± 4.8	−30 ± 19*	15.7 ± 4.5
	Roll	4.0 ± 0.9	−28 ± 22*	5.9 ± 1.1
	Yaw	4.1 ± 1.3	−25 ± 22*	5.7 ± 2.4
Rider seat–saddle front	Vertical distance	25 ± 6	−55 ± 14*	58 ± 10
Rider seat–horse (L3)	Vertical distance	38 ± 9	−5 ± 39	45 ± 13
	Longitudinal distance	41 ± 4	−14 ± 24	50 ± 24
Rider neck–horse (L3)	Longitudinal distance	53 ± 14	21 ± 33	45 ± 6
Horse neck	Pitch	8.0 ± 1.6	43 ± 50	6.0 ± 1.4
Horse trunk	Pitch	6.0 ± 0.7	53 ± 22*	4.0 ± 0.7
Horse (L5)	Vertical displacement	62 ± 7	−42 ± 8*	106 ± 8

[#] Table values represent group mean ± *SD*.

*Significant difference ($p < 0.05$) between gaits in a paired non-parametric test (Wilcoxon).

ROM, range of motion.

Reprinted from Byström, A., Rhodin, M., von Peinen, K., et al., 2009. Basic kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. Equine Vet. J. 41, 280–284, with permission from the Equine Veterinary Journal.

with trot (Table 15.1) may reflect the absence of impact effects on the rider at walk. This is supported by the fact that the range of motion for vertical displacement of the rider's body is only about 1 cm at walk (Matsuura et al., 2003) and the amplitude of the rider's body movements is significantly lower in the vertical than in the lateral and longitudinal directions, which is contrary to the findings at trot (Matsuura et al., 2005). Riders are therefore more likely to be adjusting their movements at walk to the alternating difference in height between the horse's croup and withers rather than to vertical and horizontal deceleration and acceleration of the horse's trunk as in trot (Byström et al., 2009).

To appreciate the rider's positional adjustments at walk, we note that from the tripedal support of one forelimb and both hind limbs to the tripedal support of both forelimbs and one hind limb, i.e. from forelimb midstance to hind limb midstance, the horse's croup is raised while the withers are lowered in relation to the croup (Fig. 15.9). When the horse's trunk starts to rotate cranially this transmits a forward push to the rider's seat from behind that causes the seat to slide forward (Byström et al., 2010b). To maintain balance the rider's pelvis rotates posteriorly (around the transverse axis), the neck moves backwards relative to the horse and the feet are retracted through extension of the leg joints, particularly the hip joints (Fig. 15.10). These movements are reversed after hind limb midstance when the croup descends relative to the withers.

Lateral and rotational rider movements at walk

For the rider's body movements at walk the lateral amplitude is approximately equal to the longitudinal amplitude and significantly greater than the vertical amplitude (Matsuura et al., 2005). Consequently, the extra-sagittal movements constitute a significant part of the assembled motion pattern of the walk, both for the horse and the rider and these have to be taken into account to form a comprehensive picture. This is clearly reflected in the saddle pressure pattern of walk (Fig. 15.13) and the fact that the vertical movements of the horse and rider were insufficient to explain the various force peaks observed (von Peinen et al., 2009). To explain this pattern the rotation of the rider's pelvis around the longitudinal axis (roll rotation) as well as the lateral bending and axial rotation of the horse's back must be considered in addition to sagittal plane movements. Rotations of the rider's pelvis around the vertical axis (yaw rotation) generally follow the movements of the saddle and seem to have little influence on the saddle pressure pattern.

The motion pattern has been described in high-level dressage riders riding at collected walk on a treadmill (von Peinen et al., 2009; Byström et al., 2010b). During the tripedal dual hind limb support phase, the horse's croup is rapidly lowered and, at the same time, the horse's back is bent laterally towards the left hind limb

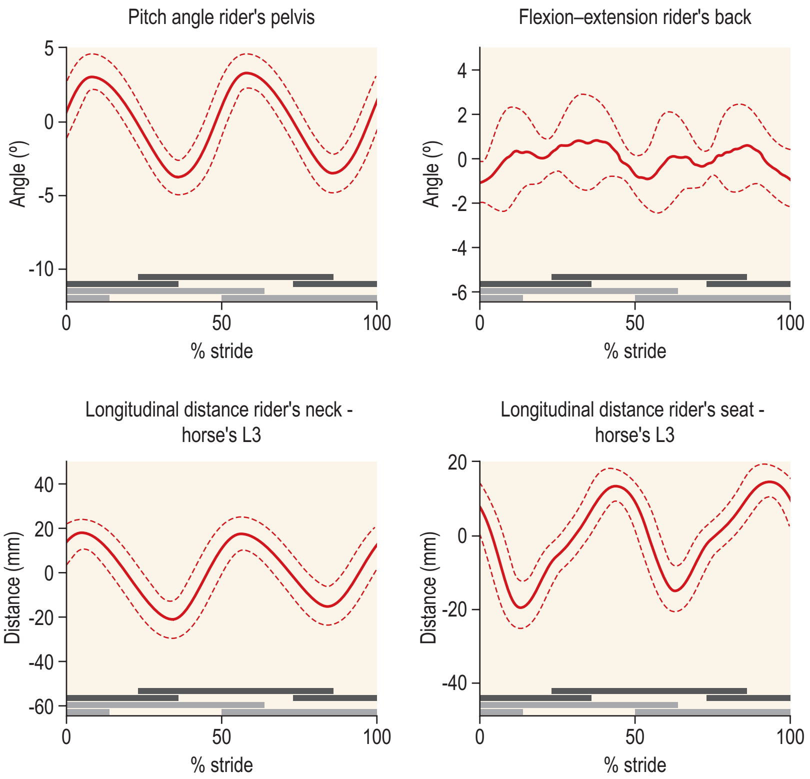

Fig 15.10 Top row, left to right: Rider pelvic pitch, flexion–extension of the rider's back and flexion/extension of the rider's hip joints in seven horses ridden in walk on a treadmill. Bottom row, left to right: longitudinal distances from the rider's neck and from the rider's seat to the horse's third lumbar vertebra (L3) in seven horses ridden in walk on a treadmill. Solid line is mean, dashed lines indicate one standard deviation. Zero value on the y axis represents mean value for the stride with each horse/rider combination curve being adjusted so individual means are zero. For the rider's pelvis, positive pitch represents anterior movement of the upper part of the pelvis relative to the lower part. For the rider's back, flexion is cranial pitch of the upper body relative to the pelvis, i.e. flexion of the lumbar spine. The lower bars show the stance of the left fore, right fore, left hind and right hind (top to bottom).

Data from Byström (unpublished).

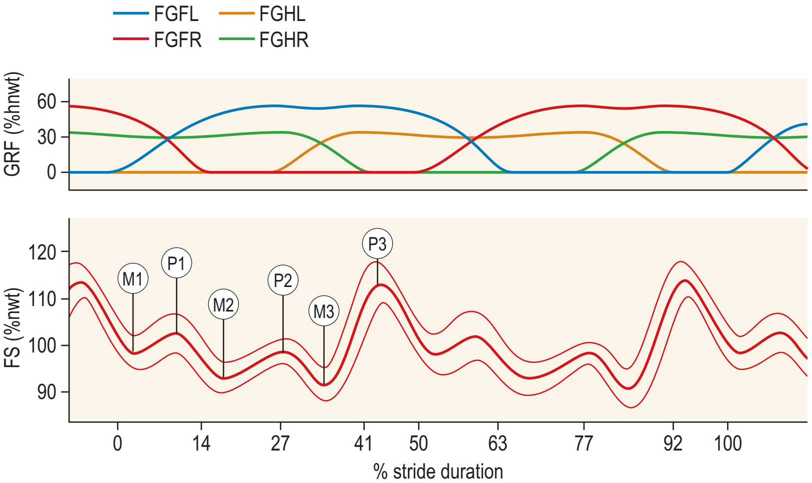

Fig 15.11 Mean stride normalized ground reaction forces of the four limb (FGFL, left forelimb; FGFR, right forelimb; FGHL, left hind limb; FGHR, right hind limb) (top) and total saddle force (bottom) of seven horses at walk. Ground reactions forces of individual limbs (FG limb) are expressed as percentage of the total weight of horse and rider (% hrwt). Total saddle force (FS) is expressed as percentage of the rider's weight (% rwt). The thick line is mean value and thin lines indicate one standard deviation. The local extremes (minima M1 to M3, maxima P1 to P3) are indicated.

Reprinted from Peinen, K., von, Wiestner, T., Bogisch, S., Roepstorff, L., van Weeren, P.R., Weishaupt, M.A., 2009. Relationship between the forces acting on the horse's back and the movements of rider and horse while walking on a treadmill. Equine Vet. J. 41, 285–291, with permission from the Equine Veterinary Journal.

such that the back is convex to the right, and rotated around the longitudinal axis such that the left tuber coxae is higher than the right. Simultaneously the rider's seat moves rapidly backwards in relation to the horse and the rider's left hip is being lowered in relation to the right hip, i.e. the rider's pelvis undergoes roll rotation to the left (Fig. 15.12). This combination of horse and rider movements causes a marked reduction in pressure under both the left and right front thirds of the saddle while pressure increases mainly on the left side under the rear part of the saddle (Fig. 15.13) (von Peinen et al., 2009).

When the right hind limb starts to break-over and the croup rises relative to the withers, the pressure under the rear left third of the

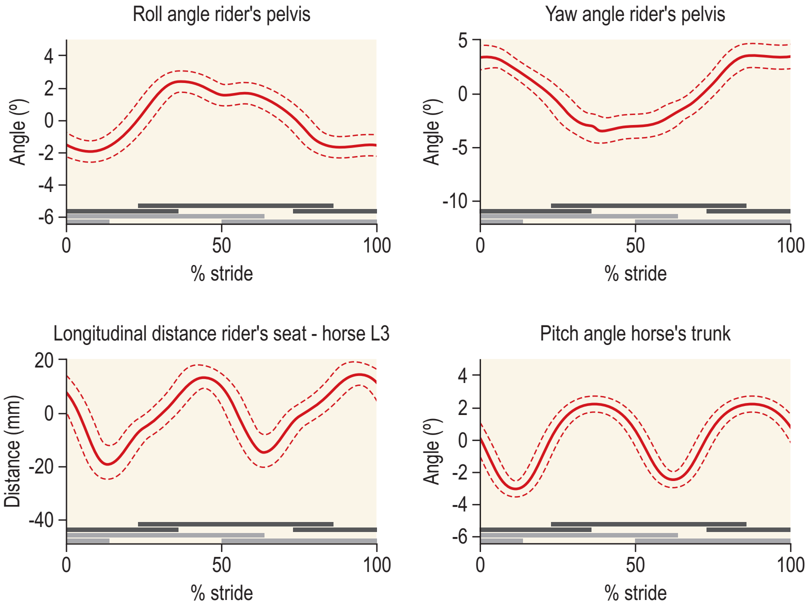

Fig 15.12 Rider kinematics in seven horses ridden at walk on a treadmill. Top row, left to right: rider's pelvic roll angle (positive is rotation to the right when viewed from behind) and rider's pelvic yaw angle (positive yaw is rotation to the right when viewed from below) during the walk. Bottom row, left to right: longitudinal distance from the rider's seat to the horse's third lumbar vertebra (L3) and pitch angle of the horse's trunk (positive pitch is lowering of the withers relative to the croup). Solid line is mean, dashed lines indicate one standard deviation. The lower bars show the stance of the left fore, right fore, left hind and right hind (top to bottom).

Data from Byström (unpublished).

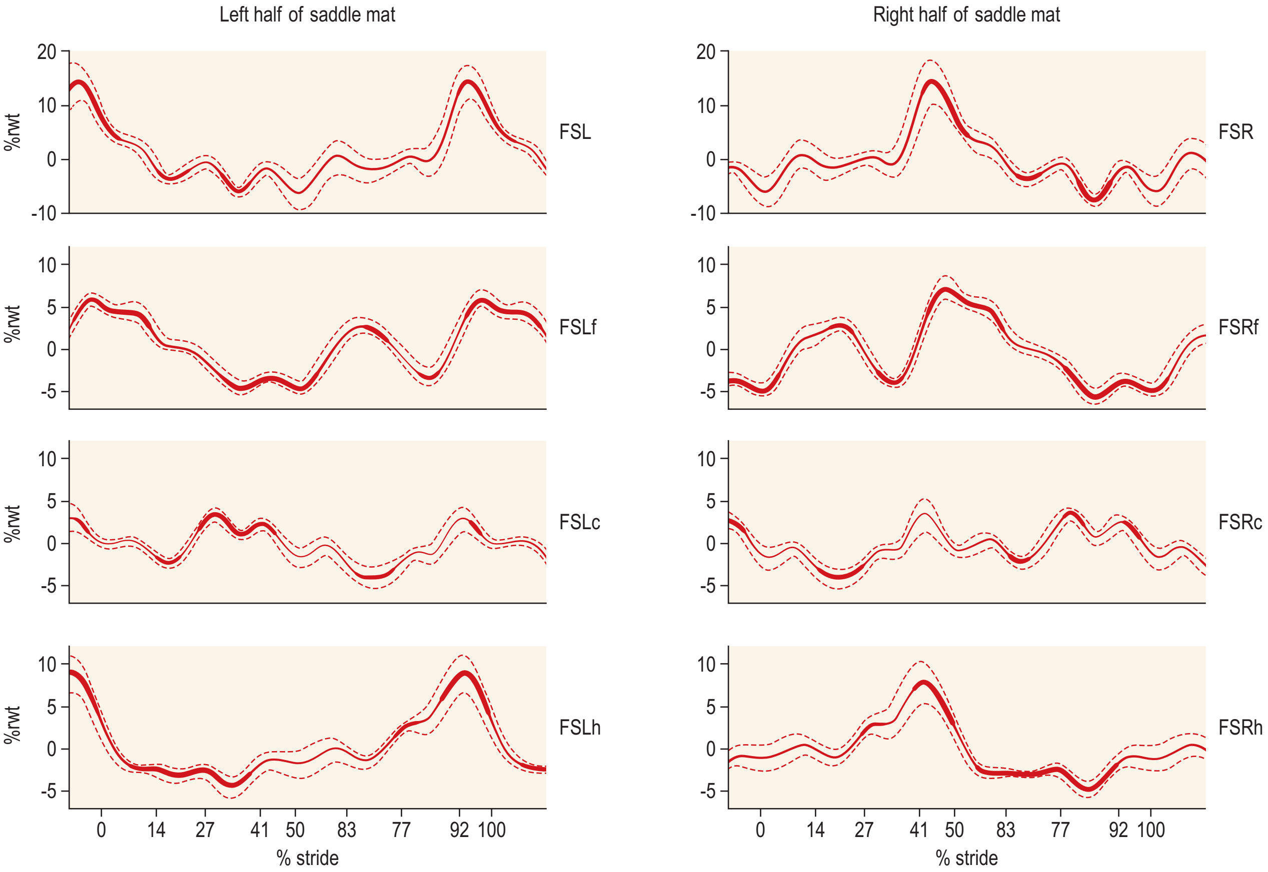

Fig 15.13 Mean (thick line) ± SD (dashed lines) for relative changes of stride standardized saddle forces of the left (FSL, left panel) and right (FSR, right panel) mat half and partial forces of six sectors (n = 7 horses). Each half of the mat was divided into a front (f), central (c) and hind (h) sector; partial forces are labeled accordingly. Forces are presented as deviation from the stride mean value of the respective sector. Bold curve sections mark significant deviations from the stride mean ($p < 0.05$). For scaling of the abscissa see Fig. 15.11. Solid line is mean, dashed lines indicate one standard deviation.

Reprinted from Peinen, K., von, Wiestner, T., Bogisch, S., Roepstorff, L., van Weeren, P.R., Weishaupt, M.A., 2009. Relationship between the forces acting on the horse's back and the movements of rider and horse while walking on a treadmill. Equine Vet. J. 41, 285–291, with permission from the Equine Veterinary Journal.

saddle increases even further (Fig. 15.12). This induces not only forwards movement of the rider's seat but also roll rotation of the rider's pelvis to the right.

During the following diagonal (right front, left hind) support phase the rider's seat moves rapidly forwards in relation to the horse. At the same time the horse's dorsal back muscles contract strongly on the left side in the cranial saddle area during retraction of the right forelimb (studied without rider) (Licka et al., 2009). This coincides with a marked increase in pressure under the left front third of the saddle while the rider's pelvis continues to roll to the right.

After the transition from bipedal to tripedal support at ground contact of the left forelimb the dorsal back muscles in the left cranial saddle area start to relax (Licka et al., 2009) and the forwards rotation of the horse's trunk slows as the left hind limb approaches midstance. Following this the pressure distribution between the front thirds of the saddle starts to even out as the pressure increases under the right front third (Fig. 15.13). Just after this, roll rotation of the rider's pelvis to the right also ceases (Fig. 15.12).

When the left hind limb has passed its midstance position the horse's back becomes progressively more axially rotated to the left (lower on the left side) and bent to the right (convex to the left). This decreases the support under the left rear third of the saddle, which is reflected in the very low pressure measured under this part of the saddle at the end of tripedal support (right front, left hind, left front) and during the following (left hind, left front) bipedal ipsilateral support phase (Fig. 15.13). Decreased support of the left rear third of the saddle, perhaps combined with the slight increase in pressure under the right front third of the saddle following lift-off of the right forelimb, explains why the rider's pelvis starts to roll to the left at lift-off of the right forelimb. Most riders also retract their left hip in relation to the right hip (left yaw rotation), this being the only period in the stride (approximately forelimb lift-off to ground contact of the next hind limb) when yaw rotation of the rider's pelvis does not follow yaw rotation of the saddle. However, at the same time the horse's dorsal back muscles in the middle saddle area contract strongly on the left side as the left hind limb is retracted (Licka et al., 2009). It is therefore not surprising that left roll and yaw rotation of the rider's pelvis are followed by an increase in pressure under the left central third of the saddle, peaking at ground contact of the right hind limb. Following this peak, roll rotation of the rider's pelvis is abruptly redirected to a right yaw rotation as the rider's pelvis starts to follow the saddle again and right roll rotation continues during the early part of the right hind limb stance.

Canter

The canter shows mixed gait mechanics where the trailing hind and leading forelimbs function essentially as rigid struts while the diagonal stance of the leading hind and trailing fore is best likened to a bounce. The trunk of the horse rotates quite extensively around its transverse axis and the back, particularly the lumbosacral joint, has the largest range of motion in flexion–extension of all gaits. The rolling motion pattern of the canter is sometimes perceived by the rider as being easier to sit than the trot. This perception is supported by the fact that measurements of the accelerations of the rider's helmet showed no differences between advanced and novice level riders at canter, which is in contrast to the differences found at walk and sitting trot (Terada, 2000).

The full stride sequence for rider movements during canter has not yet been documented. However, a preliminary study compared rider position at first contact of the trailing hind limb, the diagonal limb pair and the leading forelimb. It showed that the rider's trunk was tilted forwards during trailing hind limb stance then rotated back towards the vertical during leading forelimb stance and suspension (Lovett et al., 2005). These trunk movements of the rider to follow the rotation of the horse's trunk at canter.

Rider skill

General

The following section presents the results of studies that evaluate the effect of rider skill level with most of the results being derived from traditional riders. A large kinematic overground study by Schils et al. (1993) included 63 riders divided into three groups of beginner, intermediate and advanced based on video evaluation of their skill level by judges. Midstance and midswing rider angles were determined. Other studies have strived to evaluate rider skill (Lovett et al., 2005) and some of these results will be presented in the following paragraphs. Speed and temporal characteristics of the horse as well as riding style and the rider's degree of control of the horse's movements are likely to be important factors affecting the rider's movement pattern. The influence of these factors on the rider's movements has however not been evaluated.

Trot

The rider needs to have excellent postural control through well-timed muscle activity to constantly maintain the same posture in every trotting stride. A study using surface EMG measurements in experienced riders showed that the upper part of *m. trapezius* has strong and distinct activity during the first half of stance to stabilize the rider's head and neck and that *m. rectus abdominis* is active during the middle and later parts of the stance phase (Terada et al., 2004) to maintain pressurization of the abdomen and stabilize the trunk. The sequence and timing of activation of the other abdominal muscles of the rider have not been evaluated but are likely to be equally, if not more important, than the action of rectus abdominis, which is more easily accessible to surface EMG. Postural control is clearly something the rider must learn through training.

Comparing riders of different skill levels, three studies found that the cranio-caudal movements of the rider's head or shoulders were more regular between strides in advanced compared to less experienced riders (Terada, 2000; Peham et al., 2001; Lagarde et al., 2005). More efficient postural control in more skilled riders allowed them to maintain their shoulders closer to the vertical at diagonal midstance whereas the novice riders tilted more forwards (Schils et al., 1993). Comparisons of EMG recordings of two important postural muscles, *m. erector spinae* and *m. rectus abdominis*, and the great adductor of the thigh, *m. adductor magnus*, also confirm differences in activity pattern between advanced and novice riders (Terada, 2000). Advanced riders had forceful contractions in both *m. erector spinae* and *m. rectus abdominis* while *m. adductor magnus* was largely inactive. Novice riders, however, had proportionally more forceful contractions of *m. rectus abdominis* compared to *m. erector spinae* and *m. adductor magnus* was markedly more active compared to the advanced riders (Terada, 2000). Unbalanced activity between abdominal and epaxial muscles could reflect a less efficient postural control in novice riders and relatively greater activity of the abdominal muscles could contribute to a more protracted (rounded) shoulder position. Increased activity of the thigh adductors is likely an attempt to compensate for the unstable upper body position (Terada, 2000). Although the movements of the horse seem to dictate the basic pattern of the rider's movements, postural control is clearly influenced by the rider's active responses to the movements of the horse and these responses vary with skill level.

A different study (Pantall et al., 2009) used surface EMG to evaluate activation of *m. iliocostalis lumborum* and *m. rectus abdominis* in rising trot. All riders showed coactivation of the right and left muscles. In the novice riders *m. rectus abdominis* and *m. iliocostalis lumborum* were coactivated whereas in experienced riders there was a phase shift between them. *M. rectus abdominis* behaved as an agonist in the experienced rider, contracting as the rider made contact with the saddle on the sitting diagonal.

The rising trot is often perceived by the novice rider as being less tiring than sitting trot (German National Equestrian Federation, 2002, p. 50). As in sitting trot the skill level of the rider seems to have a significant influence on the rider's movements. Advanced riders have their shoulders further backwards relative to their hips at diagonal midstance both at the sitting and rising phases and they also extend their hip joints more when rising (Schils et al., 1993).

Walk

At walk there is more variation, compared to the trot, in the upper body movements between individual riders both regarding extent and regularity and likely also timing in relation to the horse. It is suggested that variation is caused by the individual style of the rider and/or skill level. In a group of high-level dressage riders all riders moved the neck caudally in relation to the horse when the horse's croup was raised, but the relative contribution of the pelvis and upper body to these movements varied between the riders (Byström et al., 2010b). One rider compensated by flexion–extension of the lumbar back while keeping the neck more stationary, while others tended to use their entire upper body to balance the movements of the horse (Fig. 15.14). Skill level dependency of upper body movements at walk is supported by the finding that advanced riders had a more regular pattern in their vertical head movements whereas novice riders had greater between-stride variability (Terada, 2000). This was associated with proportionally more concentric activity of the postural muscles *m. erector spinae* and *m. rectus abdominis* in the advanced riders while the novices showed a more static activity pattern (Terada, 2000). More skilled riders may exert a more active postural control leading to a more regular movement pattern and smaller phase shift in relation to the horse.

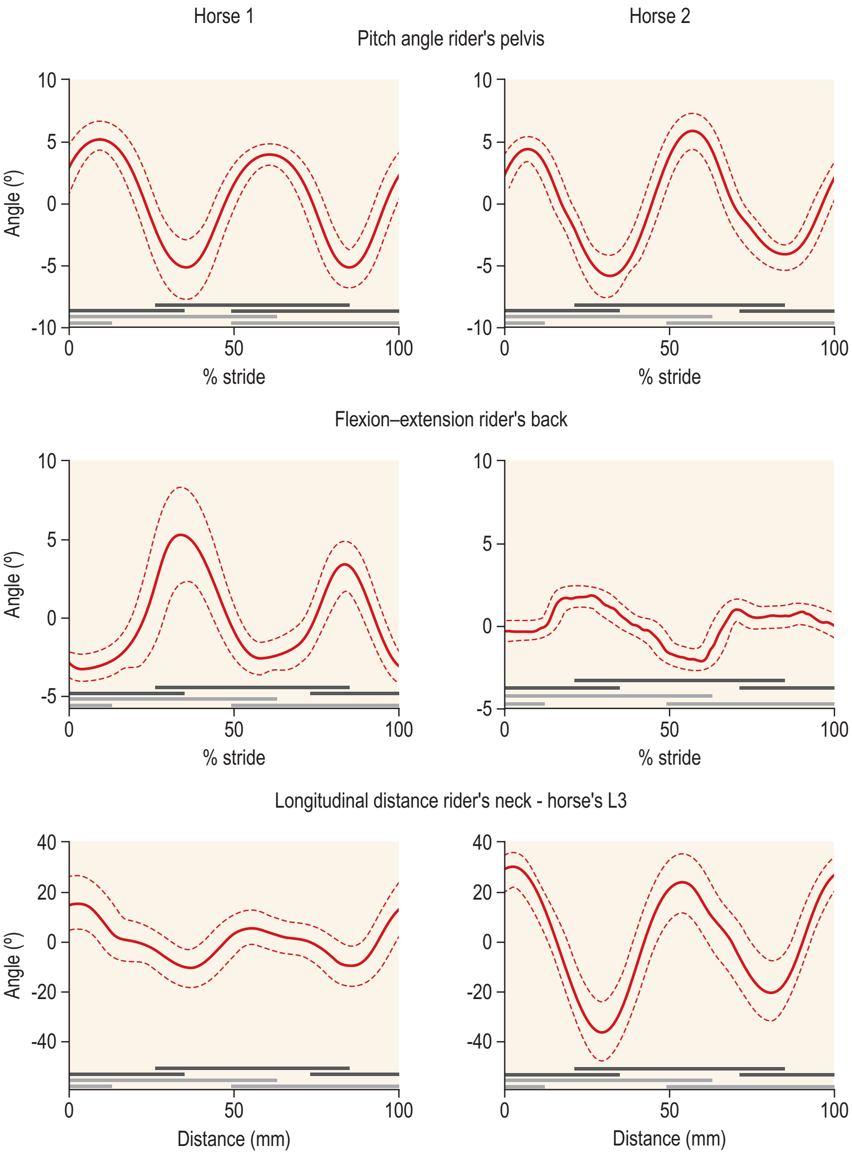

Fig 15.14 Rider's upper body kinematics in two horses (Horse 1, left panel, Horse 2, right panel) ridden at walk on a treadmill. Data are for one stride starting at left hind contact. Top row, pitch angle of the rider's pelvis, middle row, flexion/extension of the rider's back; bottom row, longitudinal distance from the rider's neck to the horse's third lumbar vertebra (L3). Zero represents mean value for the stride. Solid line is mean, dashed lines indicate one standard deviation. The lower bars show the stance of the left fore, right fore, left hind and right hind (top to bottom).

From Byström, unpublished.

The rider's stability can be assessed by tracking movements of the center of pressure (COP) using a pressure mat beneath the saddle. Able-bodied riders have been shown to have smaller amplitudes of COP motion in both the anteroposterior and mediolateral directions compared with riders with cerebral palsy. COP velocity in the mediolateral direction was also significantly smaller in able-bodied riders (Clayton et al., 2010). Although this study was directed toward the value of COP measurements for monitoring progress in a therapeutic riding program, the technique may also be useful for assessing stability of riders in general.

Rider skill level also seems to influence the rider's leg movements at walk. At forelimb midstance (i.e. approximately at hind limb contact) advanced riders show less hip flexion but similar shoulder position compared to novices (Schils et al., 1993). This could be due to a phase-shift between riders at different skill levels or it could reflect the fact that advanced riders are more exact and efficient in their movements. Compared to novice riders, advanced riders have greater concentric activity in *m. adductor magnus* at walk (Terada, 2000), which could indicate a more active control of leg movements as well as upper body movements. However, walking speed was not presented in these studies (Schils et al., 1993; Terada, 2000) and it is possible that differences in the horse's stride length and/or stride frequency between rider skill levels contributed to the observed differences in rider movement patterns.

The hand

The equestrian literature often states that the hand should be independent from the seat, meaning that the movements of the hand should follow the movements of the horse's head and mouth, rather than the movements of the rider's torso. Accordingly, well-timed flexion–extension movements of the rider's shoulder and elbow joints are necessary to compensate for movements of the rider's upper body in relation to the horse. High-level dressage riders indeed do perform such movements (Terada et al., 2006; Byström et al., 2009) and EMG measurements in experienced riders indicate that these movements are actively induced by the rider (Fig. 15.15).

During trotting, in the first half of stance the rider's neck moves forwards in relation to the horse, the rider's trunk (hip to shoulder) tilts forwards and the distance from the rider's shoulders to the bit in the horse's mouth decreases. Simultaneously the rider's shoulder and elbow joints flex while the *m. biceps brachii* and *m. deltoideus* muscles are active and *m. flexor carpi radialis* is also active to flex or stabilize the wrist. During the second half of stance the rider's neck moves backwards in relation to the horse, the rider's trunk tilts backwards and the distance from the rider's shoulders to the bit increases. At the same time the rider's shoulder and elbow joints extend and *m. triceps brachii* becomes active while the activity of the flexor muscles ceases. These compensatory movements stabilize the riders' hands at a more constant position in relation to the horse's moving head (Terada et al., 2006) (Fig. 15.16). Vertical displacement of the rider's wrist was significantly smaller than that of the rider's hips and shoulders and the distance from the rider's wrist to the bit varied significantly less than the distance from the rider's hip to the bit (Terada et al., 2006). A preliminary study comparing one novice and one expert rider also found that the expert rider had a significantly lower phase shift between the vertical movements of the head and shoulder and the wrist and elbow (Lagarde et al., 2005), further supporting the idea that these arm movements are under the rider's active control and are learned through training, rather than induced by the movements of the horse.

Horse movement in relation to rider skill

Compared with an average rider, an expert rider's movements are more consistent and less phase-shifted in relation to the horse's movements (Terada, 2000; Peham et al., 2001; Lagarde et al., 2005) indicating that the rider has a significant influence on the horse–rider system.

Peham et al. (2001) compared a professional with a recreational rider riding 20 horses at sitting trot over a sand arena with high-speed cameras recording marker positions. Angular velocities and accelerations were derived, and resulting vectors in the phase space were computed. The professional horse–rider system had the most consistent motion pattern and higher dressage scores (evaluated during the experiment), compared to the recreational horse–rider system. Using the same material, motion asymmetries of the head and sacrum were compared using markers tracked at 120 Hz (Licka et al., 2004). The lameness of the unridden horse (assessed visually using a dichotomous scale) was not reproduced under either rider. For the dressage rider there was a significant increase in hind-limb asymmetry, compared to the unridden situation. Using partly the same trials (n = 14 horses), Schöllhorn et al. (2006) used artificial neural networks to analyze kinematic parameters over time. The professional rider was able to control 13 of the 14 horses with respect to the head, while the recreational rider controlled only three horses. On the contrary, hind fetlock and hock movements were not influenced much by the riders, but were more affected by the inherent motion pattern of the horse.

Terada (2000) studied two experienced and two novice riders riding two horses over an 80-m sand arena in the three gaits, with instructions to use as few aids as possible. A camera recorded the stride durations, the riders' head movements were monitored with an accelerometer, and activity in three of the riders' muscles were recorded electromyographically. Differences were found in the walk and trot, where it was concluded that novice riders had more difficulty in stabilizing the body. At sitting trot, novice riders used their *m. adductor magnus* muscle to maintain their posture because of lack of coordination between the *m. rectus abdominis* and *m. erector spinae* (Terada, 2000; Terada et al., 2004).

In earlier work, Schamhardt et al. (1991) studied walk and rising trot using ground reaction force analysis (x, y and z) in 13 Dutch Warmbloods comparing one experienced rider, one novice rider and an equal amount of dead weight (two sandbags). They concluded that, compared with sandbags, the riders managed to shift part of the weight towards the hind limbs. However skill of rider did not, in general, influence the patterns of the ground reaction forces. It should be cautioned that velocity was not standardized in that study. Another study in which horses moved at the same trotting speed with and without a rider confirmed that there was a reduction in mass normalized peak vertical force with an experienced rider (Clayton et al., 1999).

Kinematics of 20 horses were evaluated using high-speed video to compare three conditions: unridden at trot, ridden at sitting trot by a professional rider and ridden at sitting trot by a recreational rider (Kapaun et al., 1998). Significant differences between the unridden situation and the professional rider were found for impulsion, pelvic inclination, fore and hind limb vertical movement, and fore and hind stance durations. After speed-normalization, only the difference in vertical movement of the fore and hind limbs remained significant. Comparison between the professional and recreational rider showed differences in speed, stride length, head angle, hind limb protraction, pelvic inclination, fore and hind limb vertical movement, and fore stance duration. After speed-normalization only impulsion remained significantly different.

With regard to jumping kinematics, 50 Hz video recordings of 10 horses jumping a 1.05-m fence with an experienced and a novice rider revealed no significant differences in velocity or stride length during the approach, take-off or landing (Powers & Harrison, 2002). It was concluded that horses jumped in the same way, regardless of what the riders were doing. However, the authors cautioned that the similar results could have arisen because the horses were riding school horses and not competition horses, the fence was not very high, the weight of the riders differed between 12 and 15% of the horse's weight, the novice rider was possibly too

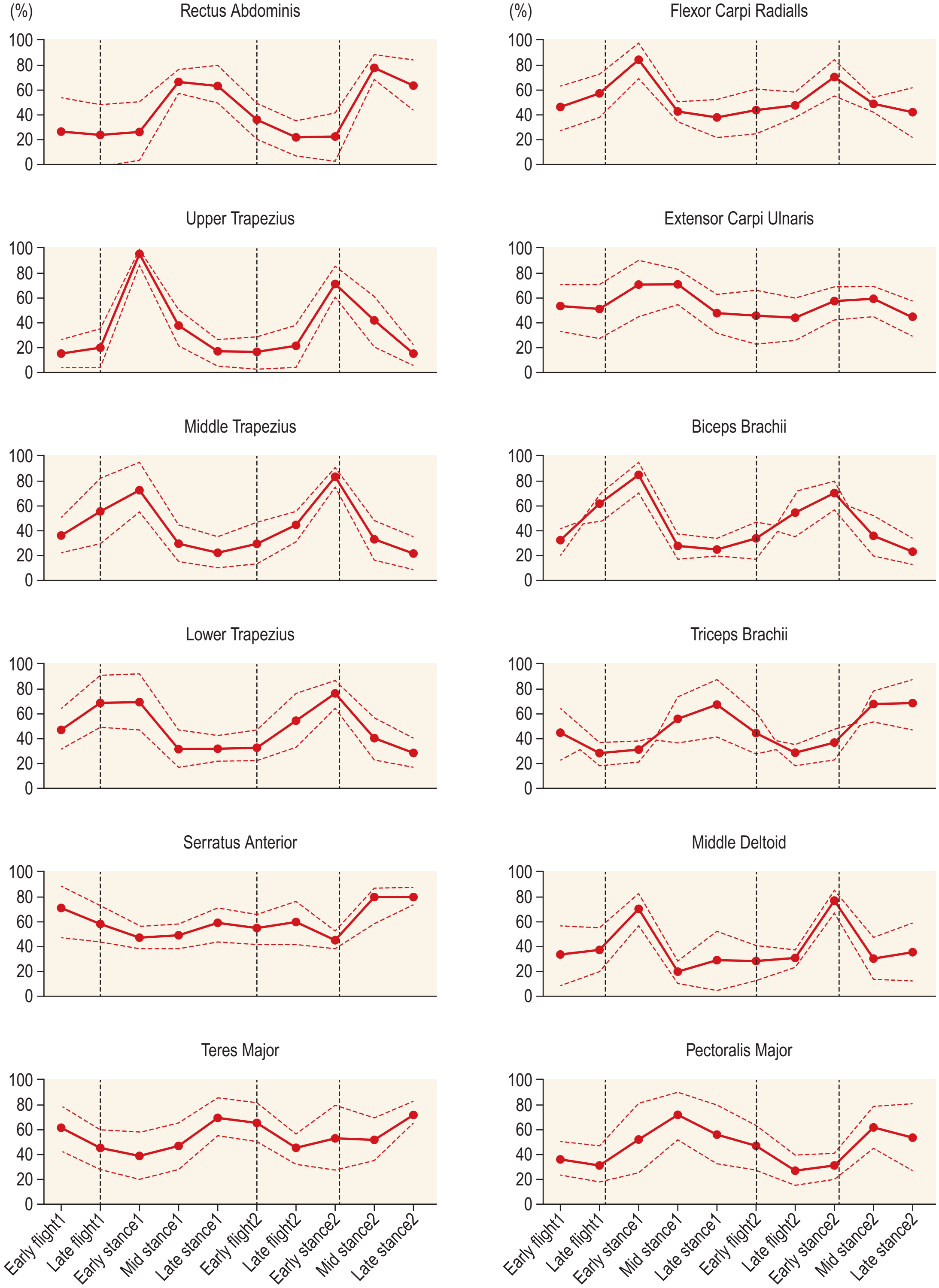

Fig 15.15 Muscular activity for 12 muscles of six subjects over 10 phases of the stride. Each datum point represents mean activity during a phase of the stride expressed as a percentage of maximal activity for that muscle. Dashed lines indicate one standard deviation. Vertical dotted lines separate the four consecutive phases of flight 1, stance 1, flight 2 and stance 2.

Reprinted from Terada, K., Mullineaux, D.R., Lanovaz, J., Kato, K., Clayton, H.M., 2004. Electromyographic analysis of the rider's muscles at trot. Equine Comp. Exerc. Physiol. 1, 193–198, with permission of Cambridge University Press.

experienced and the riders may not be representative of experienced and novice riders in general.

Warren-Smith et al. (2007) studied rein tension in one professional, one intermediate and one novice rider on 22 horses performing a simple dressage test. The novice rider used more tension for turning and the authors concluded that experienced riders can use finer aids.

Most studies that have compared experienced and novice riders relative to the motion of the horse have used only a few riders. The experienced riders often have a long riding experience and have

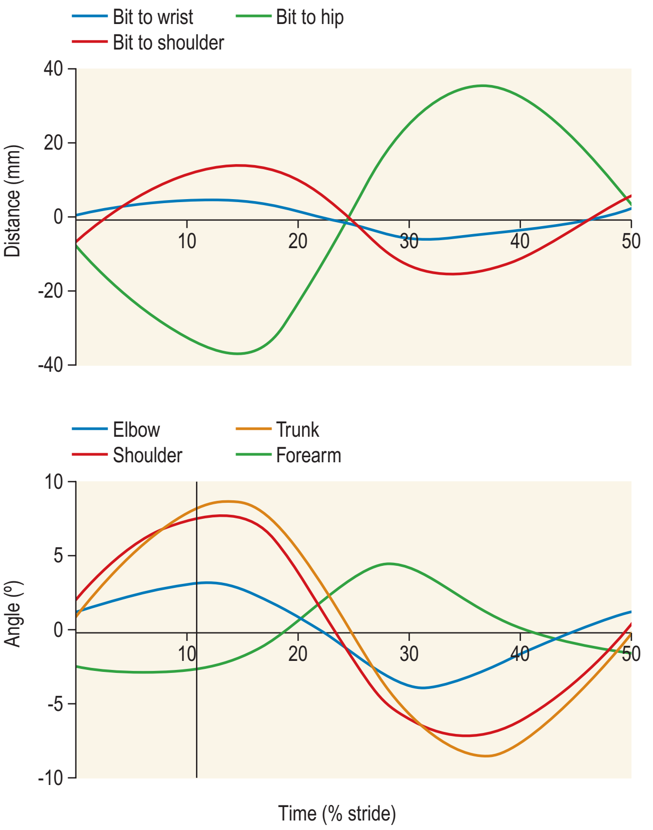

Fig 15.16 Mean values of linear angular variables in six experienced riders during half a stride at trot. Distances are measured from the bit to the riders' wrist, shoulder and hip (top panel) and angulations of the riders' elbow joint, shoulder joint, trunk to vertical (tilting the upper body back is positive) and forearm to vertical (moving the elbow forward relative to the shoulder is positive) (bottom). Ground contact time of the right forelimb is indicated by the vertical line at 11% stride. The data have been normalized so the mean value during the entire trial is represented as zero for each variable.

Reprinted from Terada, K., Clayton, H.M., Kato, K., 2006. Stabilization of wrist position during horseback riding at trot. Equine Comp. Exerc. Physiol. 3, 179–184, with permission from Cambridge University Press.

competed up to high levels, while the novice riders have less riding experience. However, the experience and ability of the novice riders likely varies between studies. A general conclusion is that professional riders are more stable than novice riders.

The influence of the rider's weight

Learning how to ride involves developing the ability to follow the movements of the horse and to influence the horse's movements. Since the rider's weight has a marked influence on the horse's movements, the effects of the rider's weight will be discussed first.

Load carrying at walk

When the horse carries a rider, the vertical and longitudinal ground reaction force peaks and impulses increase and the peaks occur significantly later during stance in the forelimb (Schamhardt et al., 1991). In the hind limb all force peaks increase except peak braking force.

Stride duration is not influenced by the presence of a rider at trot, but relative stance duration tends to increase in both fore and hind limbs (Schamhardt et al., 1991). Fetlock joint maximal extension in both fore and hind limbs increases with a rider (Sloet van Oldruitenborgh-Oosterbaan et al., 1995). Furthermore, the horse's head is carried in a higher position with a rider, so the neck is also more extended (Sloet van Oldruitenborgh-Oosterbaan et al., 1996).

Load carrying at trot

When a rider is mounted, peak vertical force and impulse increase in both fore and hind limbs (Schamhardt et al., 1991; Clayton et al., 1999). However, the relative increase is 50 to 100% higher in the forelimbs compared with the hind limbs (Schamhardt et al., 1991; Clayton et al., 1999). Overall, the relative weight bearing on the forelimbs increases by approximately 1–2% (Weishaupt et al., 2006; Waldern et al., 2009). The time of maximal vertical force, peak propulsion and the vertical force curve show a shift to the right in the second half of stance such that the vertical force remains close to maximum for an extended length of time before it starts to decline (Schamhardt et al., 1991; Clayton et al., 1999). Stride duration is not influenced by the presence of a rider at trot, but relative stance duration tends to increase (Schamhardt et al., 1991; Sloet van Oldruitenborgh-Oosterbaan et al., 1995). In the forelimb, the fetlock joint is more extended in the second half of stance compared to the unloaded condition, with the fetlock angle–time curve reflecting the shape of the vertical ground reaction force curve (Sloet van Oldruitenborgh-Oosterbaan et al., 1995; Clayton et al., 1999).

Rider weight

Peham and Schobesberger (2004) performed a biomechanical simulation using a combination of electromyographical data from *m. longissimus dorsi*, saddle mat data and kinematic data from two back markers of 15 horses ridden overground in trot with their customary riders and saddles. They concluded that the forces were higher when the back was stiffer, compared to the simple rider weight. It is of course natural that heavier riders in general yield higher forces and pressures (Geutjens et al., 2008). The effects of rider weight should be studied in the dynamic situation to gain a better understanding of what constitutes unacceptably high pressures from heavyweight riders.

Riding methodology

Numerous texts on riding and equestrianism have been written during the past 500 years but the terminology is often poorly and inconsistently defined from both a scientific and practical perspective and terms are sometimes circularly referenced (Roepstorff, unpublished). Even though riding will always have an artistic element, especially in dressage, there are also parts of the performance that should be quantifiable. Measurements of equestrian technique require definitions that relate equestrian terminology with measured biomechanical variables.

The training scale, as described in the *Official Instruction Handbook of the German National Equestrian Federation* (German National Equestrian Federation, 2002) consists of a series of steps, which are translated as rhythm, suppleness/relaxation, contact, impulsion, straightness and collection. These terms will be used as a basis for discussion of biomechanical research.

Rhythm

Rhythm, the first requirement in the training scale, is described biomechanically by temporal variables. The stride rate is the number of strides per stride interval, also denoted beat, which should not be confused with rhythm. The rhythm of the footfalls within each stride is described by the time intervals between first-contacts of the individual limbs, such as time of advanced placements and step durations. The same rhythm should be maintained through the variations in gait types (collected, working, medium, extended, free).

The rhythm of the different gaits is described in Chapter 14. The walk should have a regular four-beat rhythm. More irregularities were found in the medium and the extended walk, compared to the collected walk (Clayton, 1995), which is in accordance with general dressage rider perceptions. At trot the regular, two-beat rhythm was maintained from collected through working, medium and extended trot though stride duration was significantly shorter in the extended trot compared with collected trot (Clayton, 1994b). In canter stride duration did not differ significantly between collected, working, medium and extended canters but the timing between footfalls changed such that in extended canter the three beats were more closely associated while the time elapsing between contact of the leading forelimb and the next contact of the trailing hind limb increased (Clayton, 1994a).

Elite dressage horses show more irregularities in walk pirouette strides than in canter pirouette strides (Burns & Clayton, 1997; Hodson et al., 1999). Another aspect of rhythm is that the expert rider's movements have been found to be more consistent and less phase-shifted in relation to the horse compared to novice riders (Terada, 2000; Peham et al., 2001; Lagarde et al., 2005). These findings may explain the greater smoothness in the horse's gaits when ridden by expert riders, often in a more collected form.

Suppleness/relaxation

Suppleness and relaxation are prerequisites for all further training and, along with rhythm, are an essential aim of the preliminary training phase. The horse should be free from physical and mental tension with 'a rhythmically swinging back' (German National Equestrian Federation, 2002). Even if the rhythm is maintained, the movement cannot be considered correct unless the muscles are free from unnecessary tension.

Suppleness is difficult to measure objectively with biomechanical methods. An approach might be to use electromyography (EMG) in relation to kinetic and/or kinematic studies. Biologically, muscles must generate tension to support the body and to produce locomotion. In addition, a certain amount of contraction of antagonistic muscles is needed to stabilize the joints. Thus, it is difficult to evaluate EMG results in relation to 'necessary' and 'unnecessary' muscular activity, because there are no common and widely accepted definitions of which muscles should be active at specific periods of the stride cycle in different gaits.

Robert et al. (1998) have published several EMG studies of horses. Three horses were ridden in walk, trot and canter and activity of the *m. longissimus dorsi* was recorded in relation to the stage of the stride cycle determined by accelerometers. The *longissimus dorsi* muscle showed two bursts of activity during each stride at walk and trot but only one burst during each stride at canter. Muscles on the right and left sides acted simultaneously. There was considerable variation with speed and between-horse variation was also substantial (Robert et al., 1998). In the unridden horse, activity of the *longissimus dorsi* muscle increased both with speed and uphill slope when trotting on a treadmill (n = 4). At faster speed, muscle activity began and ended earlier in the stride cycle, while the opposite was seen with increasing slope (Robert et al., 2001).

In a study of a larger number of muscles, the basic pattern of trunk muscle activation at trot showed two bursts of EMG activity per stride. Activity of m. *splenius* started just before contact of each forelimb and ended in the middle of the corresponding stance phase. M. *longissimus dorsi* contracted bilaterally before each hind limb lifted off. M. *rectus abdominis* was consistently active as each hind foot contacted the ground (Robert et al., 2002). Similar to previous results, increasing speed yielded earlier EMG activity and increasing treadmill slope postponed it.

In a later study, reflective markers were placed bilaterally on the facial crests and the lateral aspects of C1 and C3 in six horses, to calculate the head and neck angles (Zsoldos et al., 2010a). Activity of *m. splenius* was measured with surface EMG. In trot, functional stabilization against flexion of the head and neck was found with maximal activity of this muscle at the beginning of the forelimb stance phases. Unilateral activity of m. *splenius* to stabilize against lateral movement was not found.

Surface EMG activities of the *m. rectus abdominis* and the external abdominal oblique muscles and kinematics of the hooves, withers and sacrum were measured at walk and trot in six horses (Zsoldos et al., 2010b). EMG values (minimum, maximum and mean) were significantly higher at trot than at walk in all horses for the external abdominal oblique muscle and in five out of six horses for *m. rectus abdominis*. The activities of both muscles differed between left and right sides for all horses in walk and for four out of six horses at trot. The ratio of muscle coactivation between the external abdominal oblique muscles and *m. rectus abdominis*, which was interpreted as providing trunk stability, was lower at walk than trot. The external abdominal oblique muscles were more clearly activated in an alternating left and right sequence while *m. rectus abdominis* was activated more simultaneously on the left and right sides. In both walk and trot, the activity of *m. rectus abdominis* is out of phase with that of *m. longissimus dorsi* (Licka et al., 2004; Licka et al., 2009).

Using surface electrodes the quotient of the mean of the maximal and minimal surface EMG activity of *m. longissimus dorsi* in unridden horses (n = 15) at walk was judged to be higher at the twelfth thoracic vertebra (T12) than at the sixteenth thoracic vertebra (T16) or the third lumbar vertebra (L3) (Licka et al., 2009), with some tension being maintained at the minima. Activity was maximal during the ipsilateral hind limb support; this occurred at the beginning of the support phase for L3, followed by T12 and then T16. At these instances low activity was found in the contralateral muscle. The authors' interpretation was that the large activity at T12 compared to T16 and L3 suggested that *m. longissimus dorsi* is mainly responsible for stabilising the back during locomotion, which agrees with other authors (Robert et al., 2001; Robert et al., 2002; Groesel et al., 2010). In another study it was shown that the function of *m. longissimus dorsi* may vary at different spinal levels; unilateral activity predominates in the more cranial segments at the level of the fourteenth thoracic vertebra (T14) during walking, which was interpreted as indicating that the muscle developed lateral bending moments, whereas there were more cocontractions in the caudal segments (Wakeling et al., 2007).

During lateral bending, EMG activity in *m. longissimus dorsi* at T12, T16 and L3 was present only on the concave side of the back. When the back position of standing horses was manually induced to extend or bend laterally, EMG amplitudes in *m. longissimus dorsi* were highest at T16. During extension there was a temporal correlation at the three locations, but less so during lateral bending (Peham et al., 2001; Wakeling et al., 2007).

Contact

Contact is defined as a soft, steady, connection between the hand of the rider and the mouth of the horse. The horse should go forward rhythmically according to the driving aids of the rider and seek a contact with the hand of the rider, thus going into the contact (German National Equestrian Federation, 2002).

There are no studies directly aiming at defining or validating what contact is. It has been documented that in some rider–horse combinations the contact varies between the left and right sides with one hand consistently having a larger proportion of low contacts (Roepstorff, unpublished).

Studies of rein tension have shown that the rhythmic head and neck movements of the horse produce a pattern of regular spikes in rein tension when the horses are ridden by experienced riders

(Clayton et al., 2005) or when side reins are used (Clayton et al., 2011) but not when ridden by novice riders (Heleski et al., 2009). It has been interpreted that the baseline tension comes from the rider or side rein and the spikes are from the head motion of the horse. A prerequisite to establishing a correct contact is that the rider can stabilize the hand position thus encouraging the horse to seek a contact through controlled relaxation of the cervical musculature. Within this baseline contact, inertially driven movements of the head and neck result in the rein tension spikes (Clayton, unpublished).

Impulsion

The horse is considered to have impulsion, when the energy created by the hind limbs is transmitted into the gait and into every aspect of the forward movement (German National Equestrian Federation, 2002). This is another area that has not been specifically addressed with biomechanical methodology. Accelerometers have been used to study forward motion of the body parts in relation to fore and hind quarter impulsion during the use of different types of auxiliary reins (Biau et al., 2002) (see previous section).

Straightness

A horse is considered straight when the hind quarters follow the same track as the forehand and the longitudinal axis of the body is aligned with the straight or curved track that the horse moves along. The weight should be evenly distributed between the left and right sides of the body (German National Equestrian Federation, 2002). However, every horse and rider can be assumed to be born with some kind of sidedness. Sidedness has been studied quite extensively in humans but to a much lesser extent in horses. The interesting question is how to straighten the horse and correct asymmetrical locomotor patterns associated with sidedness. A further important consideration is that asymmetry in the movement pattern is the basic concept of the lameness work up. From the diagnostic point of view there is a gray area between normal physiological responses (e.g. sidedness inherent in the horse or induced by the rider's sidedness), and asymmetry in response to painful processes (lameness). Asymmetry directly related to rider influence has been reported in several papers and has been elucidated in the section on rider skills.

Alignment of the forehand with the hind quarters has not been scientifically addressed. A number of kinematic studies have reported on different aspects of asymmetry. In the following we discuss the most relevant from a horse–rider interaction perspective. Studies targeting lameness are addressed in Chapter 9.

Asymmetry basics

In trot ridden overground, Clayton determined that three of six highly trained dressage horses in collected, working, medium and extended trot were asymmetrical (Clayton, 1994). This included a longer suspension phase (on the right one horse), longer diagonal distance (on the right one horse), and longer diagonal advanced completion times (right and left, one horse each). The fact that riders often perceive one side as easier for a canter transition, or that most horses have a preferred canter lead when unridden (unpublished observations) points to the presence of asymmetries between the two leads at canter, though the effect of the rider on this has not yet been evaluated. In a study of the kinematics of high level dressage horses and expert riders on a treadmill, some movements of the riders and saddles were more asymmetric than expected. The study design could not distinguish between asymmetries caused by laterality of the horse or rider (Byström et al., 2009).

The asymmetry during riding with various head and neck positions (see below) was larger when the rider tried to affect the horse more. For example, when trotting on a loose rein was compared with riding the horse in a vertical head and neck position (HNP2 see definition in Fig. 15.19) there was an increase in asymmetry in a number of kinematic parameters, such as the lumbar spine and sacral angle (Rhodin et al., 2009). The roll rotation of the rider's upper body was markedly asymmetrical between diagonals for some rider–horse combinations, which is likely to be an indication of rider-laterality (Byström et al., 2009). A study of 17 dressage riders with varying levels of experience showed that all had a shorter right limb, moved their left shoulders more than the right, and that they were differently asymmetric between right and left canter with the most inharmonious pattern in the right canter (Symes & Ellis, 2009).

Asymmetry in rising trot

At rising trot the load on the horse's back is lower on the rising diagonal than on the sitting diagonal and, furthermore, both of these loads are lower than when the rider sits the trot (de Cocq et al., 2010a). The same effect is seen in the ground reaction forces (Schamhardt et al., 1991). Parameters for rising trot, mainly vertical peak force and impulse, were higher for the diagonal on which the riders were sitting. Similarly for riders performing rising trot on a treadmill force loading was generally increased in the limbs of the sitting diagonal (Roepstorff et al., 2009). The following asymmetries were found: the lumbar spine was lower between midstances of the sitting and rising stance phases; pelvic roll was limited and heights of the tubera coxarum were lower on the sitting side (Fig. 15.17); maximal hind limb protraction was decreased and forelimb retraction was increased; and T6 height decreased. The conclusion was that the rising and sitting motion of the rider induced an uneven biphasic load that affected the horse's back, pelvis and limb kinematics and the vertical ground reaction force. It should be noted that phase-shifting in the rising trot differed between the left and right diagonals, which provides further evidence that inherent or rider-induced asymmetry was present in these top-level dressage horses.

Both genetic and environmental factors have been implicated in equine inter-stride asymmetry (motor laterality, sidedness) (Murphy & Arkins, 2008). There are likely two aspects of laterality, one defined by ethologists (Murphy & Arkins, 2008) and another, possibly a different phenomenon, studied by biomechanists. From the rider's perspective, the biomechanical asymmetry is commonly described as the neck muscles being more contracted on the 'stiff' side, compared to the other 'hollow' side. The 'hollow' side has the haunches positioned ipsilaterally relative to the forehand (German National Equestrian Federation, 2002). Any intra-stride asymmetry might encompass motor laterality and/or training-induced asymmetry.

In a study of seven horses, all were asymmetric to the same side (Roepstorff et al., 2009). Regardless of whether the riders were rising on the left or right diagonal, the left fore/right hind diagonal was relatively more loaded than the opposite diagonal. The more loaded left fore and right hind limbs were likely placed further under the horse. The forward placement of the right hind limb might indicate unloading of the left hind limb (German National Equestrian Federation, 2002). This is generally accepted as the horse being stiff to the left, which is perceived as the more common side (German National Equestrian Federation, 2002).

In conclusion, straightness and related expected symmetry in locomotion and force patterns are extremely important to study further and in more depth. This is definitely an important key to successful performance and in keeping the horse sound. However, these two concepts are also heavily interrelated by the fact that it is hard to compete or perform with an unsound horse. In mounted studies it is important to realize and take into account the fact that the rider's asymmetry affects the laterality of the horse.

It may be asked whether there is correlation between forces exerted on horseback and kinematic evaluation of rising trot

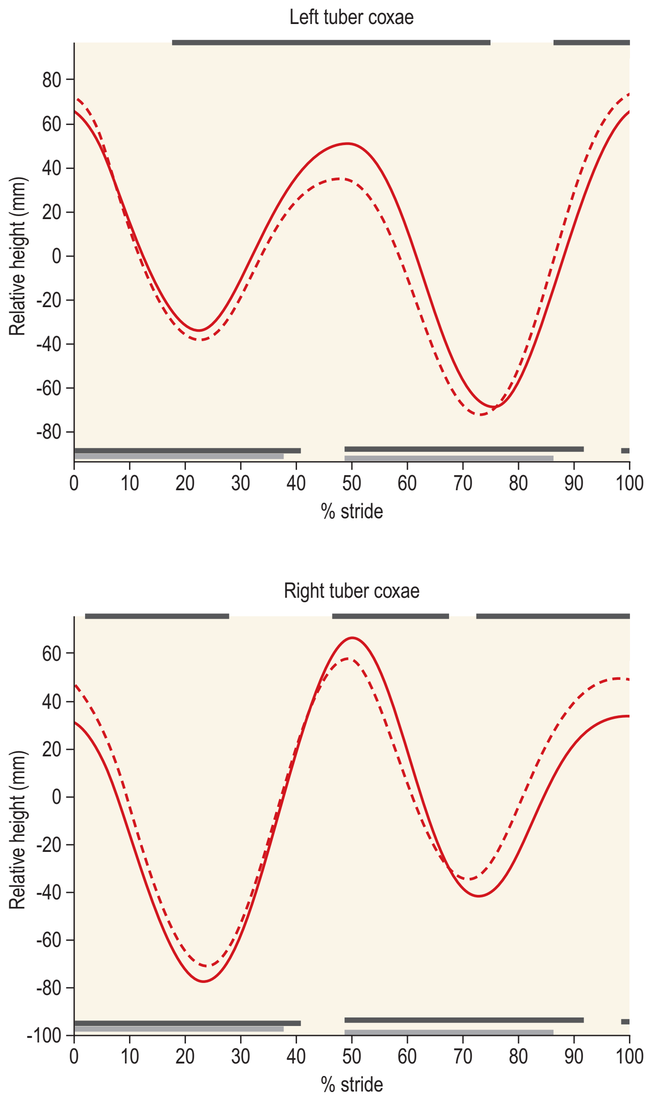

Fig 15.17 Stride-cycle parameters for kinematic variables in left (solid line) and right (dashed line) rising trot (in left rising trot the rider sits when the left fore and right hind limb are grounded). The upper bar shows when at least five consecutive points were statistically significant at $p < 0.05$. The lower bars show the stance of the left fore, right fore, left hind and right hind (top to bottom).

Reprinted from Roepstorff, L., Egenvall, A., Rhodin, M., Byström, A., Johnston, C., van Weeren, P.R., Weishaupt, M.A., 2009. Kinetics and kinematics of the horse comparing left and right rising trot. Equine Vet. J. 41 (Suppl.), 292–296, with permission of the Equine Veterinary Journal..

compared to sitting trot. A treadmill study using 10 horses ridden by one experienced rider with correctly fitted saddles, found that the range of overall saddle mat force was lower in rising trot compared to sitting trot (Peham et al., 2009). This means that the force at rising trot varies less than at sitting trot, i.e. the rising trot evens out the forces acting between the saddle and the horse's back that are caused by the vertical oscillation of the horse back. This was confirmed by de Cocq et al. (2010a) who used rider kinematics to model saddle reaction forces in sitting and rising trot. The results showed that mean force was always equal to rider weight but peak forces, which occurred in diagonal midstance, were symmetrical in sitting trot but differed between the two diagonals in rising trot with significantly higher values on the sitting diagonal than the rising diagonal. Another study with 12 horses ridden overground by one intermediate rider found an increased range of flexion–extension in the back in rising trot compared to sitting trot (de Cocq et al., 2009). Taken together, there does not seem to be a correlation between increased range of forces and increased range of motion in back flexion–extension. Whether it is good for the horse to have an increased range of motion of the back remains to be seen.

Collection

General

The aim of all gymnastic training is to create a horse that is athletic and ready and willing to perform. For the horse to meet these criteria, its weight, plus that of its rider, must be distributed as evenly as possible over all four limbs. This means reducing the weight on the forelimbs (which naturally carry more of the load than the hind limbs), and increasing the weight on the hind limbs, which were originally intended mainly for creating the forward movement. Equestrian texts indicate that in collection the hind limbs (the hock and stifle joints) flex more, stepping further underneath the horse in the direction of the center of gravity, thereby taking a greater share of the load. This in turn lightens the forehand, allowing the forelimbs to move more freely. The horse looks more 'uphill'. The strides become shorter, but without losing the energy or activity. The impulsion is maintained in full at the trot and canter, and as a result the strides become more expressive and 'stately' (German National Equestrian Federation, 2002).

The role of the forelimbs is to support rather than to push and they can only be strengthened to a very limited degree by training. It is therefore more sensible, and indeed necessary, to transfer some of the weight to the hind quarters. The increased flexion of the hind limbs results in raising of the neck. When the carrying capacity of the hind quarters is sufficiently developed, the horse is able to move in balance and self-carriage in all three gaits (German National Equestrian Federation, 2002).

Collection can be defined by several terms, which can be studied biomechanically. These definitions will be described, relevant findings from research so far elucidated and suggestions provided for what can be done to further study the subject of collection.

As already stated many of the terms are poorly defined. For example, 'increased weight bearing by the hind limbs' can be determined using appropriate force measuring methodology, while 'lowering of the back' is a more subtle poorly defined concept, therefore also more difficult to set up a measuring strategy accepted by riders, trainers or peers.

It is important to remember that collected gaits are performed at slower speeds than the same gaits with less collection. Another confounding issue relates to differences in the kinematic patterns between overground and treadmill locomotion.

In this section the concepts and the scientific background will be described for kinematic variables that are frequently used to describe collection by riders and trainers; forward stepping of the hind limbs relative to the hind quarters (hind limb protraction–retraction and overreach distance), lowering of the hind quarters and increased joint flexions, diagonal displacement and relative weight bearing. First, the biomechanical effect of using various head and neck positions (HNP) will be described. A correct HNP is thought by many to be a prerequisite for collection. Accordingly, large efforts are put into attaining a desired HNP during riding. Both novice and experienced riders frequently fixate on HNP, perhaps as a consequence of the visual ease of determining the HNP, which is also relatively straightforward for judges to assess. In the following description, HNPs in relation to the frame of the horse will be discussed using terms defined by the German National Equestrian Federation (2002).

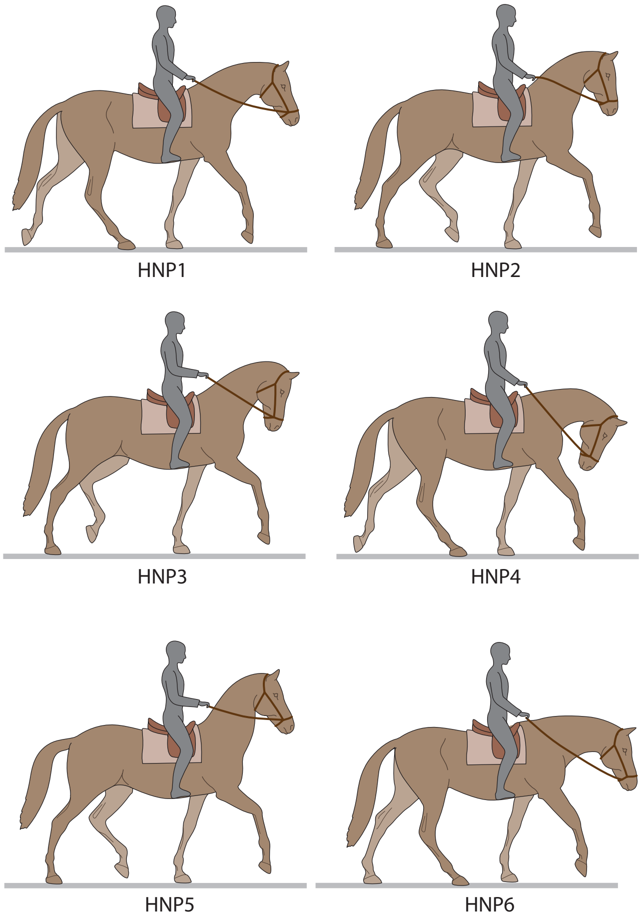

Fig 15.18 The head and neck positions used in the Zurich study. See text for description of positions.

Reprinted from Rhodin, M. et al., 2009. The effect of different head and neck positions on the caudal back and hindlimb kinematics in the elite dressage horse at trot. Equine Vet. J. 41 (3), 274–279, with permission from the Equine Veterinary Journal.

Head and neck positions

In 2005 an experiment was conducted with seven advanced-level horses ridden by their own riders on a treadmill (Gomez Alvarez et al., 2006; Weishaupt et al., 2006; Rhodin, 2008; Rhodin et al., 2009). Vertical ground reaction forces were measured by the instrumented treadmill and kinematic analysis was performed with a high-speed video system tracking 80 markers distributed over anatomical landmarks on the horse, rider and saddle. Forces between the saddle and the horse's back were measured with a pressure sensitive saddle mat and, in three horses, rein forces were measured.

The horses were ridden at walk and trot with six different HNPs (Fig. 15.18). A correct HNP was assumed to be one result, or a prerequisite of, collection. The vertical 'competition' HNP was used for comparison and therefore a series of recordings at a range of speeds were made in this position to enable speed-matched comparisons with the other positions. All of these trials were also performed without the rider achieving the head neck positions with different kinds of auxiliary reins. Finally also passage trials were performed. All in all approximately 240 trials were recorded during a 2-week period:

- HNP1: Free or natural; voluntarily acquired position, unrestrained with loose reins (free).
- HNP2: Neck raised, poll high and bridge of the nose slightly in front of the vertical; reference position (competition, the Ramener).
- HNP3: Neck raised, poll high and bridge of the nose slightly behind the vertical (behind).
- HNP4: Neck lowered and flexed, bridge of the nose considerably behind the vertical (low: to imitate Rollkür, neck low).
- HNP5: Neck extremely elevated and bridge of the nose considerably in front of the vertical (above; absolute elevation).
- HNP6: Neck and head extended forward and downward (low and open; ridden, only performed at walk, not shown in Fig. 15.19).

Walk

Kinetic evaluation in the different HNPs at walk showed that, in general, being 'above' the bit or 'behind' the vertical differed from the vertical position in the same direction, while having the neck 'free' or 'low and open' differed in the opposite direction (Weishaupt et al., 2006) (Table 15.2).

Comparing the 'competition' HNP with the other HNPs several kinematic parameters were found to be different. The sixth thoracic vertebra (T6) height was affected during three-limb support by one forelimb and two hind limbs, except for in the low and open HNP when it was increased throughout the stride. In the free and above positions there was a tendency for L5 to be higher during three-limb support by one forelimb and two hind limbs. In the behind and low and open HNPs the height of L5 increased during the second half of hind limb stance. The lumbar back angle (the 'small' angle between a horizontal plane and a line through L5 to L3) increased in the 'behind', 'neck low' and 'above' positions and decreased in the free position with the peak value coinciding with three-limb support with one hind and two forelimbs.

In the free and above positions, pelvis pitch increased (tilted forward in the free position) and decreased (tilted backward in the above position) respectively, from forelimb three-limb support to hind limb three-limb support. In the behind position a decrease in pelvic pitch was found throughout the stride and in the low and open pelvic position pitch decreased at three-limb support with one forelimb.

In the free and above HNPs the femur angle was increased in the later part of stance in the free position and decreased in early swing in the above position, relative to the competition HNP. In the 'behind' HNP it was smaller at the end of stance.

In the free position the stifle joint was more flexed during the later part of stance. In the behind position the stifle was more flexed during diagonal stance and following three-limb support with two hind limbs. With a low neck it was more flexed during midswing. In the above position the stifle joint was more flexed during diagonal support, less flexed during ipsilateral support and more flexed during the first half of swing, indicating a greater ROM (Rhodin, 2008). Figure 15.19 compares the hind limb position for the 'competition' position to the free and above positions. Generally, ROM increased in the low positions implying that these are good for gymnastic effects on the horse, i.e. increasing suppleness.

Trot

The horses shifted weight to the forequarters in the low position and a number of kinetic parameters were affected in the 'above' position (Table 15.3) (Weishaupt et al., 2006). Kinematically, in the 'free' position sacral flexion (pelvic pitch) decreased during suspension and early stance and in the 'above' position the sacrum was significantly more angled during breakover and suspension (Table 15.4). In the free position the femur angle was larger during breakover and early swing whereas in the above position it was smaller in early and late swing. In the free position the stifle flexed more slowly in early swing and in the above position the stifle showed increased flexion during stance and the first two-thirds of swing (Rhodin et al., 2009).

Table 15.2 **The directions of the statistically significant differences found for kinetic parameters comparing the competition position to various head and neck positions in ridden walk. One arrow, percentage changes <5%; two arrows, percentage changes >5%**

Parameters	**Head and neck position**				
	Free	**Behind**	**Neck, low**	**Above**	**Low, open**
Stride duration	↑	↓		↓↓	
Stride impulse	↑	↓		↓↓	
Stride length	↑	↓		↓↓	
First forelimb force peak				↑↑	↓
Second forelimb force peak	↑				↑
First hind limb force peak			↑↑		↑
Second hind limb force peak	↓				↓
Percentage of stride impulse carried by the forehand	↑			↓	↑
Forelimb duty factor				↓	↑
Hind limb duty factor	↓	↑		↑	↓
Ipsilateral step duration relative to stride duration				↑↑	
Diagonal step duration relative to stride duration				↓↓	
Overreach distance	↑↑	↓↓		↓↓	

Adapted and reprinted from Weishaupt, M.A., Wiestner, T., von Peinen, K., et al., 2006. Effect of head and neck position on vertical ground reaction forces and interlimb coordination in the dressage horse ridden at walk and trot on a treadmill. Equine Vet. J. 36 (Suppl.), 387–392, with permission from the Equine Veterinary Journal.

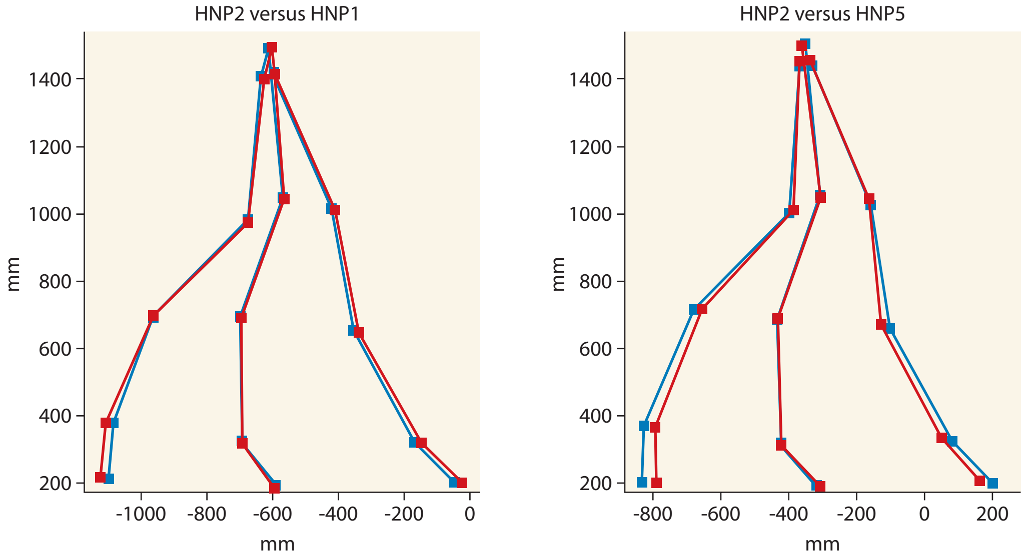

Fig 15.19 Stick figures illustrating the hind limb position during walking at first contact, midstance and toe-off for HNP2 (competition position) (blue line), HNP1 (free position) (red line on left) and HNP5 (above position) (red line on right). Markers from proximal to distal; greater trochanter of the hip joint, stifle joint, hock joint, fetlock joint and hind hoof.

Reprinted from Rhodin, M., 2008. A biomechanical analysis of relationship between the head and neck position, vertebral column and limbs in the horse at walk and trot. Dissertation, Uppsala., with kind permission of Marie Rhodin.

Data from the same horses were studied without a rider in walk and trot to study back kinematics that are impossible to interpret fully with a rider. The comparison base was the free HNP. In the 'competition', behind and above HNPs, the back was more extended in the anterior thoracic region and the ROM in flexion–extension was reduced in the lumbar region (Gomez Alvarez et al., 2006). For the low neck HNP the pattern was opposite. In the above HNP the intravertebral pattern symmetry was negatively affected and hind limb protraction was reduced.

In this study the highest neck position had the largest weight shift to the hind quarters (Weishaupt et al., 2006). This might be interpreted as collection (being one definition of collection). However, the front limb locomotor pattern changed with stance being shortened to such an extent that, even though weight was shifted to the hind quarters, the maximal peak force in the forelimb was increased. The forelimb stride simply became very short and sharp, which is not desired from an equestrian perspective.

Table 15.3 **The directions of the statistically significant differences found for kinetic parameters comparing the competition position to various head and neck positions in ridden trot as well as passage (using the competition position). One arrow, percentage changes <5%; two arrows, percentage changes >5%**

Parameters	Head and neck position				
	Free	Behind	Neck, low	Above	Passage
Stride duration			↑	↑	↑↑
Stride impulse			↑	↑	↑↑
Stride length			↑		↓↓
Forelimb force peak	↓			↑↑	
Hind limb force peak				↑	
Proportion of impulse carried by forehand				↓	↓
Suspension duration relative to stride duration	↓↓			↑↑	
Forelimb duty factor	↑			↓↓	
Hind limb duty factor				↓	
Diagonal dissociation[1]				↑↑[2]	↑↑[2]
Diagonal advanced completion relative to stride duration	↑↑	↓↓		↓↓	↑↑
Over-track distance			↓↓[3]		n.a.[4]

[1] Also called 'diagonal advanced placement'.

[2] Mean value positive.

[3] Negative, but less negative compared to competition position.

[4] Not applicable.

Adapted and reprinted from Weishaupt, M.A., Wiestner, T., von Peinen, K., et al., 2006. Effect of head and neck position on vertical ground reaction forces and interlimb coordination in the dressage horse ridden at walk and trot on a treadmill. Equine Vet. J. 36 (Suppl.), 387–392 and Weishaupt, M.A., Byström, A., von Peinen, K., et al., 2009. Kinetics and kinematics of the passage. Equine Vet. J. 41, 263–267, with permission from the Equine Veterinary Journal.

The collected body orientation achieved in this way at the passage redistributed the diagonal vertical impulse to the hindquarters. The shift amounted to approximately 3-fold of that which was observed in the same horses trotting in an extremely high elevated head-neck position (Weishaupt et al., 2006). However, because of the longer absolute stance durations, the higher limb impulses at the passage did not result in higher peak forces, in either the fore- or hind limbs. In this respect the passage seems to be less of a strain for the distal limbs compared to horses moving with the head-neck in a high elevated position in which, despite the redistribution of the vertical impulse to the rear, peak vertical forces were increased in the forelimbs due to shortened stance durations (Weishaupt et al., 2006).

This observation leads us to the conclusion that correct collection of the horse's movement is characterized by relative elevation in the forehand matched to the degree of 'Hankenbeugung' which includes increased flexion at the lumbosacral junction and of the proximal limb joints (hip, stifle, hock) during weight-bearing. Whereas an absolute elevation of the head and neck with the back held in extension (Rhodin et al., 2009) and with shortened over-track distance and consequently insufficient engagement of the hind legs forward under the body (Waldern et al., 2009; Weishaupt et al., 2006) results in an overload situation with increased peak vertical forces (Weishaupt et al., 2006).

In conclusion, as anticipated by riders the HNPs were shown to have effects on the horses. Among dressage riders one of these positions, the competition position, could be considered as an ideal, i.e. as a way to collection. However, most riders consciously vary the neck and head positions and thereby increase the range of motion of several body parts, to exert a gymnastic effect on the horse, for example during warm-up, compared to the work considered more demanding. Classically, it is said that the horse must not drop the bit and work behind the vertical. Approximating the behind position to such a state, rather few changes were found compared to the competition position and only in walk. Interestingly taking the head 'back (behind)' or 'down' (rollkur) had almost the same main effects, i.e. the measurements of back height increased and pelvic pitch and yaw decreased. The above the bit position had the largest effects on the horses and from the perspective of collection, the horse actually shifted the vertical stride impulse to the hind quarters in both walk and trot. However, force peaks increased in the forelimbs in walk and in both fore and hind limbs in trot. Such force peaks may be detrimental to, for example, riding school horses, which often trot with their heads in a high position. In walk, the total forces are lower than at trot and likely to be less harmful. Rather few riders voluntarily strive for 'above' HNP, with the exception of piaffe, where pictures of old masters are often shown with the nose in front of the vertical (Karl, 2008). A few elite horses took part in the highly controlled treadmill experiment and whether the results can be generalized extensively to more horses of various levels ridden overground remains to be studied.

In another study of seven horses lunged in various HNPs it was found that the below position (in this text translated to rollkur) had the highest rise in serum lactate dehydrogenase and most increases in variables measuring neuromuscular functionality, which was measured by single muscle fibre potentials and motor unit action potentials (Wijnberg et al., 2010). Artificial positions in general affected neuromuscular functionality more than the free position. Further, the interaction between the rider and the horse when placing the head of the horse needs elucidation also from the perspective of how much self-carriage the horse is in (whether leaning on the reins) to non-biomechanical aspects, including horse

Table 15.4 **The directions of the statistically significant differences found for kinematic parameters comparing the competition position to various head and neck positions in ridden trot as well as passage (with the competition position)**

Parameters	Head and neck position				
	Free	Behind	Neck, low	Above	Passage
Maximum T6 height	↓			↑	↑
Minimum T6 height				↓	
Stride ROM for T6 height	↓			↑	↑
Maximum L5 height					↑
Minimum L5 height			↓	↓	
Stride ROM for L5 height				↑	↑
Lumbar back angle at midstance (horizontal L5 to L3)	↓			↑	n.a.[3]
Sacral flexion	↓			↑	↑[4]
Femur angle (see text)	↑			↓	n.a.
Stifle joint angle (see text)	↑			↓	↓
Stride retraction forelimb[1]	↑	↓		↓	↓
Stride protraction forelimb				↓	↑
Stance retraction forelimb				↓	n.a.
Stance protraction forelimb	↓			↓	n.a.
Stride retraction hind limb[2]	↑				↓
Stride protraction hind limb		↓			

[1] Forelimb retraction/protraction measured as the horizontal angle through the elbow joint, to the fore hoof, except for in passage when it is evaluated from T6.

[2] Hind limb retraction/protraction measured as the horizontal angle through L5, to the hind hoof.

[3] Not applicable.

[4] Increased flexion of the lumbosacral junction throughout the stride.

Adapted and reprinted from Rhodin, M., Gomez Álvarez, C.B., Byström, A., et al., 2009. The effect of different head and neck positions on the caudal back and hindlimb kinematics in the elite dressage horse at trot. Equine Vet. J. 41, 274–279 and Weishaupt, M.A., Byström, A., von Peinen, K., et al., 2009. Kinetics and kinematics of the passage. Equine Vet. J. 41, 263–267, with permission from the Equine Veterinary Journal.

behavior (in which studies have been done), human perception and horse longevity.

Forward stepping of the hind limbs relative to the hind quarters

High-level dressage horses ridden overground do not step further under themselves as collection increases at trot, or even in passage and piaffe (Holmström et al., 1995). However, it can be argued that an increased level of collection simply implies a lower speed which means shorter strides and that this speed effect obscures a relative and perceived forward stepping of the hind limbs. Since it is difficult to study collection independent of speed, alternative solutions that correct for the speed effect may be necessary. The following sections compare different studies specifically related to hind-limb protraction–retraction or over-track distance.

Hind limb protraction–retraction?

The hind limb protraction–retraction angle is usually measured as the angle between a line connecting the hoof to L5 and the horizontal plane in front of the limb. In horses walking overground fore- and hind-limb retraction decreased in the competition HNP compared to the free HNP (Rhodin et al., 2009). In trot on a treadmill, hind-limb retraction decreased after toe-off in the competition HNP compared with the free HNP (Rhodin et al., 2009) and was further reduced in passage (Weishaupt et al., 2009). Additionally, when trotting unridden on a treadmill, hind limb protraction was reduced in the above HNP (Gomez Alvarez et al., 2006).

Over-track distance

Over-track distance (also defined as over-reach) is a well-defined biomechanical concept, i.e. the distance that a hind limb steps in front of the ipsilateral forelimb. It varies with speed of the gaits within an individual and is affected by conformation.

A related but slightly different variable is the position of the fore and hind limbs compared to each other during late swing phase, which can be measured by determining the minimum distance between the contralateral fore/hind limbs in late swing.

The mean over-track distance in overground walk decreased with collection and was negative (mean, −7 cm) in collected walk, 19 cm at medium walk and 27 cm at extended walk (Clayton, 1995). In walk on a treadmill the over-tracking distance relative to stride length was significantly larger by 34% in the free HNPs, compared to the competition HNP (Weishaupt et al., 2006).

The mean over-track distance in overground trot decreased with collection and was negative (mean -7 cm) in collected trot (Clayton, 1994b), 4 cm in working trot and 39 cm in extended trot. In trot on a treadmill the over-tracking mean distances both for free and collected trot were negative (i.e. within a stride the hind hooves did not reach the imprints of the ipsilateral fore hooves (Weishaupt et al., 2006). The difference in results has been attributed to differences between overground and treadmill locomotion.

Lowering of the hind quarters, and increased hind joint angulation

A common term is that the horse lowers its haunches. The anatomical manifestations of this term could theoretically translate to several biomechanically measurable features, including increased flexion of the lumbar spine, increased inclination of the pelvis (pitch), and increased angulations of the hind-limb joints.

At walk and trot, the metacarpus and metatarsus had a more vertical orientation both at contact and at lift-off in the more collected gaits. In other words, the limb rotated through a smaller angle during stance with less forward progression of the body mass in the more collected gaits. However, metacarpal/metatarsal angulations were generally more acute in the hind limbs than the forelimbs as a consequence of conformational differences (Clayton, 1994b, 1995). In walk when comparing the competition HNP to the free HNP, pelvic pitch decreased in the competition HNP, the height of L5 during three-limb support with two hind limbs increased, the lumbar back angle increased, T6 height during three-limb support with two forelimbs decreased, and the femoral angle in late stance and early swing decreased (Rhodin, 2008). The stifle joint was less flexed during late stance. When trotting on a treadmill sacral flexion (pelvic pitch) was increased in the competition HNP compared with the free HNP (Rhodin et al., 2009).

Piaffe has more pelvic inclination during the entire stride cycle compared to collected trot and passage (Holmström et al., 1995). Furthermore, the stifle and hock joints were more flexed at the start of stance and the hock joint was also more flexed in midstance in passage and piaffe compared to collected trot (Holmström et al., 1995). When comparing the passage with the collected trot, the horses moved at a slower forward velocity (−43.2%) and with a lower stride frequency (cadence; −23.6%), with a more elevated HNP and an overall pronounced upwards excursion of the trunk during the suspension phase. The strides were more elevated resulting from reduced limb pro- and retraction and increased limb flexion at the carpus, stifle and tarsus during the swing phase. However, the prolonged suspension duration could not be confirmed. Also Clayton (1997) observed a gradual shortening of the airborne phase from collected trot to passage.

The greater reliance for hind limb support, indicating a higher degree of self-carriage and balance, was reflected in prolonged stance duration and positive diagonal dissociation. Similar changes were described by Clayton (1994, 1997) and Holmström et al. (1995) for the over-ground situation in which the passage stride duration and fore- and hind limb stance duration increased while speed and stride length were reduced.

It seems difficult to prove biomechanically that lowering of the hind quarters is a consistent finding in collection. One likely explanation is that the human eye confuses movement during the swing phase with temporal characteristics of limb placement.

Diagonal dissociation

In speed-matched trots on a treadmill, significant decreases in diagonal dissociation relative to stride duration were found in the competition HNP compared to the free HNP (Weishaupt et al., 2006), and the mean value was negative, meaning that the fore hooves made contact before the diagonal hind hooves. Diagonal dissociation was further significantly longer on the treadmill (Weishaupt et al., 2009) in passage compared to collected trot. In this study speed-matching was not done.

Relative weight bearing

Increased weight bearing by the hind quarters is another common term used to describe collection. Although it is easy to define, it is not so easy to measure comprehensively in the practical situation. Commonly the total impulse of the fore/hind limbs is determined, which can be done with a force-measuring horseshoe, force plate or an instrumented treadmill. However, it is important to distinguish between impulse (total weight bearing of one limb during one stance phase) and peak force (Fig. 15.20).

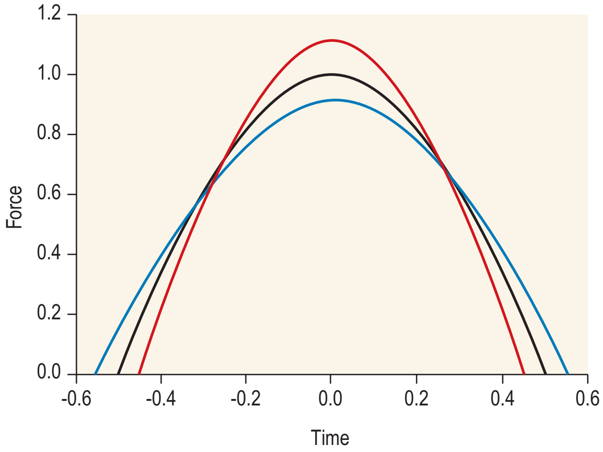

Fig 15.20 A schematic drawing of vertical ground reaction force over time, with the half-sine shape that is observed in running gaits. The highest point is the peak force and the area under the curve is the impulse. Note that the three traces have equal impulses, but peak vertical forces are inversely related to the stance durations according to $F_{peak} \sim 1/D$ if the shape of the force curve remains similar.

Absolute versus relative weight

The weight distribution of an unridden horse trotting freely overground is 55/45% on the fore/hind limbs for (Schamhardt et al., 1991), 56/44% (Weishaupt et al., 2004), and 58/42–44% (Waldern et al., 2009) when trotting on a treadmill, and 59/41% at walk on a treadmill (Waldern et al., 2009). The presence of a rider sitting passively, leads to a quotient of 52/48%.

From the free HNP to the HNPs in which most riders need to use their reins, in walk there is a small increase in weight bearing of the hind quarters that is statistically significant for the 'above' HNP (vertical impulse of the forelimbs decreased by 1.6% in walk and 1.8% in trot). However, this position was judged to be uncomfortable for the horse (Weishaupt et al., 2006). In the high HNPs, 2.5–3% less vertical impulse was carried by the forehand compared with the free HNP (Weishaupt et al., 2006). In passage the vertical impulse carried by the forehand was decreased by 4.8% compared to collected trot (Weishaupt et al., 2009).

Weishaupt et al. (2006) confirmed that, indeed, relative shifts of the center of mass can be induced by altering the HNP of the horse. The HNPs with the neck stretched out (HNP1 and HNP6) shifted the weight towards the forelimbs; more restrained HNPs and especially the elevated neck position (HNP5) shifted the weight towards the hind quarters in both gaits. However, compared to the reference position HNP2, the changes were surprisingly small; the cranio-caudal load distribution varied only between +0.7% and −1.0% at walk and +0.5% and −1.0% at the trot

A further essential finding was to quantitatively demonstrate that a load shift towards certain limbs would not necessarily increase the peak forces in those limbs and vice versa. In the free HNP and the low and open HNP peak vertical forces (Fz_{peak}) in the forelimbs decreased although the center of mass was shifted towards the forehand. In a single peak, sinusoidal curve such as the vertical ground reaction force curve of the trot, maximal values can be reduced by distributing the impulse (area under the curve) over a longer stance duration, which was the case for the free HNP and the low and open HNP. The opposite was observed in the above

HNP where the shift of load from the forehand to the hind quarters was not associated with a reduction of Fz_{peak} in the forelimbs. On the contrary, because of the pronounced vertical stride pattern of the forelimbs coupled with unproportionally short stance durations, Fz_{peak} actually increased compared to the speed-matched reference. In movement patterns that have a short stance duration, higher peak forces are to be expected!

Conflicting results between different studies may have arisen because the changes being measured are so small or they may be confounded by the use of a treadmill. Changes in timing of the force applications by the fore and hind limbs may also be important in achieving collection. As an example the vertical force in the hind limb might increase faster during the first part of stance in association with collection, i.e. the impulse may be shifted to earlier within the stride.

Trainers use terms such as 'letting the aids through' and 'working through the back' that are related to the feeling of the horse being 'between the aids' when the rider perceives that it is possible to do whatever he or she wishes without any resistance from the horse. Most riders with a certain amount of experience can identify a specific feeling when the horse and rider seem to become one unit, and the feeling is that every aid is accepted with ease by the horse. It is likely that this is related to timing between fore- and hindquarter locomotion and temporal coordination of back muscle activity (Robert et al., 1998; Licka et al., 2009). However, this field is yet to be explored.

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CHAPTER 16

Ethology and welfare aspects

Natalie K. Waran, Machteld C. Van Dierendonck

Introduction

Through the process of domestication the horse has gained survival advantages such as food, shelter, veterinary care and protection, but this has been at the cost of restriction of movement, limited breeding opportunities and a requirement to expend energy for the benefit of another species. In fact it is likely that many of the demands made on the domestic horse conflict with the evolutionary process that shaped the behavior of its predecessors (Goodwin, 1999). The evolution of the horse began some 60 million years ago (Fig. 16.1). The ancestor of the domestic horse was Eohippus or the 'Dawn Horse' (Hyracotherium). Eohippus was a small creature about the size of a fox, with adaptations for life in the swampy regions of North America, with four toes on its front feet and three on the hind feet. The 'Dawn horse' died out, and by the Oligocene period its successors had grown to the size of a large dog with three toes on each foot. Pliohippus was the first equid to walk on one digit, the two 'other' toes being reduced to long thin vestiges, more commonly referred to as the splint bones in the domestic horse. The various breeds of *Equus caballus* are derived from a 13–14 hand (130–140 cm) at the withers, social, Steppe-dwelling animal that thrived on low-quality forage through the development of hypsodontic molars as well as by evolutionary adaptations to the digestive tract.

The domestic horse is a non-territorial member of the family Equidae (Goodwin, 2002), and is often described as a follower species, because the precocial young stand and move to feed within a few hours of birth, after which they will follow the mother as she moves off with the herd. Thus the horse performs locomotory behavior from only a few hours of age. This makes perfect evolutionary sense, since as a prey animal the horse relies upon early predator detection and flight as its primary defense mechanisms.

In terms of locomotion, in its natural state, the horse has been observed to range over considerable distances. In ethological terms, the horse's home range contains resources important for survival such as watering holes and suitable grazing areas. Home ranges vary in size between and within areas where feral horses have been studied depending on the availability resources, and the available area ranges have been reported from 0.9 to 48 km^2 and more in different study sites (Berger, 1986; Boyd & Keiper, 2005; Tyler, 1972). In addition, the members of a horse band (the structured social unit within a herd) follow similar movement patterns within a common home range. Changes in band composition may occur through natal dispersal, which is the movement of young horses from one maternal group to another or to a bachelor band, as occurs in many feral herds. For example, Berger (1986) reported that fillies moved on average 4 km and males moved between 10 and 15 km away from their natal herd in the Navada region of the USA, and in Japan, the Misaki horses will emigrate over much greater distances. Having evolved from animals adapted to live in the unpredictable and open environment of the Steppe region of Asia, it is not surprising that they exhibit anatomical specializations for running. These adaptations include anatomical changes in the 3rd phalanx (the caput ridge on the distal metacarpi and metatarsi) as well as the development of the 'spring mechanism'.

Due to the spring mechanism, the energy the horse needs for locomotion is halved through storing and returning elastic strain energy in spring-like muscle–tendon units, and is optimized by the anatomical construction of the tendons and the number of distal joints affected by the tendons (Wilson et al., 2001). These features allowed the horse to respond quickly through early detection of danger due to their well-developed senses (as social behavior developed – it is likely that their sensory development may have become enhanced), followed by flight as their first defense mechanism against predators. Therefore sociality and flight became neurologically 'blue printed', and are considered a biological need even for domesticated and intensively managed horses. *Equus caballus* (the modern ancestor of the little dawn horse) exhibits similar motivation in relation to much of their locomotion and behavior.

Development of locomotion

Early kinetic activity

Simple movements initiated by the developing fetus can be detected from only a few months old and include limb stretching, becoming more complex and coordinated as it matures. Once born, the foal becomes mobile through a series of stages described by Fraser (1992) that result in teat seeking and sucking. Foals differ in their ability to achieve each stage of mobility, but usually they are stable on their limbs within hours of birth (Fig. 16.2). Its interesting that although most foals are able to walk, canter and suckle very soon after birth, they need a few days to develop the skills needed for lying down and standing up. Many foals will literally fall asleep on their feet, during their first days of life, illustrating that even in precoccial species, complex locomotory movements need to be learned and practiced. It is worth considering how much the

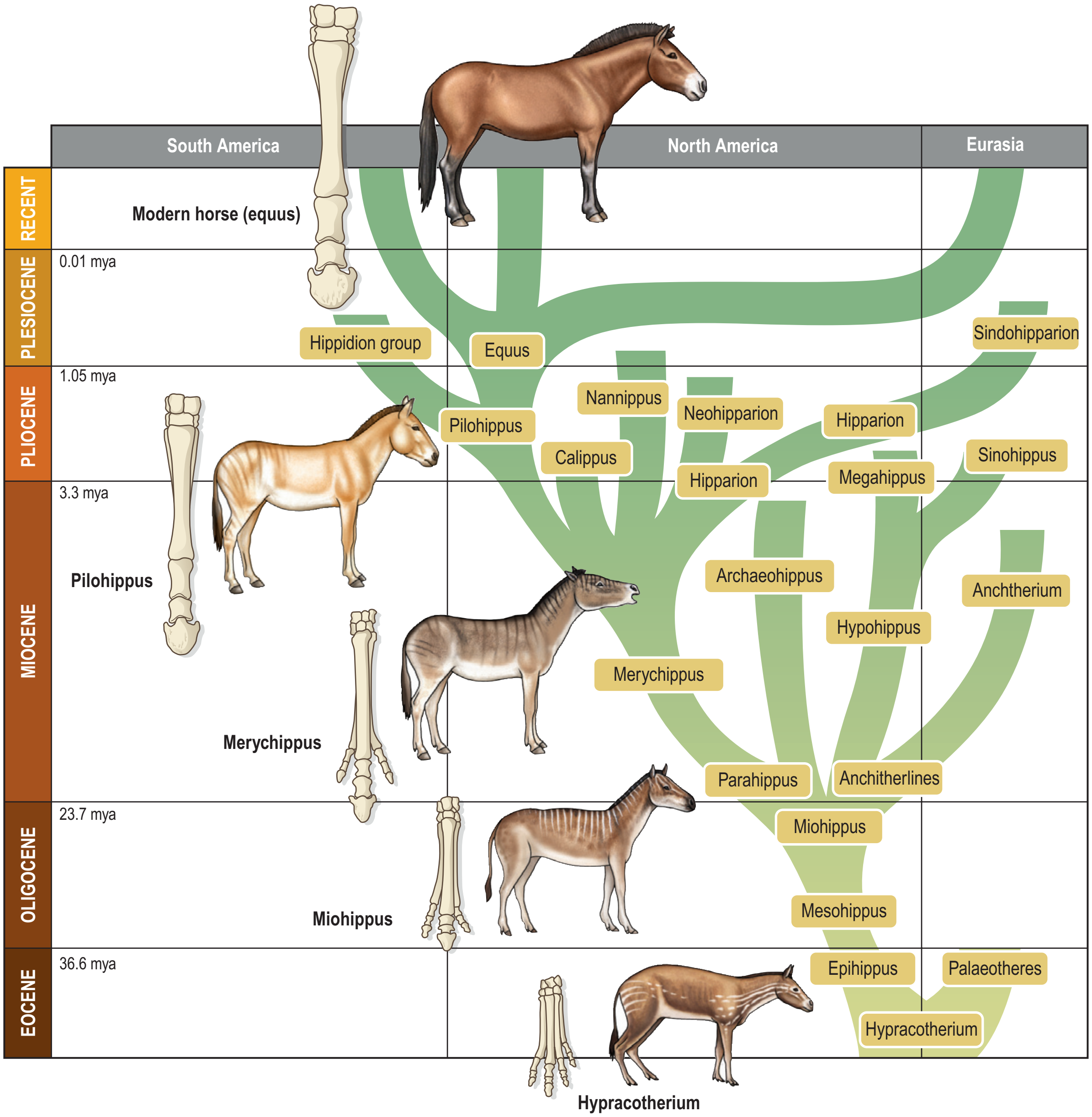

Fig 16.1 Evolutionary tree of the horse. Note the transition from browsing forest dweller to hypsodontic grass eating Steppe roamer in the Miocene, as well as the extinction in the America's in the last ice age.

intensive housing of foals at this early stage may hamper the development of many behaviors, including locomotion.

One of the primary activities foals engage in is stretching, which seems to be of greatest importance during the first few weeks after birth. Foals have been observed to perform this activity 40–60 times each day (more than sucking) (Fraser, 1992). It is suggested that both recumbent and upright stretching are important for athletic development, growth and joint formation. Especially in the first 10 days of their life, foals are engaged in many short bouts of solitary locomotory play around their dams, allowing their muscles to develop.

Grazing

During the first week of life the mare and foal spend approximately 90% of their time within 5 m of each other (Waring, 2003). During these early weeks, the mare repeatedly leaves the foal and moves a short distance away, and the foal follows. This following behavior is an instinctive tendency in a foal, refined through learning during the first week of life. Over time, the mare and foal will spend more time apart, until by the age of 1 year the youngster may be grazing for approximately 44 min/h alongside the rest of the herd. Grazing involves moving whilst foraging, an activity that horses in their natural state will perform for around 16 h each day depending on their physiological and reproductive state, the time of year, available forage and weather conditions. Thus horses have evolved to spend much of their time moving slowly with their head and necks lowered, whilst selecting suitable forage. In the natural environment, horses may travel up to 80 km during grazing and for water, and even when kept on restricted pastures, horses are estimated to move around 20 km each day (McGreevy, 2004). Increased locomotory activity has been found in horses kept socially isolated from others in which case they will walk and trot three times more frequently than horses kept in groups or in visual contact with another horse (Houpt & Houpt, 1989), apparently to try to get into more close contact with conspecifics.

Fig 16.2 A foal just after birth quickly learns to balance and to move around so it can follow its dam, even in canter. However, complex behaviors like lying down take much longer to learn.

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Fig 16.4 Fifty percent of foals develop a side preference while equally distributed left and right.

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Fig 16.3 Play in young horses is essential for the development of their physical as well as their social skills. Playmates of similar age provide a strong stimulus to the young horse to move.

Courtesy of Machteld van Dierendonck.

Play

Apart from movement associated with following and grazing with the herd, the foal engages in various locomotory activities described as play (Fig. 16.3). There appears to be no universally agreed function or homogeneous character to define play, but it is apparent that play has survived the pressures of natural selection and is an almost universal trait in mammals. There are a number of proposed functions which include development of social skills (Fraser, 1992); motor strength and co-ordination; behavioral flexibility (Spinka et al., 2001) and cognitive training. In horses, play occurs most frequently in younger animals, with colts performing more than fillies (Kurvers et al., 2006). When the spontaneous locomotion activity of foals kept under various management conditions was compared (Kurvers et al., 2006), it was found when foals were kept for 24 h/day at pasture, they exercised at a level comparable with feral foals. Interestingly the total observed daytime workload in the first month of life was approximately twice that of the following months, while locomotion activity decreased with increasing age. Foals that were stabled for some portion of the day appeared to engage in compensatory locomotion activity. However this was insufficient to reach the level of locomotion of foals kept continually outside (Kurvers et al., 2006).

There have been relatively few studies of play in non-domestic equids and where recorded this has generally been anecdotal, but social and solitary-locomotor play have been recorded in Hartmann's zebra foals (Joubert, 1972) and also in captive juvenile Przewalski horses (Zharkikh, 1999) as well as in free-ranging and feral horse populations in the UK and USA (Tyler, 1972; Berger, 1986). In these groups, the majority was social play behavior with activity patterns including: play fighting, neck wrestling and chasing and with solitary-locomotor play including gamboling, high speed turns and sudden stops (see Goodwin & Hughes, 2005). During play, absolute force values as exerted on the developing tissues are probably not substantially different from those created by cantering, but play activities result in other loading directions, including eccentric loading and loading in the sagittal plane, which might be important for the development of musculoskeletal structures (Kurvers et al., 2006) (see Chapter 13).

The findings of various studies suggest that (24 h) pasture-based management systems for foals may be superior to more intensive management systems due not only to the recognized advantages of social interaction with other mares and young foals but also the physical gains due to increased and varied locomotion in early development. One of the impacts of the pressures of producing horses as early in the season as possible, as is the case in the Thoroughbred racing industry and many sports horse registration schemes, is that in some climates, it is difficult to persuade breeders of the social, mental, physical and thus welfare advantages of the pasture-based system, when their foals are being born during the coldest months of the year.

Development of laterality (sidedness)

Equine laterality (or sidedness in horses) has been investigated in relation to equine performance and training as well as trying to understand the underlying factors that lead one horse to favor a left lead over a right leading leg. In a series of studies, (van Heel et al., 2006; Kroekenstoel et al., 2006; van Heel et al., 2010) healthy jumping bred KWPN foals were born and raised outside at the same location, and were then followed weekly for a year to observe the development of laterality (Fig. 16.4).

They were assessed at 3, 15, 27 and 55 weeks of age for pressure distribution under their feet (to determine the Centre of Pressure), external and internal development of the foot including phalangeal

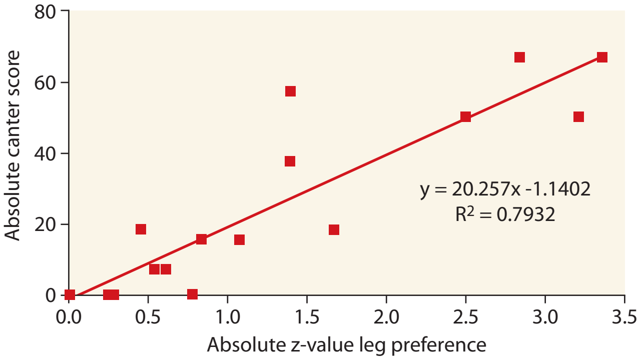

Fig 16.5 Relationship between canter (% correct lead when horse is asked to canter; 15 repeats per horse) and side preference (15 repeats) of 3-year old horses (n = 17).

Reprinted with permission from van Heel et al. (2010).

development and 'handedness' (or side preference). In addition several conformation measures were made such as relative leg length and head size, heel height and toe angle. It was shown that about 50% of the foals developed a significant preference for protracting the same limb systematically while grazing, which resulted in changes to the balance of their feet and subsequently uneven loading patterns. There was no overall preference for either left or right sidedness, with an even distribution between the two sides. However it appears that foals with relatively long limbs and small heads were predisposed to develop laterality and, consequently unevenness (van Heel et al. 2006, Kroekenstoel et al. 2006).

Seventeen of these horses were tested again when 3 years old, after they had only been handled for normal management procedures like trimming and de-worming (van Heel et al., 2010). The assessments revealed that the laterality as well as the unevenness still existed, but the relationship between the body conformation and the unevenness had weakened. In addition when these horses were also assessed in free trot to canter transitions and free jumping, laterality and unevenness were strongly related to incorrect transitions (either disunited canter or counter-canter) (Fig. 16.5).

Since in ridden horses there is a preference for left sidedness (McGreevy & Rogers, 2005; McGreevy & Thomson, 2006), the results of studying 3-year-olds suggests that left sidedness can be induced by the human interaction with the horse, which, in most cases, is predominantly from the left side of the horse. Apart from the concern that horses with strong lateral preferences might be more prone to overloading injuries of the distal limb it is also interesting to note that this could relate to performance problems later in life. For example: horses may be less balanced when running around racetracks that run to the left or right, or have problems with picking up the correct lead in canter when under saddle. There is a need for more applied work in this area to determine how motor laterality can be influenced through breeding, environment and training.

Natural rhythms of activity

Circadian rhythms reflect extensive programming of biological activity that meets and exploits the challenges and opportunities offered by the periodic nature of the environment. Bertolucci et al. (2008) found that athletic horses monitored for activity during four different times of the year (vernal equinox, summer solstice, autumn equinox and winter solstice) experienced seasonal variations in their daily activity rhythms. Athletic Thoroughbred horses kept in individual boxes (stables) with access to a paddock showed the highest daily amount of activity during the vernal equinox (spring) and the lowest during the winter solstice but in all cases horses were most active in the middle of the photoperiod. The authors suggest that information regarding the natural activity patterns of the horse should be used to plan the training schedules and competition management of athletic horses. However a recent study of the impact of biorhythm changes associated with long distance travel for competition purposes suggests that horses are far more flexible than humans in relation to coping with change (Murphy, 2008). In humans a change in the light/dark cycle has a number of effects including disturbed sleep patterns and lethargy. Given that racehorses and other high level sport horses are frequently transported long distances between hemispheres there are questions about how quickly they recover from any jetlag in order to perform well. The findings of the study by Murphy (2008) showed that melatonin levels in the two test horses that experienced an abrupt change in light/dark cycles, were reset within 24 h, whereas regulation of body temperature took approximately 3 days. These results suggest that horse performance is less compromised by the time change than human athletes and that horses possess the ability to rapidly adjust to any changes in photoperiod.

The impact of intensive management on locomotion

In the natural environment, horses move continuously as they graze between food patches with short periods of rest, social activity and locomotion. Apart from the movement associated with grazing, horses spend approximately 9% of their daily time budget engaged in other forms of locomotion (which could be play, travelling, or due to flight responses). This daily time budget changes dramatically once the horse is managed more intensively. Horses housed in stables spend a great deal of their time standing and very little time moving whilst eating.

For example, various studies of feral horses have shown that horses will spend approximately 60–80% a day on feeding, during which they walk around 5–10 km, and even up to 20 km a day (VanDierendonck et al., 1996; Feist & McCullough, 1976; McGreevy, 2004). By contrast in stabled horses both feeding and moving time are significantly reduced due to the restricted space and the fact that there is no need to move in order to obtain food (Mills & Clarke, 2002; Sweeting et al., 1985; Vervuert & Coenen, 2002; Waring, 2003). When there is a high motivation for a stabled horse to perform certain behaviors but expression is restricted due to environmental factors this can lead to frustration and hence to the development of abnormal behavior (Mills & Clarke, 2002; Rushen et al., 1993) including behavioral pathologies that are extremely difficult to manage. Foraging in itself is an appetitive behavior and is a biological need which a horse must be able to perform otherwise its welfare could be hampered (VanDierendonck, 2006). One of the problems with the intensive management of horses kept in stables or stalls is their restricted movement associated with the acquisition of food. These horses are provided with all their daily requirements in 'meals' and no foraging is required. Providing stabled/stalled horses with multiple forage types in different locations within the indoor housing environment can increase movement and has also been shown to reduce abnormal activities such as weaving (see Thorne et al., 2005)

Feeding

The effects of diet on equine locomotory responses has received surprisingly little scientific attention, despite the fact that many sports horses are fed high-energy diets in order to boost performance. A study by Nicol et al. (2005) examined the effect of different feeds on the behavior of foals aged from 2 to 40 weeks. Each foal received either a starch and sugar (SS) diet, or a fat and fibre (FF) diet, and their behavior was monitored immediately after weaning. The results showed that horses receiving the FF diet cantered less frequently and for a shorter duration and the authors described the foals receiving the fat/fiber diet as more settled. This suggests that at least during a stressful time such as occurs at weaning, high-energy diets appear to be associated with increased locomotion. However, inappropriate or over-feeding high-energy foods to horses is also known to be associated with unwanted locomotory responses, such as explosive reactions to signals (aids), and this is particularly the case for horses housed in stables (Riveria et al., 2002). Hyperactivity responses, including shying, pulling, bolting, and rushing could all be considered to be the result of a restricted environment, lack of exercise and too much sugar/starch in the diet. It is likely that the behavioral problems often experienced by horse owners and that lead to poor owner–horse relationships, and thus lower equine welfare, could be prevented through improved understanding of the effect of food and feeding on horse behavior and by providing the horse with a more natural time-budget including access to an area to enable it to perform a normal locomotion pattern.

Impact of housing/restricted grazing on locomotion

As far as locomotion behavior under more natural conditions is concerned, horses have been shown to travel distances of up to 65–80 km/day. Where horses are managed at pasture, grazing is the main initiator of locomotion and the distance they cover is therefore usually much less. There are a number of different methods for managing sports horses, however the demands of competition and training are often associated with controlled exercise, restricted feeding regimes and restricted housing for at least part of the day. There are three basic types of housing for intensively managed horses, which include the stall, the stable or loose box and group or loose housing.

The stall (known as the straight stall in the USA), in which the horse is tethered in a space usually not much greater than the width and length of the animal is therefore the most restrictive for the horse. Generally there is very limited access to other horses, and no space to turn or move around voluntarily. The horse is limited to some forward and backward movement, and lying down on its brisket and sometimes its side if the tether allows. Although stalls are less popular now than during the era of the working draught horse, they are still used where space is limited or where traditional methods of housing are valued. In some countries (e.g. Germany 'Bundesländer', Sweden and Denmark) they are forbidden by law. The most common type of housing in Europe is the stable or loose-box (also called the box stall in the USA), where the horse has limited freedom of movement, some external stimulation, and differing degrees of access to conspecifics depending on the internal partitions. Most Western European countries have a recommended minimal stable size for adult horses and ponies (e.g. 2 × height-at-the-withers). This allows a pony/horse to perform its normal feeding, resting and maintenance behaviors without space limitations. Despite this minimum requirement, in many countries (e.g. UK, The Netherlands, Belgium, Germany and Spain) most stables are standardized at 3 × 3 m or less and therefore often very restrictive for the most common breeds. In the UK 4 × 4 m is recommended for horses 'kept inside for long periods', while the European Union law uses 5 × 4 m for research horses.

Horses in the restricted stalls perform no 'normal' locomotion, possibly stepping back and forward being the only movement being possible, apart from the hour or so during which they may be exercised. Horses in stables or loose-boxes can move, but can only do so within the confines of the enclosure and generally are restricted to only walking, although some horses manage to perform other forms of locomotion such as bucking and rearing.

The third type of housing used for the performance horses is group or loose-housing in barns or yards. Group housing is mainly used for keeping breeding mares or young stock together, since these are rarely handled, and so access to each individual every day is not necessary, and they do not require as careful monitoring of exercise and feeding as competition horses do. This system works best where group composition can be kept stable, and where there is space available for horses to escape any unwanted attention from others in the group. Its advantages are that horses can interact freely, move fairly freely and live a more natural life. Group sizes vary from two or three to 60 or more and space allowances of the same dimensions as a loose-box per individual are recommended.

Relatively recently technology borrowed from the automatic milking systems for dairy cows has been adapted and used in group housing for horses. Unpublished studies by one of the authors (MvD) have shown that despite these systems needing more technical (software) development, the horses housed in this way more closely resemble the natural (semi-feral) feeding, locomotion and resting time budgets than stabled/stalled horses. Moreover, in these systems the animals can perform biologically essential behavior when they want to: so they can be social, move freely and perform locomotory behaviors more similar to those seen in horses in paddocks/at grass. This ability to perform more natural responses including locomotion is considered to lead to a reduction in stress (Weiss, 1971) and therefore enhanced welfare as compared with other intensive housing systems.

Effect of management regimes on locomotion and welfare

The method of management obviously impacts greatly on horse locomotion time and type. The confined conditions in which most performance and recreation horses are kept at least for part of a 24-h period, clearly restricts normal behavior. The stable appears to conflict with many of the horse's survival instincts, and the associated effects of restricted feeding and exercise are thought to lead to a number of problems for the horse (VanDierendonck & Goodwin, 2005). Changes in kinetic behavior associated with housing are quite extreme – horses in stables will stand for up to 40% of their daily time budget, and move infrequently, whereas horses free-ranging in Camargue district of France will only stand for 20% of the day, and will spend 60% grazing and 10% in other activities including social grooming, rolling and play (Kiley-Worthington, 1987). These figures are confirmed in studies of feral horses in other area's around the world such as New Zealand, USA, Iceland and Mongolia (Linklater et al., 2000; VanDierendonck et al., 1996; Cran et al., 1997; Sigurjónsdóttir et al., 2003).

However there is a question regarding whether exercise is actually important to the horse. That is, although there are undoubted differences in the amount of time, the type and the space available for movement in the different housing systems, is this really a problem for a horse? This issue has recently arisen due to public concern about the welfare of horses used in the Pregnant Mare Urine (PMU) industry in the USA, and in particular the fact that mares are confined for long periods in straight stalls in which they can not turn around and do not have the chance to move or exercise. To answer this, Houpt et al. (2000) developed a device based on the phenomenon of operant conditioning. In their study, horses had to learn to press a panel a number of times in succession (the switch) in order to release themselves from the stall. Houpt and co-workers measured the strength of a horse's motivation for each of three commodities: food, exercise (release into a paddock for 3 min) or companionship (access to another mare for 3 min). They found that the chance to leave the stall (i.e. to experience free movement) was less important than leaving to access food and the opportunity to exercise and have access to another mare was equally chosen. In a further trial the authors looked at the preference of the horse for engaging in exercise on a treadmill or alternatively, returning to the home stall. Interestingly most horses chose their home stall and actively avoided the treadmill, suggesting that exercise *per se*, may not be as important to the horse as often considered. However when

Houpt and Ogilvie-Graham (2002) compared the behavior of horses allowed daily turn-out with those only given access to a paddock every 2 weeks they found that there was much more movement, in fact more running, in horses that had been restricted for longer periods. This suggests that horses need to move but do not necessarily choose to exercise. Despite whether they choose to or not, exercise is important for the physical development of young horses (Barneveld et al., 1999). Group housed young horses show more locomotion than animals kept alone (Christensen et al., 2002), and it is suggested that due to the performance of movements such as bucking, rearing and chasing, they are likely to develop more coordinated movements, which is highly desirable in the sports horse. However along with such activities there is a risk of injury, especially if the enclosure is not large enough or the surfaces/internal environment is unsafe. Since it seems increased play, aggression and locomotion are associated with the rebound effect of solitary housing (Christensen et al., 2002), there appear to be more risks in relation to future injuries and behavioral issues associated with housing horses in the conventional way than raising them in groups outside where they have no need to compensate for the lack of opportunity to perform natural responses.

Impact of exercise on welfare

The inability of the stabled horse to escape from the situation it finds itself in, or to control any aspect of its physical environment, often leads to the development of somatic or body-based forms of abnormal behavior such as stereotyped pacing or box walking, weaving, head nodding and pawing. All of these activities are associated with the stable environment, and some are associated with a reduction in health and therefore their appearance must be viewed as welfare concern.

Weaving appears to be a form of frustrated locomotion, in which the horse that is prevented from moving forward by a stable door or field gate, will move its head, neck and body from side to side, or head nod. This is often accompanied by the shifting of weight from one foreleg to the other. Box-walking (or stall-walking) is a form of stereotypic pacing that follows the walls of the stable, and pacing is often seen along field fences, again apparently following the line of the barrier.

The motivation for such abnormal locomotory activities has been suggested as being related to lack of exercise, boredom, social isolation or general frustration due to confinement and management procedures. These abnormal behaviors can also be induced when horses have to undergo sudden box rest, due to some kind of injury or illness and this sudden change is not anticipated for by adapting the management around the affected horse. Reduction in these abnormal behaviors has been found through supplying the horse with increased social contact, stable mirrors, increased visual horizons (through increasing the number of openings to the outside environment), increased exercise, and changes in food presentation (Cooper et al., 2000; Cooper & McGreevy, 2002) (Fig. 16.6).

Fig 16.6 Abnormal behaviours like weaving and box walking can be reduced by offering visual (and preferably physical) access to a conspecific; but in cases where this is not possible, a well placed mirror can be a valuable substitute.

Photo courtesy of Professor D. Mills.

Structured exercise such as occurs in many racing yards may lead to a reduction in the frequency of locomotor stereotypies but this is not necessarily the case with abnormal oral behavior such as crib-biting, demonstrating that the underlying motivational causes for these behaviors are quite different (McBride & Long, 2001).

Increased and abnormal kinetic activity can therefore be used as an indicator of stress in managed horses. Such measures include a reduction in normal recreational or functional locomotion such as seen in play or grazing as well as an increase in flight responses in response to the environment.

Some trainers make inadvertent use of the rebound effect in training due to the housing and management regime in race yards. It is suggested that when horses are housed for up to 23 h each day, and then are given the opportunity to be exercised in short time frames, they are likely to be more motivated to locomote which in turn leads to greater muscle development. However, many horses who do show this rebound effect show uncontrolled and dangerous locomotion patterns and tend to be hyper reactive to stimuli from their environment, leading to a perceived need for greater rider controllability of the horse through the use of stronger bits and bridles often leading to greater problems as the horse becomes more stressed and the development of inappropriate responses and musculature.

Overtraining

In order to improve performance in sports, the training load has to be gradually increased over time. This improvement is only achieved if the training load is properly balanced with recovery. However, in both human and equine elite athletes, the ratio between training load and recovery is often in a precarious equilibrium. When this imbalance occurs over a longer period, it may eventually lead to a severe mal-adaptation to the increased workload defined as overreaching or even, in more severe cases, overtraining. In addition, in both horses and humans, several gradual stages of maladaptation to training can be observed: mechanical overload, metabolic overload (or overreaching) and overtraining (or staleness). Since a full blown overtraining syndrome can lead to a long absence from competition and is a severe welfare issue for the athlete involved, it is important to prevent this (VanDierendonck et al., 2007). In a study to systematically assess the horse's attitude, behavior and response to intensified training for identifying factors related to early overtraining or overreaching (VanDierendonck et al., 2007), early overtraining was induced in a treadmill study (Fig. 16.7).

All horses started with an 18-month training protocol on a treadmill. Next, half of the horses (controls) continued on the same schedule (4 training days, 2 days endurance training, 2 days high-intensity training), the other half went to a more intensive schedule, ending with 7 days a week unpredictable training. The study finished with 4 weeks of detraining (de Graaf-Roelfsema, 2007). All experimental horses showed significant changes in their behavior (VanDierendonck et al., 2007) and in their growth hormone release (De Graaf-Roelfsema et al., 2009). After 4 weeks of detraining, most horses were not back to their pre early overtraining levels in relation to performance and behavior. The significant factor with the greatest

Fig 16.7 Treadmill used to induce early overtraining experimentally by de Graaf Roelfsema and co-workers.
Courtesy of Wim Back.

impact on the horses seemed to be the absence of 'resting' days in the training protocol. Since there were no alterations at the muscular level, it was concluded that the applied stress involved alterations in the central neuro-endocrine system preceding the peripheral systems, indicating that physical stress started with alterations in the neuro-endocrine system: that is, the overtrained horses endured more mental stress than physical stress (de Graaf-Roelfsema, 2007). Therefore, it seems that locomotion may be important to the horse but there are serious welfare implications when early signals of overtraining (i.e. too much (forced) locomotion) are not recognized and dealt with.

Problems with locomotory behavior during training or performance

Not all forms of locomotion are desirable in the horse. Problem behaviors often result from the unwanted performance of the horse's normal flight response during the horse's training. 'Training' can be defined as the intentional modification of the frequency and /or intensity of specific behavioral responses. Such modification is achieved through different means: the shaping of a response where the specific behavior is positively reinforced in a step-wise fashion towards a specific end point and the suppression of undesirable responses. Successful and humane training relies upon the trainer having a good understanding of the application of learning theory, horse ethology and a clear understanding of the goals and the limitations of the training approach being used. Humans influence the behavior of horses, in-hand and under saddle, with stimuli from their hands on the reins and their legs on the sides of the horse and more discreetly with the use of their seat, weight position and movement. Horse riding at its most humane relies on a clear understanding of the way in which the horse makes these associations.

When problems occur during training, these usually manifest as locomotory behaviors designed to remove the horse from a potentially life-threatening situation. As a prey animal, the horse has a particularly well-developed sense of self-preservation and there are a variety of actions it may take including bolting, bucking, rearing, kicking, shying and freezing. These behaviors are often the result of a conflict between the horse's desire to escape from pain or pressure and their inability to do so due to the environment, situation or impact of the devices that control them (see McGreevy (2007) for a discussion of equitation science).

There are many trainers, advocators of different methods and training devices that advertise the various ways for dealing with problem behavior in horses; however, if a horse has learned to buck and run away from pain due to inappropriate riding or equipment causing pain, it is clear that understanding the behavioral mechanisms that underpin the response must be the most effective way to deal with it and prevent such responses in future.

There are a variety of ways in which humans can impact negatively on horse welfare in relation to locomotion. Performance horses are used for jumping high fences, running at high speeds for prolonged periods, performing highly elevated and exaggerated movements in dressage, swerving and cutting or sliding to a halt from a gallop. Although horses naturally perform these behaviors, they are trained so that they are performed more frequently, more exuberantly and to a greater extent than the animal has evolved to do. In many cases the horse has to be trained through rigorous gymnastic work to be physically strong enough, developed enough and mentally able to perform such locomotory activities for competition, and of course there are injuries, stresses and wastage (see Waran, 2002).

Locomotion and the impact of different training methods

Head and neck positions

The aim of all training is to produce a horse that is useful and responsive to signals of the rider or trainer. For the horse to meet these conditions, its weight, plus that of its rider, must be correctly distributed over all four limbs. Horses naturally carry more of their weight over the forelimbs than over their hind limbs. In collection, the hind limbs flex more, stepping further underneath the horse in the direction of the center of gravity, thereby taking a greater share of the load. This in turn lightens the forehand, allowing the forelimbs to move more freely (Gomez-Alvarez et al., 2006; Rhodin, 2008).

In attempting to achieve competition goals, trainers and riders may employ training methods that have the potential to cause pain and distress to the horse. For example in trying to achieve greater collection, some training methods advocate prolonged extreme head and neck positions (either very high carriage or very low positions, also called hyperflexion of the neck). Hyperflexion of the horse's neck is currently employed as a training method to reach maximal collection by a number of high-level competition dressage riders, and is increasingly used by eventers and show jumpers (also referred to as Rollkur or LDR (low, deep, round)) (Fig. 16.8). The FEI defines hyperflexion as 'Hyperflexion of the neck is a technique of working/training to provide a degree of longitudinal flexion of the mid-region of the neck that cannot be self-maintained by the horse for a prolonged time without welfare implications'. There is considerable debate regarding the use of such techniques, both in relation to efficacy and on welfare grounds.

Several scientific study results as well as the personal opinions of leading riders, trainers and veterinarians were summarized during a special meeting held in Lausanne (2006). Most of the presented studies related to positive and negative influences on different bony and soft tissue anatomical structures (Lausanne 2006), and few addressed concerns regarding welfare implications. Since the Lausanne meeting some of these studies have been published

Fig 16.8 Hyperflexion according to the Fédération Equestre International (Lausanne, 2006).

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(Gomez-Alvarez et al., 2006; Van Breda, 2006) and there are now a number of new studies to add to the body of knowledge (Sloet van Oldruitenborgh-Oosterbaan et al., 2006; Rhodin, 2008; Von Borstel et al., 2009).

A recent analysis (Visser & VanDierendonck, 2009) of these studies revealed that there are some methodological issues with many of the current studies, and there is still insufficient scientific evidence to confirm unequivocally whether or not there are welfare issues involved in training techniques using hyperflexion or others involving a very high carriage of the head and neck, as compared with training methods advocating a relaxed or 'on-the-bit' head and neck position (see Chapter 15, Fig. 15.19).

Additionally some aspects did not receive much attention in the latest research, even though they may have an important bearing on the perception of the horse. For example, hyperflexion most likely severely restricts the horse's vision in the direction of travel (McGreevy, 2004), could cause airway obstruction (changes in arterial O_2, and CO_2 concentrations and increased heart rates), could cause physiological exhaustion and may disturb the horse's biomechanical equilibrium (King et al., 1994; Brown et al., 2004). The possibility that these two impediments can lead to a state called 'learned helplessness' is still open to debate, but has not been seriously addressed by any study to date.

In terms of training locomotory responses, the concern is due to the confusion induced in the horse by applying one cue/signal (pulling the reins with both hands) for two responses (slowing/stopping versus over-flexing the neck). Such confusion is considered to lead to a dangerous detraining of the deceleration (stop) response. Furthermore, the subsequent confusion can induce conflict resolution behaviors in horses. This can prompt horses to escalate their active coping strategies such as causing them to trial hyper-reactive predator removal behaviors (such as bucking, rearing and shying) (McGreevy & McLean, 2007). All these effects could possibly have psychological and welfare implications.

Breeding or training certain types of locomotory responses and welfare implications

There are almost as many breeds of horses as there are different reasons why horses are kept. However the majority have directly or indirectly to do with the horse's kinetic possibilities; some performed in competition, others for recreational use (see Chapter 14). Those involved with competition have the additional risk of reducing the horses welfare when human prestige and/or prize money is involved. There are many different possible welfare issues related to training methods, so only a selection of issues is mentioned below.

In Europe and America, those disciplines in which the horse competes in age classes (or where early maturity is considered a competitive advantage) produce foals as near to January first as possible (Gibbs & Cohen, 2001). In many countries this coincides with the middle of the winter, preventing most dams and foals from being outside and exercising sufficiently thus increasing the chances of future problems in relation to bone and muscle development as discussed earlier in this chapter. These horses also often start to train and compete before they are fully grown and physically matured, possibly making them more prone to injuries or forcing early retirement.

Apart from the obvious risks in relation to the locomotory demands involved in jumping high and fixed obstacles, horses training or performing for long durations (endurance, eventing, long marathons in four-in-hand driving) or in hot climates have extra challenges on their locomotion apparatus with welfare consequences. There are also concerns regarding the impact of frequent and often long journeys overland and by air, as horses are transported internationally for competition and breeding purposes. Research has clearly indicated that even land journeys of a short duration involve restriction on locomotion in relation to space and activity, and the accelerative forces due to the transport process and imposed on the horse, cause it to adopt a 'bracing' posture to allow it to balance in a moving vehicle (see Waran et al., 2002). Apart from the increased heart rate, cortisol levels and oxygen consumption during transport, such postures as seen during transport are associated with elevated muscle enzymes indicating muscle damage. Transport is a physical challenge for the performance horse, and as such needs to be considered as a welfare risk.

There are also the welfare considerations related to the breeding and training of horses used in competitions where primarily the subjective 'beauty' of the horses' movements is judged (e.g. Arabians, Hackneys, American Saddlebreds, Warmbloods bred for dressage, Icelandics, and Friesians). There is concern regarding the use of inhumane training methods to encourage the horses to lift their limbs higher or wider or differently as required by the breed standard and competition. Some of these methods include keeping the animals in the dark until seconds before performing as seen in Arab showing (making use of slow light adaptation of the horses pupil) to all kinds of additions to or underneath the shoes and gadgets designed to attach to the horse's limbs to train a new way of moving (e.g. see Fig. 16.9). Interestingly most of the unethical methods are either frowned upon or disallowed, yet they are difficult to police and as such continue to be used. It is clear that the welfare concerns regarding the training of horses to perform unnatural gaits is an area for more research and public awareness.

Within jumping there are many different unwanted training methods that have been the subject of media attention and are still mentioned regularly. These methods are used to get the horse to jump higher and to tuck the front or back limbs up higher to avoid knocking an obstacle. Such methods include the use of caustic substances underneath the protective leg bandages, lifting of poles

Fig 16.9 The use of so called 'shoes' in training Hackneys in which the strap between the two front legs is too short, forcing the horse to lift its opposite leg earlier and higher than natural, as well as that the horse cannot stand on both feet at the same time.

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(rapping) as a horse jumps an obstacle, and other such painful stimuli to cause the horse to avoid touching the jumping poles. Given that this is a welfare issue and banned by the professional body, the extent to which this occurs and the effect on the (short and long term) welfare of the horse is largely unknown. A recent issue concerns the use of different performance enhancing boots on distal limbs in jumping horses. A study by Murphy (2008) revealed that weight and extra pressure does indeed alter the flexion of the hind legs above the jump and according to Murphy: 'In the absence of scientific appraisal, it is unclear if such boots are acceptable and innovative training aids within equitation'.

Concluding remarks – new approaches including equitation science

Several welfare issues have been the subject of the previous paragraphs, challenging scientists to find acceptable solutions to training and management issues. As van Weeren (2008) points out, the equestrian industry is a conservative one slow to adopt the available technological and scientific advances to help progress training and better safeguard equine welfare. This has been recognized as an emerging area combining many fields of equine research called equitation science (McGreevy, 2007; Goodwin et al., 2008; McGreevy & McLean, 2007).

Ever since horses were domesticated people have managed their behavior in a restrictive manner. This has had and still has serious consequences for the horse. As discussed, research has shown that foals post partum need enough 'Steppe like' space and social stimulation to exercise and develop sufficiently (Kurvers et al., 2006; Brama et al., 2001, 2009) (see Chapter 13) and it is clear that modern demands on the horse differ greatly from the requirements of horses in previous times (see Chapter 1).

Technologies which can be attached to the horse during training and use telemetry to transfer data regarding the horse and the horse–rider interaction (e.g. tension meters in the reins, and pressure sensors in the stirrups (Warren-Smith et al., 2006), pressure meters in saddle pads (de Cocq et al., 2004; Geutjes et al., 2008), on the limbs or head (Warren-Smith, pers. comm.) and heart (Von Borell et al., 2007) all have the potential to provide us with more objective empirical information to aid with training and management. In addition detailed experiments using force places, kinematic analyses with motion cameras (see Chapter 2) (van Weeren, 2002) and other such advances will lead toward better ergonomics (van Weeren, 2005), prevent overtraining (de Graaf-Roelfsema, 2007) and stimulate better skeletal development in the horse (Rogers et al., 2008a,b). Add to this advanced practice involved in the application of ethologically sound training practices using knowledge of learning processes and the horse's natural behavioral responses (McGreevy & McLean, 2007), we will develop a greater understanding of what is acceptable from the horse's point of view.

There are many and varied demands made upon the horse by humans. All forms of performance and recreational use of the horse relate to its locomotory behavior – and in all cases humans have modified the horse's normal behavior to accommodate our needs. The breeding, management and training of horses to enable humans to enjoy interacting with the horse often compromise the horse's welfare. Recognition of this fact, and questioning the way in which we apply such pressure on horses is an important step forward in improving our relationship with them.

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CHAPTER 17

Rehabilitation of the locomotor apparatus

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General introduction

Equine sport sciences are evolving along similar lines to human sports sciences. There has been considerable research on normal and pathological gaits, and the high prevalence of locomotor injuries in athletic horses is well established (Ely et al., 2009; Scott, 2008). Physical therapy and rehabilitation play an important role in performance enhancement, injury prevention and restoration of full function during recovery from injury. This is particularly relevant in relation to back pain and lameness prevention strategies in horses participating in exercise or performance-related activities, including racing, and in horses stabled in smaller operations for pleasure activities, as there is increased risk of lameness for active horses (n = 3925 horses in 138 randomly selected yards; Ross et al., 1998). As described in previous chapters, numerous studies have described factors that may predispose the horse to injury, lameness and lack of or loss of performance (Burns et al., 2006). These include: morphology; conformation; training; environmental conditions; type of competition; age and sex; performance limitations; exercise effects on the neuromuscular and skeletal systems; and interaction between rider and horse. Rehabilitation encompasses broad-based concepts that relate to all the aforementioned factors with a focus on tissue healing, biomechanics and neuromotor control, which all ultimately affect equine locomotion. Veterinary sports medicine and rehabilitation follows in the footsteps of the human counterparts encompassing many professional fields and areas of research, including: physiotherapy (PT), osteopathy, chiropractic, and other complementary medicines.

Objective measures of locomotor kinematics and kinetics (see Chapter 2) are useful in monitoring progress and obtaining outcome measures in rehabilitation, both clinically and for research purposes. Conventional diagnostic equipment can also be used in rehabilitation including electromyography (EMG) (Cottriall et al., 2008) and ultrasonography (McGowan et al., 2007b; Stubbs et al., 2010, 2011), along with relatively inexpensive functional measurement tools such as pressure algometry (Haussler& Erb, 2003, 2006a,b; Haussler, 2006; Varcoe-Cocks et al., 2006; Sullivan et al., 2008; De Heus et al., 2010), goniometry (Liljebrink & Bergh, 2010), digital photography, videography and the tape measure. However, as shown in human studies many of the measurement tools such as goniometry, used to document limb passive motion at the fetlock, carpus and hock are only reliable when used by the same investigator, with further studies needed to validate this tool in the horse (Liljebrink & Bergh, 2010). Complementary objective and subjective clinical outcome measures of performance and function are also vital in the rehabilitation setting which may include force plates to measure and monitor neurological signs and or lameness during the rehabilitation process (Clayton et al., 2003; Ishihara et al., 2009) and motion analysis to measure intervertebral and limb motion as described elsewhere in the text. For example, Faber and colleagues presented a single case study in a dressage horse with scoliosis at T10–L1 that caused severe loss of performance. After two sessions of thoracolumbar (TL) manipulation the effects were assessed using a validated kinematic analysis protocol (Faber et al., 1999, 2001) to measure TL motion and spatiotemporal parameters with the horse walking and trotting at standardized speeds on a treadmill. Spinal motion was quantified by range of motion in the three planes of motion and intervertebral pattern symmetry (Faber et al., 2000). Data were collected pre-treatment, 48 h after treatment and at weeks 3, 7 and 36. Treatment involved 'direct short-lever thrust towards the neutral position of the areas where an impaired mobility had been noted during the clinical examination', labeled as 'orthomanual realignment technique'. Progressive mobilization exercises were also given (walking along serpentines).

The aim of this review is to summarize equine rehabilitation from an evidence-based perspective utilizing references from databases, such as Pubmed. There is a long history of physical therapy in the treatment of animals. A book on physiotherapy for horses, written by the physiotherapist Sir Charles Strong, was published in 1967 in the UK. Two other early publications on physiotherapy for horses appeared in the 1970s (Hopes, 1970; Downer, 1978) focusing on back pain.

In this chapter, back pain will be used as an example to illustrate the principles and practice of rehabilitation. Fundamental concepts of neuromotor control and rehabilitation will be addressed in the context of equine sports medicine.

Historical background: rehabilitation defined

The word rehabilitation comes from the Latin 'rehabilitare' meaning to make fit again. Traditionally this encompasses treatments designed to facilitate the process of recovery and restoration to a former capacity following an illness or injury. These are the founding principles of the physiotherapy profession as described by the World Confederation for Physical Therapy. Complementary medicine including PT in all species is concerned with identifying and maximizing quality of movement potential within the spheres of promotion of health, prevention of injuries, treatment/intervention, rehabilitation and, more recently, performance enhancement and sports medicine. Physiotherapy has been defined as 'A holistic approach to the prevention, diagnosis and therapeutic management of pain, disorders of movement or optimization of function to enhance the health and welfare of the community from an individual or population perspective'. McGowan et al. (2007c) emphasized that one of the fundamental differences between PT and the medical or veterinary profession is that physiotherapists are trained to focus on the assessment and management of a patient's function, rather than focusing purely on the specific patho-anatomical diagnosis. The aim of PT and rehabilitation is to restore function and promote tissue healing by assisting normal physiological processes through the application of manual therapy techniques, electromodalities and exercise-based regimens. Buchner and Schildboeck (2006) and McGowan et al. (2007c) recognized these specific areas: manual/manipulative therapies (PT, massage, chiropractic, osteopathy) and complementary alternative medicine (CAM) also known as physical or technical/modality based therapies (physiotechnical therapies): acupuncture, electrotherapy, exercise, hydrotherapy, laser therapy, magnetic field therapy, thermotherapy and therapeutic ultrasound.

Rehabilitation in veterinary medicine involves the veterinarian as primary patho-anatomical diagnostician, a thorough objective functional assessment of the patient and consultation with other health professionals (McGowan et al., 2007a). Using knowledge and skills unique to these professions the patient's movement potential is assessed, with all information and confounding factors being incorporated to establish an accurate functional diagnosis, problem list, management plan and goals. Clinically, and particularly in relation to research, it is imperative that during the rehabilitation process valid and reliable objective measurements are taken to determine accurate outcome measures. The integration of research into evidence-based practice continues to be a challenge in veterinary medicine and rehabilitation is no exception. Currently there is limited research in equine locomotion in relation to rehabilitation, though many animal models have been used for human rehabilitation research with the findings being integrated into current concepts of equine rehabilitation.

Textbooks and review articles in the area of veterinary PT and rehabilitation include *Animal physiotherapy: assessment, treatment and rehabilitation of animals* (McGowan et al., 2007a). This is an evidence-based textbook that reviews the literature in relation to animal PT and is a useful reference with respect to outlining the foundations of rehabilitation and equine locomotion. A recent review *Equine Physiotherapy: the science behind the profession* (McGowan et al., 2007c) also highlights the potential input of PT in equine rehabilitation. Another useful text is *Physical Therapy and Massage for the Horse* which complements both evidence based and clinical practice (Denoix & Pailloux, 2005). In addition there are clinical and evidence based articles, chapters and textbooks (Porter, 2005; Bromiley, 2007; Henson et al., 2009; Pusey et al., 2010). The profile of rehabilitation and performance enhancement has also been heightened in recent years by the official use of physiotherapists during international equestrian competitions. In this context, equestrian sports are rapidly catching up to other international competitive sports, such as football and athletics, in which individuals and teams utilize the professional service of physiotherapists not only in treatment of injuries, but also in maintenance and enhancement of performance.

In addition, there is a growing body of literature describing research studies in equine rehabilitation (e.g. Wakeling et al., 2006; Haussler et al., 2007, 2010; Ramon et al., 2004; Wennerstrand et al., 2006; Xie, 2005; Clayton et al., 2008, 2010a,b, 2011a,b; De Heus et al., 2010; Stubbs et al., 2010, 2011). Many forms of PT, manual therapies and alternative medicine can play a role in the horse's return to optimal performance. Human therapeutic texts should be consulted to further the reader's understanding of manual therapies, soft tissue mobilization/massage (Boyling et al., 2004), myofascial pain and dysfunction techniques (Simons et al., 1999), electrotherapy (Watson, 2008) and integrative therapeutic approaches relating to mechanical passive constraints of locomotion and neuromotor control including facilitation and strengthening techniques (McGill, 2007; Mooney, 2007; Lee & Vleeming, 2007).

Longevity and musculoskeletal disorders

The clinical need for rehabilitation interventions and justification for research into this field are verified by the amount of wastage in equine sports due to musculoskeletal injuries (Peloso et al., 1994; Valentine, 2008; Barr et al., 2009; Ely et al., 2009). Statistics related to longevity and life spans are often collated according to insurance company records. These indicate that diseases of the musculoskeletal system are the predominant cause of death in sport horses (Clausen et al., 1990; AGRIA, 1995 cited in Wallin et al., 2000; Heisele, 1995), whereas diseases of the digestive system are the most frequently reported cause of death in companion horses (Baker & Ellis, 1981). In a follow-up 5-year survival study of 2495 horses with at least one costly veterinary-care event and 15 576 horses with no costly veterinary care event evaluated for 1 year, the risk of death increased linearly with age and with increasing life-insurance value (Egenvall et al., 2006). Horses with previous lameness had the lowest survival. Horses with previous locomotor problems continued to have considerably more veterinary-care events and higher costs for locomotor problems during the follow-up period (Egenvall et al., 2008), highlighting the potential need for further and improved rehabilitation strategies. The most common disease in 107 310 horses of varying age, gender, breed and use requiring veterinary care covered by complete insurance in Sweden from 1997 to 2000 was arthritis, which most frequently affected the fetlock (28%) or multiple joints (16%) (Penell et al., 2005).

In a 5-year study of 5140 horses from 136 riding schools the overall yearly incidence rate was 1584 events of veterinary care per 10 000 horse-years at risk (Egenvall et al., 2009). The total and diagnostic mortalities were 790 and 763 deaths per 10 000 horse-years at risk. Rates varied substantially among riding schools. For locomotor problems the rates were 1116 events of veterinary care and 524 deaths per 10 000 horse-years at risk. For the outcome veterinary care for locomotor problems, the hazard ratio (HR) increased with increasing life-insurance value, was higher in horses than ponies, and was higher in Warmbloods than other horses. The HR increased by 33% for each year of age at entry. Age at entry ≥8 years was associated with decreased HR due to locomotor problems.

Wallin et al. (2000) investigated the longevity, causes of death and culling of Swedish Warmblooded and Coldblooded horses via a retrospective owner questionnaire. Data were retrieved from horses born 1968–1986 participating in Riding Horse Quality Tests as 4-year-olds, with information about the horses available until 1990. Of the 1847 Warmbloods, 503 were dead, 85% had competed in different sporting disciplines and many were used as leisure horses after retirement from competition. Data also included horses of the Swedish Cavalry Horse Foundation born between 1970 and 1975 with information available until 1989: 208/344 Warmbloods and 97/204 Coldbloods were dead. The most common causes of death were musculoskeletal diseases (56–57%), respiratory diseases (8–9%), diseases of the digestive system (5–6%), accidents (3–9%), and causes unknown in 13.0% of Warmblooded horses. In the Coldblooded horses death was attributable to temperamental disorders (23%), diseases of the musculoskeletal system (14%) and hoof diseases (8%). A written questionnaire among (Swiss) horse owners (n = 2912 horses and ponies) indicated that a veterinarian examined 718 horses (24.7% of the sample population) within the 12 months prior to the survey (Knubben et al., 2008). Orthopedic and traumatic disorders (41.5%) had the largest proportion, followed by gastrointestinal (27.1%) and respiratory (14.0%) diseases. Half of the lameness cases occurred as a direct consequence of an injury. In 25.6% of all cases diagnosed by a veterinarian, alternative therapeutic methods were used either in addition to traditional medicine or exclusively (Knubben et al., 2008).

A UK study surveyed owners of registered dressage horses (n = 2554) reporting that 33% of horses had been lame at some time during their career, with 24% of these within the previous 2 years (Murray et al., 2010). A number of factors were associated with the occurrence of lameness in the last 2 years, with increased risk for older and bigger horses; use of arenas that were indoors, not privately owned, and that became deeper in wet conditions or were sand-based; use of and longer time spent in horse-walkers (cause or effect); not lunging; shorter turnout time; and back pain.

It is well established in the literature that flexor tendon and suspensory ligament injuries are the most frequently reported injuries in sports requiring the horse to perform at high speed and over jumps (Rooney & Genovese, 1981; Jeffcott et al., 1982; Rossdale et al., 1985; Mohammed et al., 1991; Marr et al., 1993; Colbourn & Yovich, 1994; Reef, 1998). In the Thoroughbred (TB) racing industry musculoskeletal injuries account for three times more wastage than all other medical problems (Rossdale et al., 1985; Robinson & Gordon, 1988). More than half of the 2–4-year-old racehorses become lame and 20% of all racehorses eventually suffer a career ending musculoskeletal injury or disease (Bourke, 1995). Ely et al. (2009) found that fractures, tendon and suspensory ligament injuries were important causes of morbidity and mortality in 1223 National Hunt racehorses in training in the UK. Ramzan and Palmer (2010) recently investigated musculoskeletal injuries in three training yards (616 horses) in Newmarket (UK) finding a total of 248 injuries that occurred in 217 horses with fractures of the tibia (20.7%) and proximal phalanx (14.5%) being the most common. A post mortem study of the third metacarpal and metatarsal bones of 64 TB racehorses reported a 67% prevalence of palmar/plantar osteochondral disease (Barr et al., 2009), which is considered to be a consequence of repetitive cyclical high intensive overload resulting in arthrosis (Pool, 1996). This painful condition is recognized in most racing breeds including TB (Arthur et al., 2003; Pilsworth, 2003), Standardbreds (Mitchell et al., 2003; Torre, 2003), Quarter Horses (Lewis, 2003) and Scandinavian Coldblooded trotters (Ertola & Houttue, 2003). Overall, the incidence of catastrophic musculoskeletal injury of Thoroughbreds in the USA has been reported as 1.2/1000 race starts (Hernandez et al., 2001). Incidence of injury was significantly higher for turf races (2.3/1000 starts) than for dirt races (0.9/1000 starts). The number of days since the last race (≥33 days) was associated with a higher risk of injury.

A study of 265 Danish Standardbreds evaluated over a 5-month period showed that a change of trainer affected the risk of lameness (Vigre et al., 2002). Compared to the period in which horses had been with the same trainer for >3 months, horses that entered a different training regime within the past 1.5–2.5 months had a higher risk of lameness. Participation in races increased the risk of lameness significantly in the 5 days following a race.

In a (USA) study of 357 lameness cases, 78.6% were reported to have recovered after a median duration of 18 days (Ross et al., 1999). Some type of treatment was administered in 82.9% of lameness incidents. Of 619 total treatments used, 53.2% were administered or applied by a veterinarian. Horses experiencing hoof lameness were more likely to recover than those with other types of lameness. Horses that had participated in exercise-related activities during the study period and prior to the development of lameness were more likely to recover. Treatment of the lameness was associated with an increased likelihood of recovery. Cases with a veterinarian involved in the diagnosis were associated with a decreased likelihood of recovery and a longer duration of lameness, which might indicate that these cases were more complex or severe. Although cases treated for lameness were more likely to recover, treatment did not affect lameness duration (Ross et al., 1999).

Gibson et al. (2002) reported the frequency of soft tissue injury in 70 elite sport horses competing at the 2000 Sydney Olympics in dressage (8), show jumping (15), and eventing (47). As reported previously (Reef, 1998), suspensory desmitis (n = 4) was most common in dressage horses affecting both fore and hind limbs. Some were able to compete despite having suspensory desmitis, others had to withdraw. The most common lesion in show jumpers (n = 10) was suspensory desmitis including desmitis of the extensor branches, with four medalists amongst this group. The authors suggest that show jumpers can continue to compete successfully with good management despite chronic low-grade injury. Tendon and ligament injuries occurred more frequently in eventers due to the requirement for speed and jumping. Soft tissue lesions were present in 45/47 horses that were presented to the veterinary clinic, 10 horses had multiple affected sites, most commonly superficial digital flexor tendonitis and/or suspensory desmitis (proximal or branches), tenosynovitis, desmitis, core lesions and diffuse loss of echogenicity. Many did not complete due to retiring on course (n = 10), elimination on course (n = 3) or withdrawal before the third inspection (n = 6). However, 20 horses passed the veterinary inspections and completed the event, whilst adhering to the veterinary rules of the Fédération Equestre Internationale (FEI) (2011) with respect to non-pharmaceutical treatments (www.fei.org). Fourteen horses were presented for veterinary evaluation before the start of the competition, only one of these completed all three phases (proximal suspensory desmitis), five did not complete because of the existing injury at the time of arrival in Sydney or during training leading up to the Games. The remaining eight horses fell or were eliminated during competition for reasons other than a lesion.

A study in event horses training to compete in Concours Complète Internationale (CCI) showed that 21% did not start due to injury: 43% had soft tissue injuries, 33.3% involving the superficial digital flexor tendon and 30.6% involving the suspensory ligament (Singer et al., 2008). Of those competing in the CCI, the most common injuries included lacerations and abrasions to the carpus and stifle, superficial digital flexor tendonitis and exertional rhabdomyolysis. These injuries were significantly higher in CCI competitions than at one-day events, most likely due to the increase in demands of athletic performance.

Scott (2008) performed an extensive literature review summarizing the musculoskeletal injuries in non-racing Quarter Horses which included palmar foot pain, osteoarthritis of the proximal interphalangeal joints, pastern fractures, suspensory ligament desmitis, osteoarthritis of the distal tarsal joints, stifle injuries and back pain. The review presents the current literature on the diagnosis, treatment and rehabilitation strategies including concepts of injury predisposition and prevention. A retrospective study by Dabareiner et al. (2005a) identified types of musculoskeletal problems associated with lameness or poor performance in 118 horses used for barrel racing. The forelimbs were more frequently affected than the hind limbs, with forelimb foot pain and osteoarthritis of the distal tarsal joints being the most common abnormalities. Reasons for presentation were lameness (61%) or poor performance (39%). The most common performance change (41%) was refusal or failure to turn properly around the first barrel. Dabareiner et al. (2005b) also reported on 118 team roping horses presenting with lameness or poor performance. A significantly greater proportion (74/118) of horses used for ‘heading’ (roping the steer around the horns) presented for examination compared to (44/118) horses used for ‘heeling’ (roping around the hind limbs of the steer). Most horses examined for poor performance were lame, however, the biomechanical loading patterns influenced the type of lameness: ‘headers’ had more right forelimb lameness (35%) compared with ‘heelers’ (16%); ‘headers’ had a significantly greater proportion of bilateral forelimb lameness (24%) compared with ‘heelers’ (9%), but ‘heelers’ had more bilateral hind limb lameness (7%) compared to ‘headers’ (0%). The most common musculoskeletal problems for ‘headers’ were pain limited to the distal sesamoid (navicular) area, with or without osteoarthritis of the distal tarsal joints and soft tissue injury in the forelimb proximal phalangeal (pastern) region. The most common signs of pain in 'heelers' were in the navicular area, osteoarthritis of the metatarsophalangeal joints and osteoarthritis of the distal tarsal joints.

Veterinarians are more often consulted for the more complex lameness cases, with 25% of the cases diagnosed by a veterinarian being reported to receive alternative therapeutic methods (Knubben et al., 2008). Physiotherapists who work in racehorse training yards routinely treat horses' backs and hindquarters. It has been reported that racehorses presented for PT showing pelvic bony asymmetry, muscle atrophy of the hindquarters and/or spasm or tenderness on palpation of the gluteal muscles should alert the physiotherapist to the possibility of impending pelvic or hind limb fracture (Hesse & Verheyen, 2010).

Prevalence of neck and back pain

Equine back pain is a condition where PT and rehabilitation strategies are clinically useful and is an area of expanding research interest. As discussed in Chapter 10, back problems are associated with alterations of gait and performance (cause and/or effect). Improved diagnostic capabilities combined with increased clinical and research interest has raised awareness of the importance of equine back pain. Historically, Jeffcott (1980) reported the prevalence of equine back pain to be 0.9% in general veterinary practice, 2% in TB racehorse practice, 5% in a veterinary school referral practice, 13% in a mixed equine practice (dressage, show jumpers, eventing), and 47% in a spinal research clinic. These figures can be compared with a reported rate of 94% at an equine chiropractic clinic (Haussler, 1999a, 2000). Racehorse trainers in Sydney, Australia reported back problems to be in the top quartile ranked conditions (Bailey et al., 1997), and one of the most common injuries preventing training and racing. In a survey of registered dressage horse owners in the UK, 25% (644/2554) of the respondents indicated that their horse had a 'back problem' (Murray et al., 2010), though the majority (80%) had not been diagnosed by a veterinary surgeon. Of those that sought treatment (447/644) complementary therapy was the most common (63%) followed by saddle fit (24%); veterinary involvement (20%); rest (20%); a change in training (13%); and other (6%) (Murray et al., 2010). From the 25% of horses thought to have back pain, 2.5% received veterinary care alone and 3% received a combination of veterinary care and complimentary therapy, highlighting the need for a team approach to treatment and owner education. Interestingly horses reported to have a 'previous back problem' that was resolved by complimentary therapy or rest were more likely to have been lame in the last year. Historically Jeffcott (1979) reported that in 190 horses treated for chronic back problems 57% recovered completely, 17% showed no improvement and 38% had a recurrence or continuation of signs of low-grade back pain. This highlights the need for research into rehabilitation strategies and long-term management of chronic and recurrent back pain in horses.

Equine back pain often presents with more than one lesion or problem area including limb lameness. Osseous lesions of the thoracolumbar (TL) spine and the lumbopelvic complex are widely recognized as significant causes of equine back pain, poor performance, loss of performance, and altered back and limb kinematics (Jeffcott, 1975, 1980; Townsend et al., 1986; Denoix, 2005, 2007; Wennerstrand et al., 2004; Cousty et al., 2010; van Weeren et al., 2010). Such lesions may arise as primary injuries to the vertebral column and related structures, or secondary to other musculoskeletal injuries (Landman et al., 2004; Meehan et al., 2009; Girodroux et al., 2009). In a population of 805 horses (70% dressage, 20% show jumpers, 10% trotters) with orthopedic problems, 74% that were presented with a back problem were lame and 32% of those presented for lameness had a back problem (Landman et al., 2004). These percentages were significantly higher than those recorded in the same study for a control population of 399 horses, in which 20% were lame and 12% had back problems. Therefore there is a strong association between lameness and back problems. Even subtle hind limb lameness can cause changes in spinal kinematics at trot involving increased range of motion and hyperextension in the TL spine and reduced range of motion in the lumbosacral region (Gomez Alvarez et al., 2007a).

It is widely reported that the TL spine is predisposed to damage and/or pain (Wennerstrand et al., 2004). A retrospective study by Jeffcott (1980) reviewed 443 cases of equine back pain. The primary pathological lesions associated with TL pain were vertebral lesions (38.6%), soft tissue injuries (25%), sacroiliac strain (13%) and non-TL lesions (13%). Vertebral lesions were predominantly crowding and over-riding dorsal spinous processes (DSP), which were most common beneath the saddle from T12–T17 and were most prevalent in young adult to middle aged horses used for jumping or dressage and in Thoroughbreds (TB) with short backs. Soft tissue lesions were predominantly in the *longissimus dorsi* muscles and supraspinous ligament in the caudal withers and cranial lumbar regions. Specific causes of back pain that have now been identified include muscle strain (Jeffcott & Dalin, 1980; Piercy & Weller, 2009); ligamentous lesions (Jeffcott, 1980; Henson et al., 2007; Tomlinson et al., 2003); fractures of the TL and/or lumbo-pelvic complex (Sumner, 1948; Mason, 1971: Jeffcott & Whitwell 1976; Vaughan & Mason 1976; Haussler & Stover, 1998; Driver & Pilsworth, 2009); vertebral body osteophytes and spondylosis (Geres, 1978; Jeffcott, 1980; Haussler et al., 1999b; Meehan et al., 2009); osteoarthritis and ankylosis of the inter-transverse and or lateral inter-transverse joints (Mitchell, 1933; Stecher & Goss, 1961; Smythe, 1962; Haussler et al., 1999b); impingement of the DSPs (Roberts, 1968; Jeffcott & Hickman, 1975; von Salis & Huskamp, 1978; Walmsley et al., 2002; Cousty et al., 2010); sacroiliac disease (Rooney, 1977; Jeffcott, 1980; Jeffcott et al., 1985; Haussler et al., 1999b; Goff et al., 2008); degenerative intervertebral disc disease (Hansen, 1959; Rooney, 1970; Taylor et al., 1977; Townsend et al., 1986; Denoix, 2007); and osteoarthritis of the synovial intervertebral articulations (facet joints) (Jeffcott, 1980; Haussler et al., 1999b; Girodroux et al., 2009; Cousty et al., 2010; Stubbs et al., 2010). Historically, the most widely documented osseous lesion is impingement or over-riding of the DSPs (Jeffcott, 1980; Walmsley et al., 2002; Erichsen et al., 2004; Cousty et al., 2010). More recently, osteoarthritis of the facet joints has been identified as a source of pain and dysfunction (Denoix & Dyson, 2003; Girodroux et al., 2009; Stubbs et al., 2010). Nuclear scintigraphy showed moderate to intense increased radiopharmaceutical uptake in the facet joints of horses with pain in the region from T13–L1 compared with clinically normal horses (Gillen et al., 2009). However, only 61.5% of 67 horses with back pain associated with radiographic evidence of osteoarthritis had increased radiopharmaceutical uptake in one or more facet joints, highlighting the inherent difficulties, even with advanced technology, in localizing the cause of back pain and loss of function.

Haussler et al. (1999b) highlighted the potential under-diagnosis of TL vertebral or pelvic lesions in a post mortem study of 36 TB racehorses that were euthanized for reasons unrelated to back pain. An alarming rate of osseous lesions was reported in the caudal thoracic and lumbar regions. Degenerative changes were observed at lumbar intertransverse joints and sacroiliac articulations in all specimens, with variable degrees of degenerative changes of the TL articular processes in 97% of specimens. Impingement of the DSPs (92%) and transverse processes (97%) was very prevalent, with many specimens having widespread and severe osseous changes including stress fractures of the facet joints. The relationship between the changes observed at necropsy examination and the presence of pain or loss of function could not be established. Stubbs et al. (2010) reported osseous pathologies in a group of 22 TB racehorses euthanized at the Hong Kong Jockey Club for reasons unrelated to back pain. Osseous lesions were graded as mild, moderate or severe at vertebral levels from T9–Ca1 in a non-cumulative fashion. All horses exhibited lesions of moderate severity and 77% had evidence of severe (grade 3) osseous pathology at various sites in the TL spine and pelvis (Fig. 17.1).

Turner (2003) evaluated 5352 medical records from 1997 to 2002 at a veterinary teaching hospital and found the occurrence of true back problems to be 2.2% in the lameness caseload of mixed breeds and sporting disciplines. One hundred and twenty-four horses presented with the complaint of back pain with the diagnosis confirmed in 102 (82%) cases. An additional 16 horses that were presented for other problems were diagnosed with back problems. The most prevalent lesions involved the sacroiliac area (66). Other problems included kissing spinous processes, dorsal spinous ligament injuries, muscle pain, wither injuries, polysaccharide storage myopathy (PSSM) and saddle fit problems. Sixteen horses also had limb lameness. The treatment protocol included administration of systemic anti-inflammatories and/or a local anti-inflammatory injection and a variable combination of acupuncture, chiropractic techniques, massage therapy, electro-stimulation, magnetic therapy, therapeutic ultrasound, extracorporeal shockwave and training (exercise) management. Follow-up information was available on 112 horses with 90% returning to work; however, 15 of those horses did not return to their previous level and were retired or used for other activities. Of the 86 horses that returned to their previous level of work, 60% did not need further therapy but the remaining 40% continued to receive some form of therapy. The need for therapy was based on the owner's and trainer's

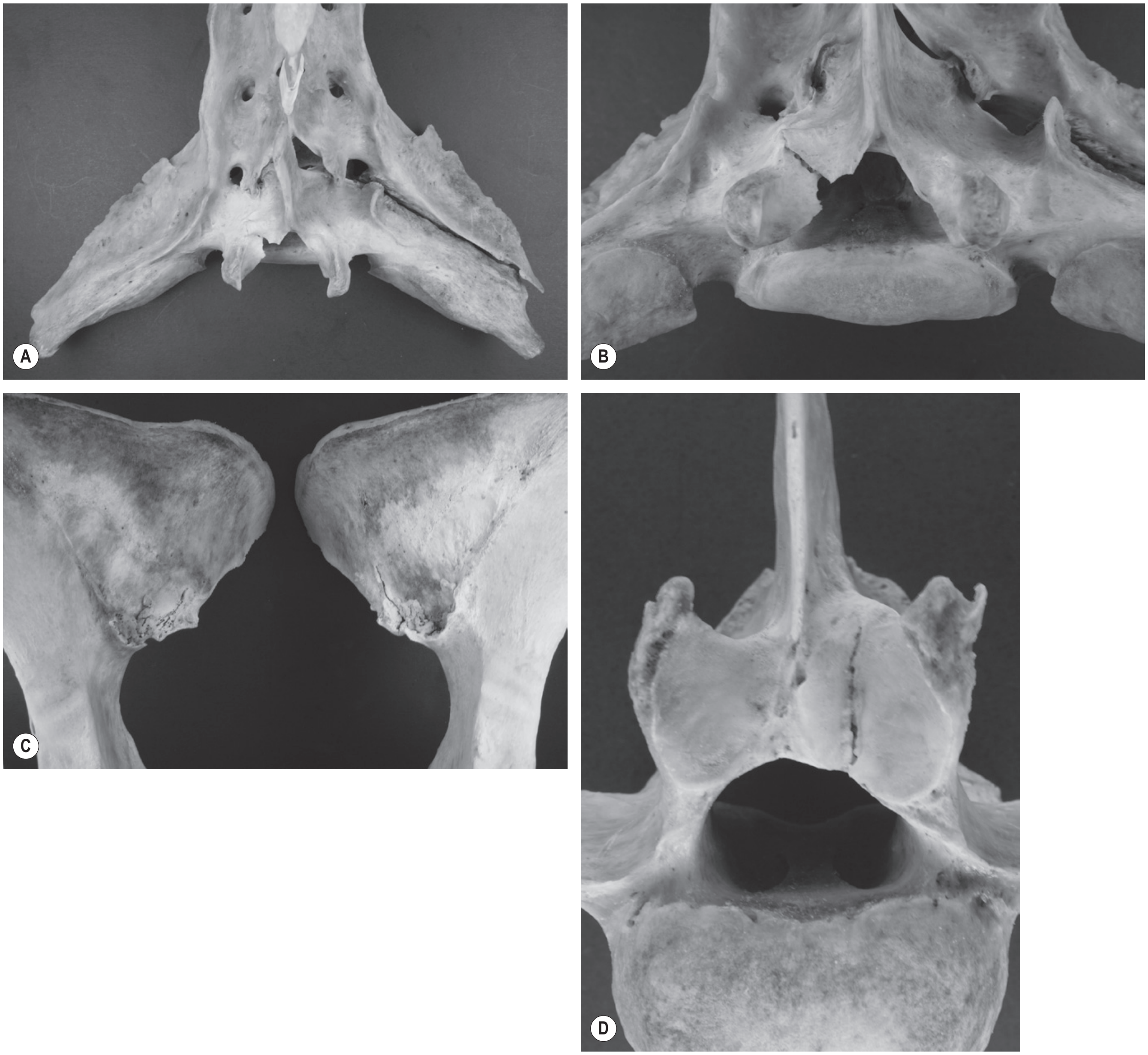


Fig 17.1 Severe osseous lesions and asymmetry in the lumbosacral/pelvic region in a Thoroughbred racehorse. (A) Sacral transitional that is ankylosed to the pelvis on the right side of the specimen (left side of photo). The biomechanical effects of unilateral ankylosis on the lumbosacral and sacroiliac biomechanics likely contributed to (B) a fracture with some displacement on the opposing sacral facet, lamina and articular pillar. (C) Severe sacroiliac degenerative joint disease, including marked new bone formation on the ventral ilial surface and bilateral fracture lines, and (D) an intra-articular facet joint fracture.

impression of the horse's behavior. The rate of successful return to previous level of work is much higher than reported by Jeffcott (1979), which may reflect advancements in veterinary diagnostics, medical management and the implementation of complementary therapies as part of the rehabilitation strategy.

There is a smaller body of literature describing the equine cervical spine, neck pain and pathology. Studies of cervical osseous pathologies have focused mainly on cervical vertebral compressive myelopathy (van Biervliet et al., 2006; Levine et al., 2007). Arthropathy of the cervical facet joints has been cited in the aetiology of reduced performance in the horse and has been reported to cause forelimb lameness (Ricardi & Dyson, 1993), stiffness in movement, neck muscle atrophy, and neck pain (Beck et al., 2002; Dyson, 2003). A recent examination of six cadaveric necks by Claridge et al. (2010) developed a three-dimensional model of the cervical facet joints based on radiographs and computed tomography (CT) images and used the model to determine that effusion within the articular facet joints of the cervical spine is unlikely to cause compression of the spinal cord, which is known to be associated with neurological manifestations (Ricardi & Dyson, 1993).

In vitro kinematic studies of the cervical spine have demonstrated that dorsoventral flexion and extension, axial rotation and lateral bending take place at each of the intervertebral joints with the largest ranges of motion in the upper (occiput to C2) and lower (C5–T1) joints (Clayton & Townsend, 1989a). There is a general reduction in overall cervical spinal mobility from foal to adulthood (Clayton & Townsend, 1989b). *In vivo* kinematics of the cervical spine have confirmed that most of the flexion–extension occurs at the poll and the base of the neck when the horse voluntarily performs dynamic mobilization exercises to end range of motion in cervical flexion (Clayton et al., 2010a) or in cervical lateral bending (Clayton, et al., 2012).

There have been few published anatomical descriptions of the facet joints in the equine cervical spine, particularly with reference to the prevalence, clinical signs and pathological features of degenerative changes. Ultrasonographic imaging of the equine cervical region provided a reference for normal appearance of cervical vertebrae, facet joints, and paravertebral structures in eight horses of unspecified breed, between the ages of 2 and 14 years (Berg et al., 2003). A retrospective study of radiographic images of 122 horses concluded that the size of the caudal cervical facet joint at the level of C5–C6 increases with age but it is not known whether there is an association between such changes and clinical symptoms or performance (Down & Henson, 2009). Claridge et al. (2010) described normal anatomical shape, spatial orientation and joint volume for the cervical facet joints in six subjects.

Little is known about cervical intervertebral disc disease in horses. The only study of the gross anatomy of the discs (Bullwein & Hannichen, 1989) involved evaluations of midline sections the cervical vertebrae without preparing histological sections. The authors saw no evidence of an annulus fibrosus or a nucleus pulposus and some discs showed disintegration of the tissue fibers. Cervical disc disease has been reported in horses, but is likely underreported since it poses a diagnostic challenge that may be solved by modern imaging equipment. Information on disc structure and common pathological changes will facilitate the interpretation of images of the discs. The joints in the mid neck (C3–C4, C4–C5 and C5–C6) undergo considerably less motion *in vivo* even when the neck is fully flexed or extended (Clayton et al., 2010a). It seems likely, therefore, that the equine cervical intervertebral discs will vary in thickness. Future CT imaging studies may provide information about the size and structure of the discs that cannot be obtained from standard radiographic or ultrasonographic imaging.

As discussed in Chapter 13, disorders and lesions affecting skeletal muscle and peripheral nerves are common in horses and adversely affect athletic ability (Cardinet & Holliday, 1979; Freestone & Carlson, 1991; Martin et al., 2000; Gregory, 2004). Frequently, muscular dysfunctions are secondary to underlying bone pathology in horses with back pain but may also be due to pathology of the muscles themselves or to a generalized muscular disorder (Valberg, 1999; Quiroz-Rothe et al., 2002). It is suggested that this is due to altered motor control as a result of the underlying lesion in the spine and/or due to peripheral joint disease with pain and inflammation which causes reflex inhibition of motor neurons resulting in weakness and atrophy of associated muscles (Young, 1993). Local muscle damage attributed to a poorly fitting saddle, for example, can also cause atrophy of the epaxial muscles (Gellman, 1998; Harman, 1999). Figure 17.2 visually shows three examples of asymmetrical hindquarter muscle development, or relative. The authors suggest objectively measuring muscle size using ultrasonography, which may be a reliable tool for comparative measures across time and during the rehabilitation process. Research is currently underway using this modality in the horse. Jeffcott (1980) surveyed 443 cases referred with TL disorders finding that 23.37% had evidence of epaxial muscle pain. Stubbs et al. (2010) reported that there was a relationship between muscle function and pathology via ultrasonographic and necropsy analysis where significant atrophy of the *multifidus* muscles was evident at the level and site/side of TL lesions in 22 racehorses.

Valentine (2008) investigated the pathological findings in equine muscle (excluding PSSM) in 229 equids (217 horses and eight ponies of multiple breeds, three donkeys and one mule) over a 2.5-year period through necropsy and histopathology. Muscle lesions were present in 65% with the most common findings being chronic myopathic changes (15%), generalized muscle atrophy (13%), denervation atrophy (6%), and other lesions and pathologies that occurred less frequently (<5%) including myonecrosis, bone fractures, bacterial infections, muscle rupture, selenium deficiency, exertional rhabdomyolysis, intramuscular protozoa, neoplasia, injection site reactions, lymphocytic infiltrates, ring fibers, fiber splitting, and fat infiltrations. The aetiology was undetermined in 4% of cases. Hunt et al. (2008) performed an epidemiological study of myopathies in Warmblood horses in which the most common was PSSM (72/132 horses), followed by RER (7/132), neurogenic or myogenic atrophy (7/132) and non-specific myopathic changes (14/132). Thirty-two biopsies were normal. Recently there have been significant advances in understanding the etiopathogenesis underlying these disorders including recognizing the similarities between human and equine muscle diseases (Piercy & Rivero, 2004). Myopathies often present as gait abnormalities or overt RER, with slow improvements in clinical signs through dietary management and a regulated exercise routine as part of their rehabilitation (Hunt et al., 2008).

Patho-anatomical diagnosis

Accurate patho-anatomical diagnosis of back pain is clinically challenging. It requires a lengthy clinical examination and multiple diagnostic procedures including radiography, ultrasonography, scintigraphy, local analgesia, kinematics and EMG imaging in the attempt to reach a diagnosis and increase the knowledge about the possible causes (Jeffcott, 1980; Steckel, 1992; Weaver et al., 1999; Denoix & Dyson, 2003; Peham et al., 2001; Peham & Schobesberger, 2006; Roethlisberger Holm et al., 2006; Gillen et al., 2009; Girodroux et al., 2009; Meehan et al., 2009; Fuglbjerg et al., 2010). Further, as previously stated, many horses have multiple osseous lesions that can be detected along the length of the vertebral column (Meehan et al., 2009; Girodroux et al., 2009; Gillen et al., 2009; Cousty et al., 2010; Stubbs et al., 2010). Post mortem studies have confirmed the presence of multiple types of osseous lesions at multiple sites; unfortunately these horses were unable to be examined ante-mortem to determine the relationship between the grades of lesions and pain and function (Townsend et al., 1986; Haussler & Stover, 1998; Haussler et al., 1999b). Thus it is

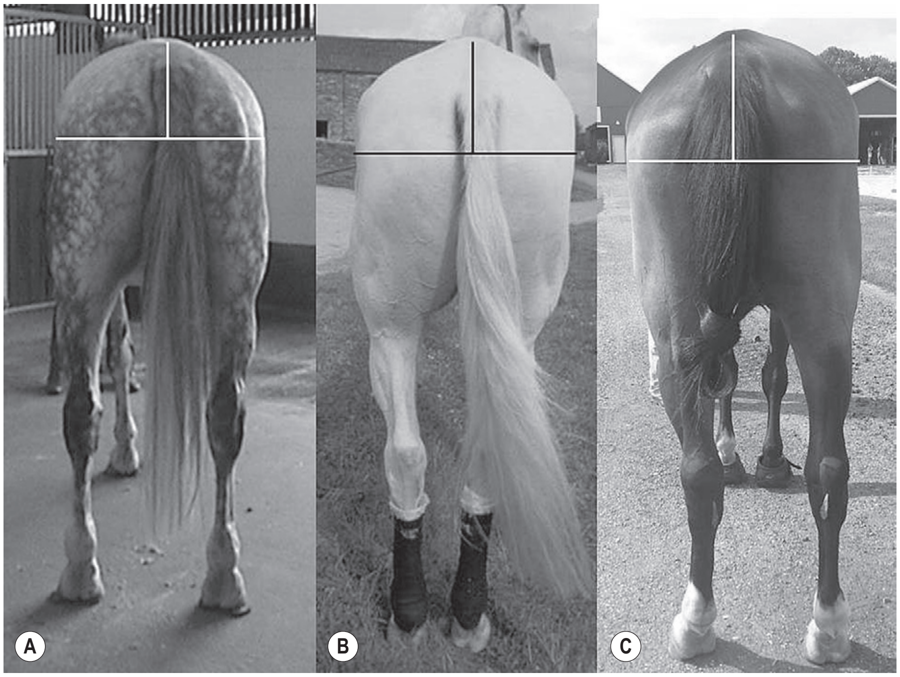


Fig 17.2 Three horses with asymmetrical hindquarter muscle development or relative atrophy on one side. (A) Right hemipelvis has markedly reduced muscle mass compared with the left, particularly biceps femoris and gluteus medius, secondary to degenerative joint disease of the right tarsus. (B) Right hemipelvis muscle mass moderately reduced compared to left in a successful international eventer with a history of limb lesions and degenerative pathology. (C) Gross generalized disuse and secondary muscle atrophy affecting primarily the left hind limb following luxation of the superficial digital flexor tendon off the calcaneus. The lines on the photographs facilitate a more objective assessment of asymmetry.

still difficult to determine the relationship between clinical signs, diagnostic findings (the grade/severity of the lesions) and level of pain, as this is very variable between individual performances and horses (Haussler et al., 1999b; Meehan et al., 2009). The clinical signs associated with a variety of osseous lesions of the vertebral column and pelvis are poorly described, often non-specific and difficult to validate objectively, with a decrease in performance being the main complaint of the rider/owner. Clinical diagnosis is further complicated by the fact that horses vary in their response to pain and it is believed that temperament also plays a role (Jeffcott, 1999).

Functional assessment

Clinical signs of back pain in horses include both behavioral and physical signs including altered sensitivity to palpation, which may be described as decreased mechanical nociceptive threshold (MNT); sinking when placing the saddle on the horse, when securing the girth ('girthiness') or when the rider mounts ('cold back'); resistance in work, for example, not wanting to trot, canter or rein back, refusing to jump or tail swishing; and/or lameness of one or more limbs without a cause or possible diagnosis (Martin & Klide, 1997; Haussler et al., 2006; Mills et al., 2007). Horses may express pain by fleeing or evasion; adopting an abnormal stance, gait or speed; vocalizing or showing signs of aggression during movement or manipulation; restlessness; swishing the tail; and muscle tension and tremors (Gregory, 2004; Mills et al., 2007). When back pain becomes chronic, muscular atrophy of the back can become visible (Fig. 17.2). Chronic pain, unlike acute pain, can be present without inflammation or noticeable tissue damage. Horses with chronic pain can be aggressive or evasive when they cannot react in their natural way by fleeing. This is why owners and/or riders sometimes believe their horse has a behavioral problem, as they are not able to identify the underlying painful process (Ridgway et al., 2005). In summary, the clinical signs often are unclear, so it is important to exclude other problems in order to arrive at a diagnosis of back pain. Microtrauma from chronic overuse because of poor saddle and tack fit (Harman, 1999), sub-optimal riding technique or an inappropriate training schedule can all predispose horses to back pain (Haussler, 2000).

Objective assessment of musculoskeletal pain in horses is challenging (Casey, 2002). Local tenderness is the major manifestation of most, if not all, musculoskeletal pain (Vanderweeën et al., 1996). Tenderness in the axial skeleton has traditionally been assessed by manual palpation, although the interpretation of its outcome is highly subjective (Haussler et al., 2007). Nonetheless, palpation plays an important role in the clinical examination of cases with suspected neck and back muscle sensitivity. Therefore, both equine veterinarians and physiotherapists have included palpation in their physical examination protocol (Ranner et al., 2002; Denoix & Pailloux, 2005; Cauvin, 1997). This is obviously particularly important for clinical decision-making and evaluation of therapeutic intervention (Ashley et al., 2005). Pathological findings of the vertebral column identified on radiographs often do not correlate with the clinical findings (Gundel et al., 1997; Ranner et al., 2002). Thus, Ranner et al. (2002) concluded that palpation remains one of the most important clinical examination methods to determine whether or not a horse is suffering from neck and back muscle sensitivity or pain. Pain in the TL region of a horse is very complex as it can originate from various pain receptor structures. Afferent nerve endings are found in various types of connective tissue including fascia around muscle bundles, muscle spindles, joint capsules, tendons and ligaments, blood vessel walls and bone. Some of these receptors are nociceptors (pain receptors) and respond to noxious stimuli, including mechanical, thermal or chemical stimulation. Muscle pain may range from very intense sharp localized pain in the acute setting (for example, a muscle tear), to chronic muscle pain, which may be dull and diffuse. Referred pain from abdominal or thoracic organs can project onto different parts of the body including the back (Gregory, 2004). Although very difficult to quantify in the horse neurogenic and or referred pain may also be present which is well documented in the human literature. Macgregor and von Schweinitz (2006) identified equine myofascial trigger points with similar objective signs and electrophysiological properties to those documented in human and rabbit skeletal muscle tissue. Unfortunately, referred pain patterns and reproduction of the pain profile cannot be determined in animals. Comparative pain characteristics between muscular and ligamentous saline injections have been investigated, as these methods are commonly used to induce human and animal back pain (Tsao et al., 2010). Interspinous ligament injections produced pain of greater intensity and duration compared to injecting the paraspinal muscles in the normal human lumbar spine. Interestingly muscle pain was reduced with contracting and stretching the injected muscle, but this did not affect the pain produced from the ligament injection. The authors were also surprised that many of the subjects (n = 10) pointed to a region of pain 1–2 segments away from the injection site (Tsao et al., 2010).

Pain works as a protective mechanism to prevent further tissue damage and to allow healing of wounds and damaged tissue. Pain cannot be objectively measured, because it has no units. Changes in heart rate, blood pressure, plasma cortisol and behavior can be helpful to identify and study pain (Ashley et al., 2005; Robertson, 2006). Examples of ways to subdivide pain are acute versus chronic, somatic versus visceral and physiological versus pathological, which occurs when the tissue is damaged and responds with inflammation (Robertson, 2002). In mammals, inflammation is the greatest source of pain (Gregory, 2004). During inflammation, the nerve endings that respond to noxious stimuli such as heat, pressure and chemical stimuli become sensitized. When normal, non-painful stimuli are applied to sensitized tissue, the patient experiences a painful sensation. In the human this is commonly referred to as 'allodynia' (Woolf & Mannion, 1999). Bussières et al. (2008) established the value of behavioral and physiological criteria by developing and validating a composite multifactorial pain scale (CPS) in an experimental equine model of acute orthopedic pain. Eighteen horses were allocated to control and experimental groups that received Amphotericin-B injection to induce pain in the tarsocrural joint and various forms of analgesia. Inter- and intra-observer reproducibility was good ($0.8 < K < 1$), with the key specific and sensitive behavioral indices being palpation of the painful area and the horse's posture. Other less valuable signs were pawing the floor, kicking the abdomen and head movement. There was a statistical correlation between the CPS and both non-invasive blood pressure ($p < 0.0001$) and blood cortisol ($p < 0.002$). Van Loon et al. (2010) recently investigated the reliability and clinical applicability of applying a CPS to objectively monitor somatic and visceral pain under hospital conditions in 94 horses (control, acute and chronic surgical and non-surgical groups). CPS showed low baseline values in healthy animals with non-painful conditions and these were not affected when general anesthesia was the only intervention. Inter-observer reliability was very high (n = 23 horses; weighted kappa correlation coefficient, $\kappa = 0.81$). Horses with painful conditions responding well to analgesic treatment could be discriminated from horses that had to be euthanized on humane grounds because of painful non-responsive conditions. It was concluded that the CPS is a promising tool to potentially provide a basis for direct day-to-day assessment of pain status in equine patients with various painful conditions in the future. The CPS may be a useful subjective tool as an adjunct to other subjective/objective measurements during the rehabilitation process.

Objective measurements

For evaluation of back function there are various diagnostic possibilities. Firstly, a thorough clinical evaluation is important, including a complete lameness examination, general and specific palpation to assess tissue irritability, gross and intersegmental movement evaluation, and specific provocation tests of the vertebral column, osseous structures and pelvic soft tissue. Additional techniques include radiography, ultrasonography, CT, magnetic resonance imaging (MRI), EMG, scintigraphy and kinematic analysis.

Kinematics

Kinematic measurements describe stride and step timing, stride and step lengths, and intervertebral joint motion and the symmetry in different gaits. It is a useful tool in evaluating the effectiveness of therapeutic interventions like chiropractic manipulation (Faber et al., 2003, Gomez Alvarez et al., 2008; Haussler et al., 2010). Johnston et al. (2004) performed a kinematic evaluation of the back in horses without a history of back problems in order to develop a database on kinematics. Older horses were shown to have decreased flexion and extension of the TL junction in trot. Kinematic analysis can be a useful tool to identify horses with back pain because the movement pattern of the back changes so that dorsoventral flexion and extension at T13 and T17 at walk and at T17 and L1 at trot are significantly reduced compared to horses without back pain but there is no difference in lateral bending between horses with and without back pain. During walk, horses with back pain have a decreased axial rotation of the pelvis. Decreased back motion can also be present due to pathological conditions (Wennerstrand et al., 2004; Gomez Alvarez et al., 2007a, b), with the most significant differences being visible in walk rather than trot. This is likely due to the fact that the trot inherently has less intervertebral motion than the walk. However, these studies were performed only on a treadmill and further investigation is warranted on a circle, on varying gradients and under saddle in a larger number of subjects with different types of back pain/pathology.

EMG

The 'normal' movement of the horse's back has been investigated via EMG in conjunction with comparisons of locomotor kinematics and kinetics. Many factors contribute to locomotion including the muscular system (*longissimus dorsi, iliocostalis, semitendinosus, biceps femoris, and gluteus medius*), acceleration from the hind legs, gravity and the influence of the rider (Licka et al., 2004, 2009; Peham & Schobesberger 2006; Wakeling et al., 2007; Zaneb et al., 2009). *Gluteus medius* is considered an epaxial muscle as it covers the majority of the dorsal lumbar spine, with attachments onto the thoracolumbar fascia and *iliocostalis* ventrally. The anatomical epaxial musculature of the lumbar spine is displayed in Figure 17.3.

EMG is becoming a widely accepted tool for the examination of muscle function in horses (Robert et al., 2000; Wakeling et al., 2007; Zsoldos et al., 2010; Groesel et al., 2010). The *longissimus dorsi* is medially located directly overlying *multifidus* (Stubbs et al., 2006). It runs from the transverse processes of the thoracic and lumbar vertebrae and the dorsal extremity of the ribs to the tuber sacralae and the ventro-medial aspect of the iliac crest (Haussler, 1999a; Stubbs et al., 2006). The *longissimus dorsi* muscle contributes to supporting the weight of the rider and saddle against dynamic forces (Licka et al., 2004). Bilateral contraction of the epaxial muscles produces extension of the spine and unilateral contraction produces lateral flexion and rotation (Haussler, 1999a; Denoix & Pailloux, 2005; Peham et al., 2001). At the walk, the back moves passively but at the trot, the back muscles are active to control back movements (Robert et al., 2001). Walk and trot are symmetrical gaits, and the movement of the back in these gaits is highly symmetrical (Jeffcott, 1979). Wakeling et al. (2007) found segmental variation in the activity and function of *longissimus* during walk and trot. Zaneb et al. (2009) investigated the quantitative differences of back and pelvic muscles during walk and trot between chronically lame and non-lame horses using surface EMG (SEMG). For each muscle

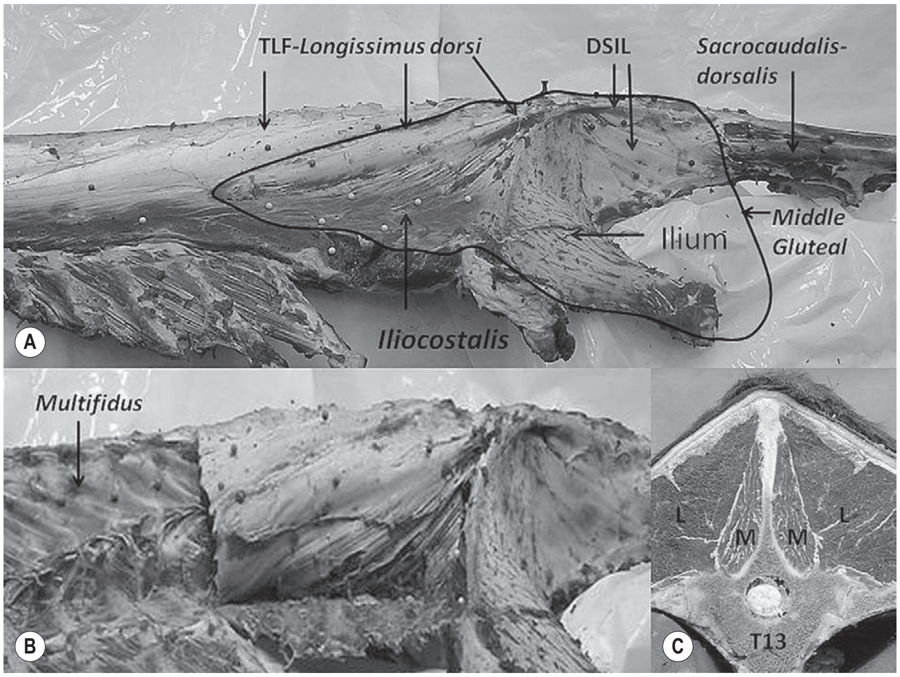


Fig 17.3 Lateral view of the dorsal thoracolumbar spine and pelvis. (A) Dissection of the caudal thoracic, lumbar and sacral outline of the middle gluteal muscle, which has been removed. Note that this muscle covers a large area of the lumbar region and attaches cranially at the level of the last rib which can be seen ventrally. Underneath the middle gluteal lies the thoracolumbar fascia (TLF), longissimus dorsi, and the more lateral iliocostalis. The dorsal and lateral parts of the dorsal sacroiliac ligament (DSIL) are labeled. Underneath the lateral DSIL are sacrocaudalis dorsalis medialis and lateralis, the latter having attachments to the caudal lumbar dorsal spinous processes. (B) Part of longissimus dorsi and iliocostalis have been removed to reveal the underlying multifidus, which has multiple fascicles originating from each spinous process that run caudally spanning 1–5 more caudal vertebrae. (C) Cross-sectional image at the level of the 13th thoracic vertebra showing the structure and location of multifidus (M) and longissimus dorsi (L) muscles. Note the fibrous content of multifidus.

(longissimus dorsi, semitendinosus, biceps femoris, gluteus medius, extensor digitorum longus) kinematics and SEMG data were recorded synchronously at walk and trot on a treadmill; mean, maximum, and minimum muscle activities and maximum-to-mean and minimum-to-mean activity ratios were calculated. For each horse (lame or non-lame) pelvic limb data were averaged; in lame horses, data were also examined separately (NL–L and L–L values, respectively). Comparisons were made between gaits. At walk the NL–L maximum-to-mean ratios for *biceps femoris* and *gluteus medius* muscles were significantly greater, and in lame horses, L–L and NL–L minimum-to-mean ratios for *semitendinosus, biceps femoris, gluteus medius*, and *longissimus dorsi* muscles were significantly less in NL horses. At trot minimum-to-mean ratios for *semitendinosus, gluteus medius* and *longissimus dorsi* muscles in lame horses were significantly lower than those for NL horses. Activity of *extensor digitorum longus* muscle was not affected by lameness. In chronically lame horses, back and pelvic limb muscle activities were affected differently during walking and trotting. SEMG has confirmed that motor control is altered in the lame horse, whereby the compensation strategy is an increase in muscle activity in the NL limb which may have major implications in the assessment and treatment of horses, especially those with chronic lameness and adaptive motor control patterns and/or secondary muscle atrophy.

By combining kinematics and EMG, the relationship between the muscle activity and back movement can be determined (Peham & Schobesberger, 2006). The maximal EMG activity of the back precedes the maximal vertical movement. It is theorized that at the end of stance and during the suspension phases of every stride cycle, the *longissimus dorsi* muscle provides lumbosacral extension and provides the propulsion force for the hind leg (Denoix & Pailloux, 2005). The highest muscle activity of *longissimus dorsi* both during passive flexion and extension of the back in stance and during trotting on a treadmill is at T12 (Peham et al., 2001; Licka et al., 2004).

It is only through needle/fine wire EMG that the electrical activity of the motor unit can be evaluated. In this way a possible pathological process can be detected and the difference between neurogenic and myogenic disorders can be made (Wijnberg et al., 2002). The advantages of SEMG compared to needle EMG are that it is less invasive and that measurements during movement are possible (Franssen, 1995). However, the clinical relevance of SEMG is still limited because of the great variation in measurement outcomes (Licka et al., 2004). In pathological conditions, muscle tension changes the relation of the minimal and maximal EMG activity independent of muscle mass, the conduction of the skin, the exact location of the electrodes, the EMG measuring device or its configuration (Licka et al., 2004), as well as the presence of the *cutaneous trunci* muscle directly attaching to the skin in the shoulder and thoracolumbar and abdominal regions. In people, back pain can be induced, by injecting hypertonic saline into the back muscles with recordings showing an increase in mean EMG signal compared to a control group. However there was no correlation between degree of pain and changes in the EMG signal (Arendt-Nielsen et al., 1995).

In the horse manual therapy has been proven to significantly alter/decrease muscle tone and total muscle activity measured by EMG (Wakeling et al., 2006), though the direct mechanism has yet to be established. In contrast, EMG measurements following acupuncture in healthy humans, showed no difference in muscle activity (Tough et al., 2006), although whether motor control may be altered by therapeutic intervention is debatable. A decrease in left-right asymmetry of the EMG signal was found after applying acupuncture to the paraspinal muscles in the human back (Tanaka et al., 1998). Further research, particularly using fine wire EMG with respect to rehabilitation techniques is definitely warranted.

Pressure algometry

Pressure algometry (PA) is a subjective and potentially objective diagnostic tool used in both human and equine research to assist in quantifying musculoskeletal pain relative to the tissues response (irritability) to mechanical pressure, whereby the mechanical nociceptive threshold is determined (MNT). It is used in research and clinical practice to evaluate treatment results in humans and horses (Fischer, 1998; Pöntinen, 1998; Haussler & Erb, 2003). Pressure is applied via the algometer probe with the investigator subjectively noting the tissue response (e.g. muscle fasciculation or spasms and/or behavioral avoidance reactions). The MNT is expressed in kg/cm^2 (Fig. 17.4). Pressure algometry has proved to be repeatable in humans and horses (Pöntinen, 1998; Ylinen 2007; Ohrbach & Gale, 1989a; Fischer, 1987; Varcoe-Cocks et al., 2006; Love et al., 2011), but its reliability depends on the device itself as well as the experience and technique of the examiner (Pöntinen, 1998; Nussbaum & Downes, 1998; Ohrbach & Gale, 1989a; Antonaci et al., 1998). There is still much debate amongst human and equine researchers with respect to whether this technique requires further validation utilizing other objective measures such as EMG. The human literature still classes PA as a subjective tool that should be combined with other pain scale measurements, such as the visual analogue scale, for clinical and experimental purposes (Ylinen, 2007; Ylinen et al., 2007).

Pressure algometry is a relatively new tool in equine medicine. Benefits include the non-invasive character of the method and the ease of use in horses (Haussler & Erb, 2003). Regional median MNT values were 9 kg/cm^2 in the cervical area, 12 kg/cm^2 in the thoracic area, 13 kg/cm^2 in the lumbar area and 16 kg/cm^2 in the pelvic area (Haussler & Erb, 2006a). MNT values were higher in non-TB horses, thus emphasizing the need to collect MNT values for horses of different breeds and performance levels.

When using PA, the pressure should be increased gradually at a constant rate and should stop when the horse shows a behavioral and/or tissue reaction that may reflect pain (Varcoe-Cocks et al.,

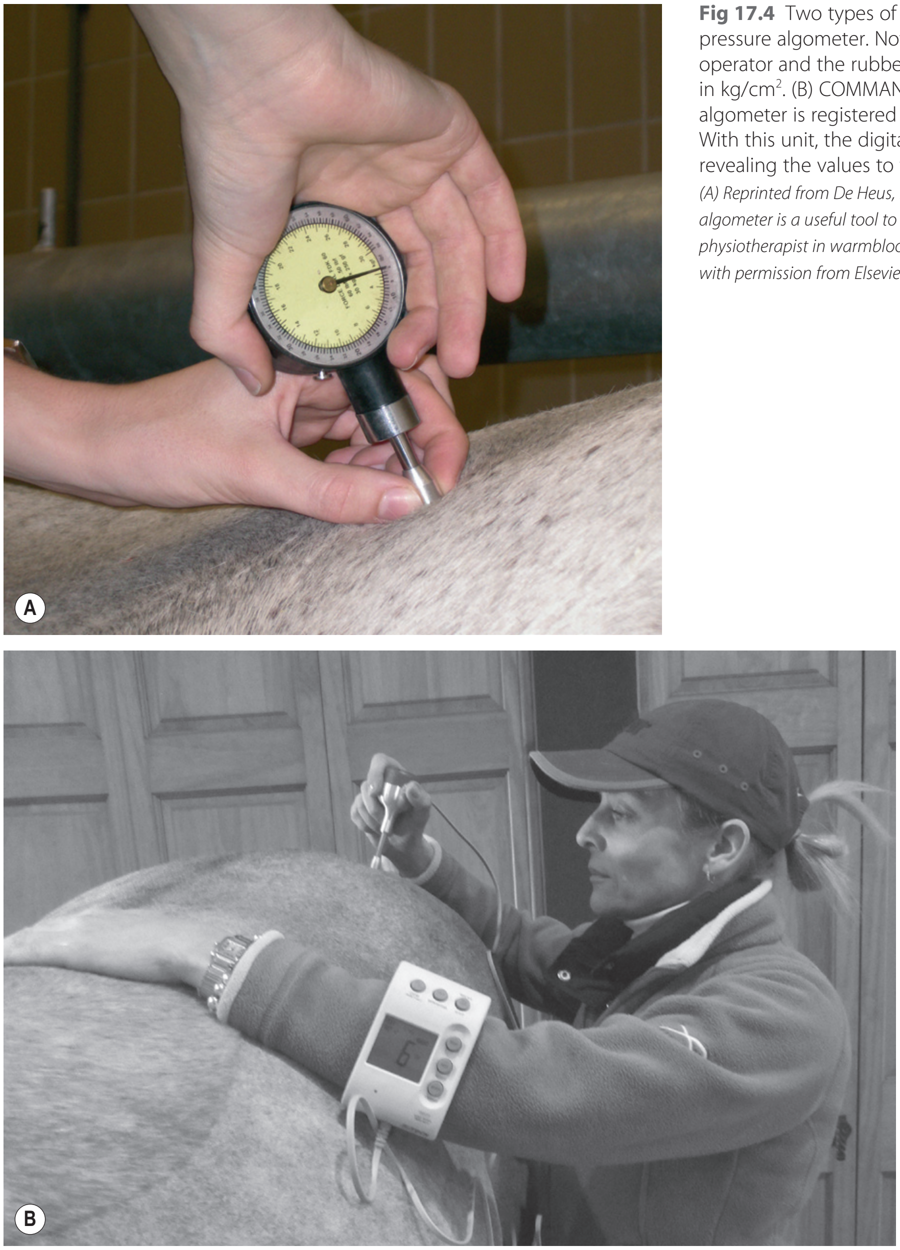


Fig 17.4 Two types of pressure algometers used in research. (A) FPK 60 pressure algometer. Note the position of the device in the hand of the operator and the rubber tip. The dial indicates pressure applied to the skin in kg/cm^2. (B) COMMANDER™ algometer. Pressure applied to the tip of the algometer is registered digitally on the unit worn on the operator's arm. With this unit, the digital readings can be stored and downloaded without revealing the values to the examiner.

(A) Reprinted from De Heus, P., Van Oossanen, G., Machteld, C. et al., 2010, A pressure algometer is a useful tool to objectively monitor the effect of diagnostic palpation by a physiotherapist in warmblood horses, Journal of Equine Veterinary Science 30 (6), 310–321, with permission from Elsevier (B) Courtesy of JTECH Medical, Salt Lake City, Utah, USA.

2006; De Heus et al., 2010; Love et al., 2011). This can be a twitching of the skin, ear movement, sinking, stepping aside, kicking or biting. The maximal applied pressure until a pain reaction occurs is recorded as the MNT for that site. When performed by an experienced investigator, PA may be a reliable and repeatable tool that correlates significantly with palpation score in horses. It may contribute to a clinical examination of the back and may be a useful adjunct subjective tool for evaluation of the effectiveness of therapeutic or analgesic interventions (Varcoe-Cocks et al., 2006; Haussler, 2006; Sullivan et al., 2008; De Heus et al., 2010). However, horses have been shown to develop a learned response in which they respond to a stimulus in anticipation of it becoming aversive. Regular sham testing may avoid this problem (Kamerling et al., 1985).

In humans, bruising was observed in some subjects after a 3-day PA study with a total of 18 measurements on one location (3 days, three trials/day by two examiners) (Nussbaum & Downes, 1998). In horses, bruising after repeated measurements has not yet been reported (Haussler & Erb, 2006a), but local bruising can be difficult to differentiate since dark skin coloration masks the presence of a hematoma. Different pain scales are commonly used in humans including visual analog scales to assess pain intensity, which can also be transferred to horses: the numeric rating scale (NRS) and the simple descriptive scale (SDS) (Holton et al., 1998; Williamson & Hoggart, 2005). For the NRS, the patient picks the number that best represents his or her pain. The SDS is usually a four-point scale with numbers attached to descriptive terms, such as 0 (no pain) to 3 (severe pain) (Holton et al., 1998; Williamson & Hoggart, 2005). The pain intensity scales were developed for self-reporting of pain in humans, something that is obviously impossible in veterinary medicine, thus an observer has to score the pain on behalf of the animal, relying on behavioral observations and sometimes physiological variables (i.e. heart rate, respiratory rate). The physiological variables are, however, not exclusively influenced by pain and are more useful in combination with behavioral responses (Pritchett et al., 2003). The pain behavior construct proposes that pain affects behavior in ways that are accessible to observers and that the magnitude of change correlates with the severity of the pain (Hansen 2003). As previously stated, scoring systems used in equine research to assess pain severity were designed to evaluate the effectiveness of an epidural block or to quantify postoperative pain in orthopedic surgery or colic (Pritchett et al., 2003). Ashley et al. (2005) concluded in a review that there is strong evidence that aggressive behavior emerges from pain.

Dyson and Murray (2003) reported clear behavioral responses to palpatory actions in horses with pain in the sacroiliac joint. Vertical forces or painful stimuli applied near the lumbosacral junction often induced maximal extension at the lumbosacral joint (Haussler et al., 2001). Wennerstrand et al. (2004) used palpation as an inclusion criterion for back pain in her research on back kinematics in horses with back pain. She reported the following adverse reactions to palpation commonly seen in horses with back pain: bolting or rearing, tail swishing, unruliness, rapid caudal movement of the ears, or stiff, jerky movements. The palpation scoring system of Varcoe-Cocks's et al. (2006) included many aspects of palpation (muscle tone, pain and stiffness) in a single scale. Wolf (2002) related muscle tone and pain through chronic irritation of muscles leading to permanent elevation in muscle tone, which continuously feeds back to reinforce the condition. This is the mechanism by which segmental dysfunction leads to muscle spasm. Wennerstrand et al. (2004) found that the clinical manifestation of back pain resulted in diminished flexion–extension movement at or near the TL junction. These examples again indicate that musculoskeletal pain, increased muscle tone and stiffness often concur, and seem to be related.

Research conducted by De Heus et al. (2010) is an example of subjective/objective evidence of the use of PA to evaluate the use and possible effect of (diagnostic) palpation applied by physiotherapists. This study tested inter-examiner repeatability of animal physiotherapists and tried to correlate subjective clinical scores of neck and back function in horses. Owners frequently believe that their horse has improved after the physiotherapist made a diagnosis, even though the actual treatment had not yet started. Therefore, it was hypothesized that PT diagnostic intervention in itself could have a therapeutic, objectively measurable effect that would increase the MNT of horses evaluated physiotherapeutically compared to the control group. Therapeutic effects were especially expected from stiffness testing, since this is also a spinal manipulative technique used as therapy by physiotherapists and there is some evidence that manipulative therapy is effective in horses (Haussler et al., 2007; Haussler et al., 2010). The effects of three consecutive diagnostic palpation examinations within 1 day on MNTs were measured, with three physiotherapists examining and grading the same horses, which made it possible to evaluate agreement between physiotherapists.

De Heus et al. (2010) studied six clinically sound Dutch Warmbloods. Since they were riding school horses, they were expected to have some neck or back pain that could lower the MNT and alter other palpation criteria, even though they did not have a current history of lameness or therapy. Horses were randomly assigned to an experimental (n = 3) or control (n = 3) group. The experimental group received diagnostic PT intervention between morning and evening PA measurements, the control group received only the two PA measurement sessions.

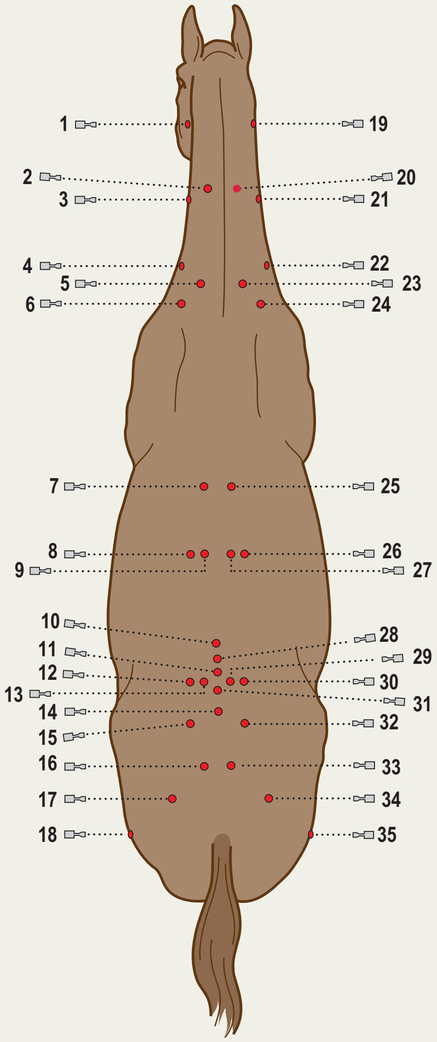
A non-electrical PA (FPK 60 Wagner Instruments Inc., Post Office Box 12.17, Greenwich, Connecticut, USA) was used (Fig. 17.4A), which has a force gauge with a 1 cm^2 rubber tip and a maximal reading of 30 kg. According to the certificate of calibration it has an accuracy of ± 2 graduations below 2.5 kg and an accuracy of ± 1 graduation above 2.5 kg. Since there is a learning curve associated with the use of a PA (Nussbaum & Downes, 1998; Ohrbach & Gale, 1989a,b; Antonaci et al., 1998), operators learned to increase pressure at a constant rate (force/time) and to recognize pain behavioral reactions of horses in response to the pressure algometer. The authors suggested practicing exerting a constant force over time using a pressure mat (RsScan Flexible Solutions System, RSscan INTERNATIONAL, Lammerdries 27 B-2250 Olen, Belgium), which is designed for measurement of intra-articular pressure in the equine fetlock joint. Secondly, the operators practiced PA on horses under the supervision of an equine behaviorist. MNT measurements should be made in a quiet room, with both the room and the technique being familiar to the horses to avoid a conditioned fear response that could interfere with the reaction to a painful stimulus through opiate release (Fanselow et al., 1989).

Pressure algometer measurements were performed with the neck straight holding the PA in one hand and stabilizing the neck on the contralateral side with the other hand. The plunger tip of the PA was held between thumb and forefinger (Fig. 17.4A), to avoid accidental shifting of the tip (Haussler & Erb, 2006a). Pressure was applied perpendicular to the surface and increased at a constant value of 10 kg/cm^2, which was similar to that used by Haussler & Erb, (2006a). The pressure stimulus was applied until a behavioral avoidance reaction was evoked (muscle fasciculations, *cutaneous trunci* reflex, active vertebral movement or stepping away (Haussler & Erb, 2003)). The presence of the 'pain face', which is recognized as a fixed stare, with the eyes puckered slightly, the ears held back slightly, and the nostrils dilated (Fraser, 1969), was observed and reported. When an avoidance reaction was observed, the pressure was immediately stopped and the value recorded was considered to be the MNT value. To increase reliability, measurements were repeated in three successive trials at one site (Nussbaum & Downes, 1998). Measurements were performed blinded: the PA was passed to a third party to record the result.

The 35 anatomical locations were adopted from Haussler & Erb (2006a) and Varcoe-Cocks et al. (2006) (Table 17.1). The anatomical measurement sites were marked because identification of

Table 17.1 Anatomical locations for pressure algometry measurements

Abbreviation	Anatomical location
Bony landmark (four bilateral sites)	
1, 19	Caudoventral aspect of the wing of the atlas
3, 21	Dorsolateral aspect of the caudal portion of the 3rd cervical transverse process
4, 22	Dorsolateral aspect of the caudal portion of the 5th cervical transverse process
16, 33	Dorsal aspect of the sacral tuber
Supraspinal ligament landmark (five sites)	
10	Between 15th and 16th thoracic spinous process
28	Between 17th and 18th thoracic spinous process
11	Between 18th thoracic and 1st lumbar spinous process
31	Between 1st and 2nd lumbar spinous process
14	Between 2nd and 3rd lumbar spinous process
Muscle landmark (11 bilateral sites)	
2, 20	Middle of the splenius muscle at the 3rd cervical vertebral level
5, 23	Dorsal portion of the cervical serratus ventralis muscle at the 6th cervical vertebral level
6, 24	Brachiocephalicus muscle at the base of the neck, at the level of C7
7, 25	Dorsolateral aspect of the thoracic spinalis muscle at the 9th thoracic spinous process
9, 27	Thoracic longissimus muscle at the 13th thoracic vertebral level, 2 cm lateral to the dorsal midline
8, 26	Mid-portion of the thoracic longissimus muscle at the 13th thoracic vertebral level, 10 cm lateral to the dorsal midline
12, 30	Thoracic longissimus muscle at the 18th thoracic vertebral level, 2 cm lateral to the dorsal midline
13, 29	Mid-portion of the thoracic longissimus muscle at the 18th thoracic vertebral level, 10 cm lateral to the dorsal midline
15, 32	Mid portion of the middle gluteal muscle at the 3rd lumber vertebral level, 10 cm lateral to the dorsal midline
17, 34	Mid point between the cranial aspect of the tuber sacrale and tuber coxae (middle gluteal muscle)
18, 35	20 cm dorsal to the greater trochanter, over the vertebral head of the biceps femoris muscle



anatomical landmarks is subject to wide variation (Weller et al., 2006). Measurements started on the left of the withers moving caudally, then continued at the poll and neck. They were repeated in the same order on the right side. All three physiotherapists/examiners graded four elements of neck and back dysfunction ('temperature', 'pain', 'muscle tone', and 'mobility') in the experimental group (n = 3) between the MNT measurements using a scoring system specifically developed for this study. The elements were scored according to a grading system. Temperature was scored: 0, cold; 1, normal temperature; 2, mildly increased temperature; 3, moderately increased temperature; 4, severely increased temperature. Pain was scored as: 0, pain free; 1, mildly painful; 2, moderately painful; 3, moderately increased pain; 4, severely painful. Muscle tone was scored as: 0, hypotonicity; 1, normal tone; 2, mildly increased muscle tone; 3, moderately increased muscle tone; 4, hypertonicity. Mobility was scored as: 0, hypermobility; 1, normal mobility; 2, slight decrease in expected range of motion; 3, moderate decrease in expected range of motion; 4, stiff and rigid, no range of motion. For further description of the scoring system see De Heus et al. (2010). A mean physioscore was calculated from the scores of the three individual physiotherapists.

Local assessment of back or neck dysfunction at and adjacent to the MNT measurement was recorded, since stiffness and increased muscle tone can be manifestations of back pain and they are included in the scales modeled as an SDS (Holton et al., 1998; Williamson & Hoggart, 2005).

Both the MNT measurements and the physiotherapeutic diagnostic intervention were well accepted by the horses. The three successive pressure algometer measurements did not differ significantly from each other, and there were no significant differences between left and right sides, which were pooled for analysis, or at the same site over time. There were significant differences in MNT values at different sites and between morning and evening values at the same site (Tables 17.2 and 17.3). Median MNT values increased from cranial to caudal in both the morning and the evening (Tables 17.2 and 17.3). MNT values of muscle were significantly higher than those for the supraspinous ligament and bone. There were significant differences ($p < 0.05$), in scores between the three physiotherapists for 'temperature', 'muscle tone' and 'mobility' but not for 'pain'.

This study showed that the palpation findings of individual physiotherapists were correlated with the objective MNT measurements Horses that received scores indicative of being more sensitive (higher scores for pain, temperature, and muscle tone) had lower MNT values. On the contrary, there was a positive correlation between the subjective 'mobility' score and the objective PA measurements, illustrating that the more rigid vertebral columns will show higher MNT values. Inter-horse differences in MNT reflected differences in individual sensitivity. The lower MNT values of horses in the evening may have been due to sensitization of the measurement location, a learning effect of the horses or a diurnal fluctuation. Haussler & Erb, (2003) found that the majority of horses did not demonstrate accommodation or sensitization to serial pressure algometry measurements. Sullivan et al. (2008) reported 20% sequential increase, 13% sequential decrease and 67% no change or consistent pattern, similar to De Heus et al. (2010). Pain threshold shows diurnal variation in humans (Göbel & Cordes, 1990; Procacci, 1993) but different pathological conditions vary in the time of day when pain is more severe. Circadian rhythms of pain could be related to the time-dependent variation in endogenous opiod peptides, which are higher in the morning and lower in the evening in man (Labracque & Vanier, 2003). Hamra et al. (1993) found a strong positive correlation between the equine plasma immunoreactive β-endorphin and nociceptive threshold, both peaking in the morning at 09.00 hours and again less high at 15.00 hours, which corresponds with the significantly higher MNTs in the morning measurements.

In humans as well as in horses the MNT between individuals varied more than that within one individual (Haussler & Erb, 2006a; Ylinen et al., 2007; Pöntinen, 1998; Vanderweeën et al. (1996), which was confirmed in this study. Haussler and Erb (2003), noticed that the individual MNT measurements varied greatly between horses, but were very consistent within horses.

Table 17.2 MNT recorded in the morning (mean ± SD) from a group of riding school horses (**Heus et al., 2010**)

Site	Left	Middle	Right	Site
Cervical				
1	4.9 ± 1.6		3.7 ± 1.7	19
2	6.0 ± 2.6		4.8 ± 1.9	20
3	5.2 ± 1.9		4.8 ± 1.9	21
4	5.5 ± 1.6		5.5 ± 0.9	22
5	7.2 ± 1.2		6.8 ± 1.2	23
6	5.8 ± 2.6		5.8 ± 1.8	24
Thoracic				
7	7.3 ± 1.8		6.6 ± 1.3	25
8	6.7 ± 1.7		7.5 ± 0.9	26
9	6.8 ± 1.2		6.6 ± 1.1	27
10		8.1 ± 2.4		10
28		7.3 ± 2.2		28
11		6.7 ± 1.0		11
12	6.9 ± 1.7		8.8 ± 1.5	30
13	6.6 ± 2.1		8.0 ± 1.7	29
Lumbar				
31		7.3 ± 1.4		31
14		7.6 ± 1.6		14
15	8.2 ± 1.6		9.3 ± 1.8	32
Pelvis				
16	9.7 ± 2.5		11.0 ± 2.4	33
17	9.7 ± 2.7		10.2 ± 2.5	34
18	13.3 ± 2.8		12.7 ± 1.4	35

Table 17.3 MNT recorded in the evening (mean ± SD) from a group of riding school horses (**Heus et al., 2010**)

Site	Left	Middle	Right	Site
Cervical				
1	4.5 ± 0.9		3.8 ± 1.2	19
2	5.1 ± 1.3		4.6 ± 0.5	20
3	4.5 ± 2.5		4.7 ± 1.7	21
4	4.7 ± 1.7		5.7 ± 1.4	22
5	7.7 ± 3.3		6.4 ± 0.8	23
6	4.5 ± 1.4		5.7 ± 1.3	24
Thoracic				
7	6.3 ± 1.4		6.6 ± 0.9	25
8	6.1 ± 1.6		6.7 ± 1.4	26
9	6.4 ± 0.8		6.5 ± 1.3	27
10		5.8 ± 1.7		10
28		5.9 ± 0.9		28
11		6.6 ± 1.6		11
12	7.7 ± 1.8		7.9 ± 1.5	30
13	7.4 ± 1.7		7.5 ± 0.9	29
Lumbar				
31		6.7 ± 2.4		31
14		7.4 ± 1.9		14
15	8.5 ± 2.5		8.8 ± 1.4	32
Pelvis				
16	9.9 ± 2.5		9.7 ± 3.3	33
17	8.9 ± 2.9		9.3 ± 1.5	34
18	11.7 ± 2.7		11.4 ± 2.9	35

Reprinted from Clayton, H.M., Lavagnino, M., Kaiser, L.J. and Stubbs, N.C. (2011b) Hind limb flexion response to different types of tactile devices, with permission from the American Journal of Veterinary Research, http://avmajournals.avma.org/loi/ajvr

Pöntinen, (1998) argued therefore that it would be impossible to determine absolute reference values, since the variation between individuals is too large. Therefore, relative values are considered to be more specific and more sensitive. Interpretation of the measurements at the cervical points were disputable in the study of De Heus et al. (2010) because some horses started head shaking before pressure was applied, possibly in anticipation of experiencing pressure that they found aversive. Since right-left MNTs are not significantly different (Haussler & Erb, 2006a; De Heus et al., 2010), the contralateral side can be used to compare MNT values in case of unilateral pathology.

In conclusion, a PA can be a useful tool to objectively monitor the palpation of individual physiotherapists. It has proven difficult to maintain a constant rate of pressure leading to repeatable results. Introduction and implementation of a more detailed protocol describing the procedure for diagnostic examination by palpation of the neck and back area, describing for example hand movement and aimed-for hand pressure, could aid in achieving a more uniform scoring outcome. This is not standardized yet in physiotherapeutic and veterinary diagnostic palpation protocols. The effects of physiotherapeutic diagnostic palpation in relation to MNT must be taken into account when applying the PA to assess the effects of physiotherapeutic intervention in rehabilitation programs. Pressure algometry may be useful for quantifying clinical neck and back muscle sensitivity in horses possibly leading to dysfunction, as well as for evaluating treatment outcomes. Repeated measurements on the same day and at the same location along the vertebral column may influence absolute MNT values. It is important that the operator is trained in use of the PA.

Ultrasonography

In the field of human physiotherapeutic rehabilitation, ultrasonography (US) has emerged as an invaluable tool for objective functional assessment and management of neck, low back and pelvic girdle pain and dysfunction in relation to muscle function and motor control (see section XVIII.3.2: Motor control) (Jull & Richardson, 2000; Pietrek et al., 2000; Richardson et al., 2002; Whittaker et al., 2007; Hodges & Cholewicki, 2007). Ultrasonographic measurement of *multifidus* CSA and function has proven to be a reliable, objective guide in the assessment, management and prevention of recurrence of back pain in man (Hides et al., 2008). Comparison of measurements of muscle size (cross sectional area, CSA) from the left and right sides at a given vertebral level provide a method of direct assessment of muscle function by indicating whether the muscle is of normal size, atrophied, or hypertrophied. This is a functional assessment that can be used to monitor the effectiveness of treatment over time in rehabilitation (Rantanen et al., 1993; Stokes et al., 2005; Whittaker et al., 2007). Ultrasonography is used extensively in equine veterinary practice and many practitioners already have an ultrasound machine, thus the use of ultrasound measurements has practical value in equine rehabilitation (Stubbs et al., 2010).

Historically in veterinary medicine, US has been widely used to diagnose and monitor tendon and ligament lesions in the distal limbs, with more recent clinical applications being recognized in the vertebral column and pelvis (Tomlinson et al., 2001; 2003; Kersten & Edinger, 2004; Mattoon et al., 2004; Denoix & Dyson, 2003; McGowan et al., 2007c; Stubbs et al., 2010; 2011). In comparison to other modern diagnostic and biomechanical technology, US is relatively inexpensive, non-invasive, easy to use, and allows rapid analysis by an experienced practitioner. For clinical and research purposes both objective and subjective scales of measurement are used (Reef et al., 1998; Genovese et al., 1997; Pickersgill et al., 2001). These involve comparison of contralateral tissues and determination of echogenicity using gray-scale analysis and predetermined ordinal scales (Martinoli et al., 1993; Gillis et al., 1993; Tsukiyama et al., 2005).

Ultrasonography provides an immediate image of structures beneath the probe enabling the practitioner to determine soft tissue sizes, particularly ligamentous and muscle CSA and linear measurements (Stokes & Young, 1986; Pickersgill et al., 2001). It also allows real-time acquisition of muscle activity, whereby the practitioner can visually observe and measure changes in muscle shape during both concentric and eccentric volitional activation in comparison to the relaxed state (Kidd et al., 2002; Hodges et al., 2003b; McMeeken et al., 2004). In people, changes in muscle thickness as measured by ultrasound have been shown to be highly correlated to EMG activity of the lumbar *multifidus* in asymptomatic subjects (Kiesel et al., 2006). McMeeken et al. (2004) also found that changes in thickness of *transversus abdominus* are indicative of electrical activity of the muscle. The use of US in this manner has been extensively described in the human literature, including reliability and normative data, particularly with respect to back pain and rehabilitation (Hides et al., 1998; 2001: 2008; Ferreira et al., 2004; Hodges, 2005; Koppenhaver et al., 2009).

Despite US being an essential imaging modality in the assessment and rehabilitation of the equine musculoskeletal system, data on its accuracy and reproducibility in veterinary medicine are extremely limited. Research in equine biomechanics and PT interventions is using both functional objective measures including US and the human motor control model to investigate various equine problems including TL-pelvic pain including sacroiliac joint biomechanics (Degueurce et al., 2004, Goff et al. 2006) and equine back pain (Denoix, 1999, Stubbs et al., 2006; Stubbs et al., 2010a; 2011; Clayton et al., 2010). Data describing repeatability and validity of US in the horse are limited to the tendon and epaxial musculature (Pickersgill et al., 2001; van Schie et al., 1999, 2000; McGowan et al., 2007c; Stubbs et al., 2010). Pickersgill et al. (2001) performed a quantitative investigation of the reliability of US analysis of the morphometric properties of the equine SDF tendon. The effects of three variables on tendon CSA measurements were determined by comparing two skilled operators acquiring US images and measuring CSA values in 16 National Hunt TB racehorses. Variables analyzed included inter-operator reliability during image acquisition and CSA measurement, and intra-operator reliability when using different analytical equipment from previously stored images. There was no statistically significant difference in the inter-operator image acquisition ($p > 0.05$) but inter-operator image analysis showed a significant difference ($p < 0.01$) with one operator consistently returning larger measurements. The use of different equipment within one operator was not reliable in the distal metacarpal region. It was concluded that consistency of image acquisition across skilled ultrasonographers was good but the images should be evaluated by a single-skilled operator.

Van Schie et al. (1999) used first-order gray-level statistics of US images in an *in vitro* study to quantify the effects of some instrumental variables on the evaluation of equine SDF tendons to compare normal tendon tissue, an acute lesion, or a chronic scar. Results showed considerable effects on the gray levels of the US image with slight variations in scanner settings and transducer handling. Tilting the transducer had substantial effects on mean gray levels, especially in acute lesions (40%) and, to a lesser extent, in normal tendon tissue (18%) and chronic scar tissue (12%). Displacement of the transducer causes relatively small changes in normal tendon tissue, but changes the mean gray-level by 7% in chronic scar tissue and 20% in an acute lesion. The US image is also substantially influenced by the total amplifier gain output: a low gain setting in an acute lesion results in an almost completely black image and, conversely, a marked 'filling in' effect on the lesion occurs with higher gain settings. Therefore, the value of exclusively using a quantitative evaluation method on the first-order gray-level statistics may not discriminate accurately enough to assess the integrity of tendon during rehabilitation. A further study that quantified the transverse US image by use of first-order gray-level statistics concluded that the method was not sufficiently sensitive to accurately and unequivocally determine the type of tendon tissue (van Schie et al., 2000). Therefore, quantitative analysis should incorporate both transverse and longitudinal information. These studies highlight the need for standardized techniques and instrumentation for image acquisitions over the period of rehabilitation.

In human medicine and rehabilitation, reliability data and clinical rehabilitative applications are more accessible, and US is widely used for functional muscle diagnosis, real time analysis during treatment, and as an objective measure of motor control enabling the practitioner to monitor rehabilitation and performance (Hides et al., 1992; 1994, 1995; Kidd et al., 2002; Hodges et al., 2003b; McMeeken et al., 2004; Whittaker, 2007). The methodology and intra-operator reliability for the use of ultrasound imaging to measure skeletal muscle has been described for the following muscles: *anterior tibial; quadriceps; transversus abdominis; multifidus; rectus abdominis; internal and external obliques; erector spinae; splenius capitis, semispinalis capitis; masseter; iliopsoas*; muscles of the pelvic floor; and the diaphragm (Hides et al., 1992; Martinson & Stokes, 1991; Stokes & Young, 1986; Kelly & Stokes, 1993; Blaney et al., 1999; Norasteh et al., 2007; Ferreira et al., 2004; Watanabe et al., 2004; Raadsheer et al., 1994; Barker et al 2004; Rezasoltani et al., 1998a,1998b; Pressler et al., 2006; Wallwork et al., 2007; Lee et al., 2007; Delaney et al., 2010).

In the horse, McGowan et al. (2007c) determined the reliability of US measurements of CSA of *multifidus mm, longissimus dorsi mm*, and *sacrocaudalis dorsalis mm* complex. These studies determine intra-operator reliability of repeated measurements of muscle CSA, using magnetic resonance imaging (MRI) as the gold standard for comparison. MRI images were taken in 1 cm axial slices from T11 to the tail. Measurements of CSA were repeated three times using the standard Bruker analysis package on each image of the *multifidus* muscle at four vertebral regions (T13/14, T18/L1, L3/4, L5/6) and the *sacrocaudalis dorsalis* muscle complex at the S3 (Figs 17.3 & 17.5). Digital photography was used to record the CSA in the same spinal segments that were cut in cross-section after freezing. Anatomical dissection verified the anatomical relationship of *multifidus, longissimus dorsi* and *sacrocaudalis dorsalis* muscles and comparisons were made with MRI (Fig. 17.5). Median coefficient of variation (CV) for all individual MRI readings was 1.7%, showing good intra-operator reliability of measurement of *multifidus* CSA using MRI. The pooled SD for all readings was calculated to be 0.22 cm^2 with 95% confidence interval ± 0.43 cm.

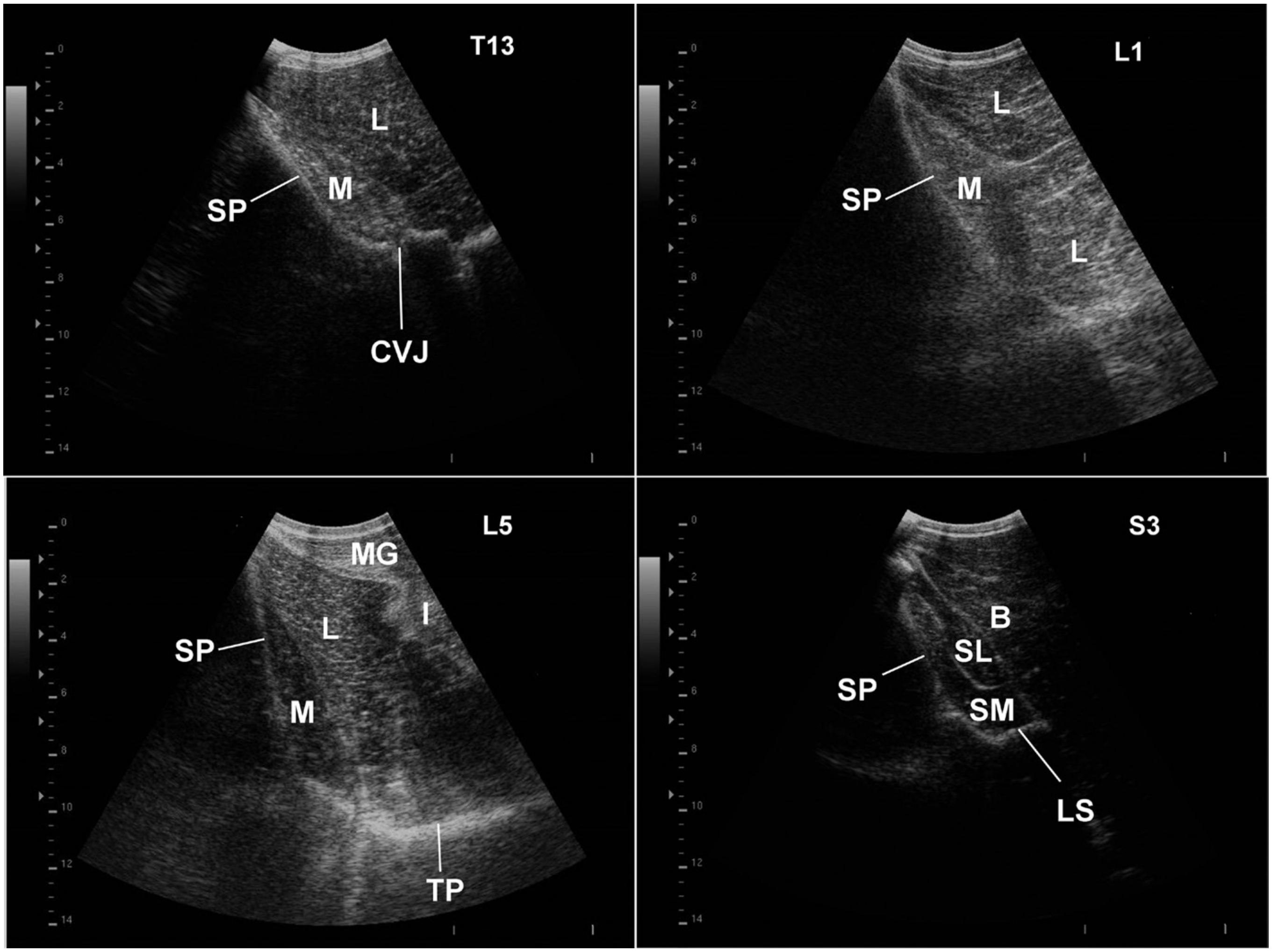


Fig 17.5 Ultrasonographic images of multifidus (M), sacrocaudalis dorsalis medialis (SM) and sacrocaudalis dorsalis lateralis (SL) muscles at the levels of the 13th thoracic vertebra (T13) (top left), the 1st lumbar vertebra (L1) (top right), the 5th lumbar vertebra (L5) (bottom left), and the 3rd sacral vertebra (S3) (bottom right). The vertebral spinous process (SP) forms the medial border of these muscles. Longissimus dorsi (L) lies on the lateral side in the thoracolumbar region and biceps femoris (B) is on the lateral side at S3. The ventral border at T13 is the costovertebral joint (CVJ), at L5 is the transverse process (TP) and at S3 is the lateral sacral crest (LS). The gluteus medius (MG) and iliocostalis (I) muscles are also shown.

Reprinted from Stubbs, N.C., Clayton H.M., Hodges P.W., Jeffcott, L.B. and McGowan C.M. (2010) Osseous spinal pathology and epaxial muscle ultrasonography in Thoroughbred racehorses. Equine Vet. J. 42 (Suppl. 38), 654–661, with permission from the Equine Veterinary Journal.

McGowan et al. (2007c) further investigated the reliability of measuring *multifidus* CSA using a 4–7 MHz curved linear probe at a depth of 15 cm. Two skilled examiners independently collected three images at each site. CSA measurements were analyzed blindly on three occasions by both examiners using Image J software. Data were analyzed for overall intra- and inter-operator reliability at each level, and measurements of left and right sides in the same horse were compared. Images taken over the intervertebral space at all levels were most repeatable, with greater variability over the facet joints possibly due to differences in facet size and/or shape. Reliability for *multifidus* CSA was good: Interclass coefficient (ICC) was 0.83; standard error of the measurement (SEM) was 0.78 cm; and the smallest detectable difference was 1.5 cm across all levels. The relative variance components of measurement of CSA were 56% inter-operator variance, 11% intra-operator variance and 33% image variance. Hence the variance was minimized by having just one operator and taking several images of each site. Comparing repeatability of US measurement of CSA with the gold standard of MRI, the pooled SD was 0.4 cm^2, almost double, but still within acceptable limits. *Longissimus dorsi* CSA could be measured in the lumbosacral region (L5), just cranial to the tuber sacrale, where it narrows down sufficiently to be entirely visible in the US image.

In normal horses without back pain the epaxial muscles are symmetrical on the left and right sides. Ultrasonography of thoracolumbar and sacral epaxial musculature revealed significant individuality and regional variation in the shape and size of *multifidus*, which is largest in the lumbosacral region. From a functional biomechanical perspective this would be expected since maximal dorsoventral flexion and extension occurs at the lumbosacral junction, and the primary role of *multifidus* mm is stability and proprioception (Stubbs et al., 2006).

Ultrasonography is a repeatable and reliable tool for measuring epaxial muscle size in clinical cases of equine back pathology (McGowan et al., 2007c). Stubbs et al. (2010) reported that in 22 TB racehorses there was a significant reduction in *multifidus* size (CSA) at the level of significant injury or pathology seen on post mortem examination. This is comparable with research in people with back pain (Hides et al., 1994, 1996) in which US imaging has shown a significant reduction in CSA of *multifidus* on the symptomatic side of the spine, indicating a relationship between pain and muscle atrophy (Hides et al., 1994). Pre-clinical examination of 22 racehorses presented for euthanasia for primary reasons other than back pain, showed that 91% had asymmetrical development of *biceps femoris* muscle and 82% had asymmetrical gluteal muscle mass (McGowan et al., 2007c). Ultrasonographic images were acquired on the left and right sides at 5 TL levels to measure CSA of *multifidus* or *sacrocaudalis dorsalis.* At necropsy, osseous pathological lesions of the TL spine and pelvis were recorded according to spinal level and anatomical site, and graded (0–3) according to severity. The mean typical measurement error in estimating *multifidus/sacrocaudalis dorsalis* CSA was used to determine the significance of left/right asymmetries. An association between *multifidus* CSA asymmetry and asymmetrical grading of pathological lesions was sought using Pearson's chi-squared analysis. All horses had significant left/right asymmetry of *multifidus* CSA at >2 spinal levels, most commonly at L5 with a total of 74 sites affected in the 22 horses. Seventeen horses had severe (Grade 3) pathology and 16 of these had ipsilateral atrophy of *multifidus/sacrocaudalis dorsalis*. There was a significant association between pathological grade and degree of *multifidus* asymmetry. Severe osseous pathological changes were common in this population of TB racehorses and were associated with measurable left/right asymmetry in *multifidus* at or close to the level of pathology (Fig. 17.6). Ultrasonography of *multifidus* muscles is a useful and reliable clinical tool in the functional diagnosis and rehabilitation of back problems in horses, potentially together with other US functional muscular measures (linear, and contraction measurements).

B-mode ultrasonography, which has the ability to produce images of moving objects almost instantaneously, has been used to measure CSA of *longissimus dorsi* (D'Angelis et al., 2007). Images were acquired before, during and after a 90-day aerobic training program on a treadmill. With the horse stationary, images were recorded at the level of the last rib with *longissimus dorsi* relaxed. CSA of *longissimus dorsi* increased significantly during the exercise period. Unfortunately, reliability data were not published for the US methodology with respect to both image acquisition and calculation of CSA.

In the human field advancements have also been made in the measurement of muscle contraction over time using M-mode ultrasonography. This technique is reliable within a single operator when the probe is fixed to the antero-lateral abdominal wall to measure *transversus abdominis* in supine, standing and walking human subjects with and without back pain (Bunce et al., 2002; Kidd et al., 2002). To date there are no reports in the literature using M-mode ultrasonographic muscle assessment in the horse.

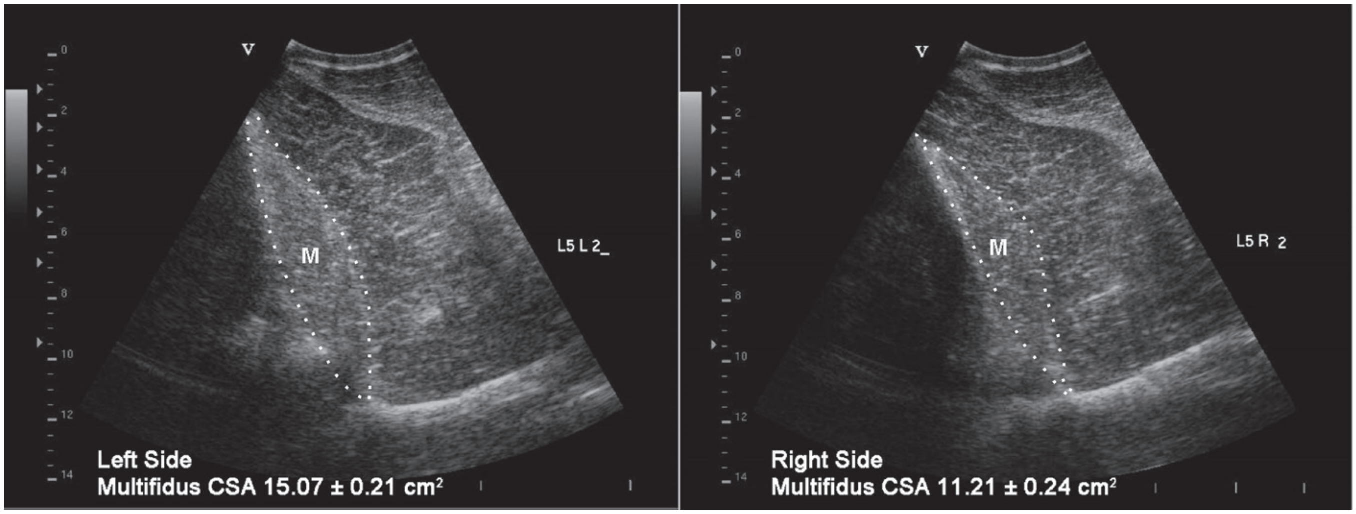


Fig 17.6 Left and right ultrasonographic images of multifidus (M) at the 5th lumbar vertebra. Osseous pathology on the right side (facet and neural arch fractures with incomplete vertebral body spondylosis) matches the reduction in multifidus CSA on the right. (Left mean CSA 15.07 cm^2 (SD ± 0.21); right mean CSA 11.21 cm^2 (SD ± 0.24); absolute difference: 3.86 cm^2.)

Reprinted from Stubbs, N.C., Clayton H.M., Hodges P.W., Jeffcott, L.B. and McGowan C.M. (2010) Osseous spinal pathology and epaxial muscle ultrasonography in Thoroughbred racehorses. Equine Vet. J. 42 (Suppl. 38), 654–661, with permission from the Equine Veterinary Journal.

In conclusion, US is a valuable functional, objective, diagnostic tool that can be used to monitor the rehabilitation process, especially in cases where objective measures are difficult to derive, such as back pain (Stubbs et al., 2011) which will be discussed later in this chapter.

Rehabilitation techniques: manual therapy

The modern sports medicine literature indicates that rehabilitation of an athlete should begin as soon as possible after an injury occurs, in combination with therapeutic measures such as anti-inflammatory and other pain killing agents (Frontera, 2007). Complementary and alternative medicine (CAM) has applications in performance enhancement, injury prevention and therapy, especially with regard to back pain in the equine athlete. Examples of CAM treatment are PT, chiropracty, osteopathy and acupuncture (Chan et al., 2001, Haussler, 1999b), exercise-based therapies and swimming (Roethlisberger Holm et al., 2006). To educate and advise the owner/rider of horses with back pain, riding instructions are also vitally important in successful rehabilitation (Marks, 1999).

Manual therapy techniques are recommended for many conditions following a veterinary *patho-anatomical diagnosis*. Within the PT profession, manual therapy is defined as clinical methods using skilled, specific hands-on techniques, including but not limited to manipulation/mobilization to diagnose and treat soft tissues and joint structures for the purpose of modulating pain; increasing range of motion (ROM); reducing or eliminating soft tissue inflammation; inducing relaxation; improving contractile and non-contractile tissue repair, extensibility, and/or stability; facilitating movement; and improving function (American Academy of Orthopedic Manual Physical Therapists). A chiropractic definition of manual therapy is ‘procedures by which the hands directly contact the body to treat the articulations and/or soft tissues’ (Gatterman & Hansen, 1994).

Degenerative joint disease (osteoarthritis) is an example of a common cause of lameness and loss of performance in the horse. It has been reported clinically that manual therapy can be successfully applied, as in human cases. Many manual therapy techniques such as passive mobilizations and manipulation can be applied to the articular system including the vertebral column and peripheral joints, with complementary soft tissue techniques applied to the associated neuromuscular and fascial tissues. These repeated movement techniques have been reported to have effects on the intra-articular, peri-articular (capsular, ligamentous) and extra-articular (muscular, fascial, neural) structures, thereby affecting the passive and active constraints of the joint complex and assisting in pain modulation (Goff & Jull, 2007; Haussler, 2009; Goff, 2009). The human literature supports manual therapy techniques and the underlying biomechanical and neurophysiological mechanisms, and many of the studies have used animal models (Wright, 1995; Vicenzino et al., 1998, 2007; Sluka et al., 2006). Evidence has shown that manual therapy produces an initial local treatment-specific hypoalgesic and sympathetic-excitatory effect beyond placebo or control conditions, followed by a non-opioid-mediated systemic hypoalgesia (Sluka et al., 2006).

Numerous myofascial and neuromuscular mobilization techniques can be used, including massage (friction, effleurage, petrissage, tapôtement, vibrations and shaking), trigger point therapy, direct and indirect myofascial release, positional release, reflex inhibition techniques, craniosacral therapy, adverse neural tension techniques and stretching (mobilization exercises) (McGowan et al., 2007a; Paulekas & Haussler, 2009) (Fig. 17.7). The aim of many manual therapy techniques directed at the myofascia, tendons and ligaments is to normalize tissue irritability, muscle ‘tone’, which has also been demonstrated in the horse (Wakeling et al., 2006), extensibility, length, contractility, strength and coordination, and ultimately improve motor control. Addressing these impairments is a key feature of the rehabilitation process in an attempt to regain function and optimize performance.

Fig 17.7 A therapist performs myofascial release, a deep soft tissue mobilization technique, in the cervical spine.

It has been reported in the clinical literature that following soft tissue trauma or pathology, dynamic and or passive stretching can be implemented to regain and maintain full range of motion during the healing process. As a preventative measure this also applies to any horse that is on restricted exercise or confined to the stable for other reasons, to assist with avoiding the detrimental effects of immobilization (Paulekas & Haussler, 2009).

Passive stretching techniques are difficult to apply because horses are usually standing during treatment and this requires persistent muscle tonicity. Therefore the stretching procedure is always dynamic and never completely passive, even when intermittently ‘stretching’ the horse’s limbs. This may also be the case in the unsedated human according to a newer sensory theory suggesting modulation of muscle activity, rather than an increase in extensibility of the myofascial and neural systems (Weppler & Magnusson, 2010). Until recently the proposed physiological mechanisms to explain the immediate increased extensibility of muscle as a result of intermittent stretching have been predominantly passive and mechanical in nature including: viscoelastic deformation (Chan et al., 2001; Willy et al., 2001), plastic or permanent deformation (Warren et al., 1971; Sapega et al., 1981; Wessling et al., 1987), increase in sarcomeres in series with sustained prolonged stretching (Gajdosik, 2001) and neuromuscular relaxation as a result of a stretch reflex, many of which are not supported experimentally (Sharman et al., 2006). In the 1990s, many researchers tested the mechanical theories of stretching and found that the only change in passive torque/angle curves was an increased joint angle at end range with the same applied torque. It was concluded that the end point was determined by a subjective sensation (Magnusson et al., 1996a, b; Weppler & Magnussun, 2010). The mechanism of altered myofascial extensibility is still under debate in the human stretching literature, however the current theory indicates that stretching alters pain perception and thus there is more tolerance immediately after stretching and in the short term (3 to 8 weeks) (Folpp et al., 2006; Weppler & Magnussun, 2010).

Rose et al. (2009) studied the effects of two different 8-week stretching regimes on stride length and range of motion (ROM) in the equine trot. There was no significant effect on stride length but a number of significant differences between treatments were found in ROM of the shoulder, stifle and hock joints, which suggested negative biomechanical effects of the stretching. However, the methodology was flawed and the results need further clarification; multiple variables including individual horse variation may have played a role and the specific stretching techniques and forces applied need to be quantified in a larger number of subjects.

An osteopathic technique that is reported in the clinical literature suggests that a form of gentle passive stretching ('positional release') in the treatment of chronic myofascial restrictions can be performed under sedation or anesthesia. Clinically this technique has been reported to have some success (Pusey et al., 2010). The technique is often utilized after all other avenues have been exhausted due to the anesthetic risk. These techniques are performed rhythmically or in a sustained manner dependent on the desired response and effect on the tissues. Therefore tissue and/or joint 'mobilization with movement' exercises may be a more apt title for many forms of stretching techniques in the horse, an example being those exercises described in Stubbs et al., (2011), which have been coined in the clinical and lay literature as 'neck and back stretches', which is discussed later in this chapter.

If there is a primary lesion of a soft-tissue structure such as muscle, ligament or tendon, it is the authors' suggestion that these active mobilizations with movement exercises of the affected structures and/or the whole horse are appropriate, in conjunction with other therapies. The mobilizations may be appropriate to avoid excessive scar formation and disorientation of the fiber alignment in the subacute and chronic phases of healing, along with primary or secondary disuse atrophy. With respect to rehabilitation of distal tendon and ligament lesions, it has been widely reported in the human literature that dynamic motor control-based exercises including eccentric loading exercises accelerate healing and tensile strength, especially in relation to Achilles tendon lesions (Kingma et al., 2007). This type of rehabilitation strategy, sometimes referred to as *active rest*, is being implemented in horses by commencing a walking program along with other forms of therapy as soon as the lesion is determined to be stabilized. It is the authors' suggestion to also include unmounted dynamic mobilization exercises to increase the dynamic 'core' muscle strength as described above (Stubbs & Clayton, 2008; Clayton et al., 2010a, 2012; Stubbs et al., 2011).

Evaluation of information on manipulative/mobilization intervention

Specific techniques in PT, chiropracty and osteopathy are passive accessory and physiological joint mobilization and manipulation techniques that have been clinically reported to be successfully adapted to treat the horse (Goff, 2009; Haussler, 2009; Paulekas & Haussler, 2009), with some evidence indicating positive effects in reducing muscle tone and increasing range of motion (Wakeling et al., 2006; Gomez-Alvarez et al., 2008). These techniques encompass the application of very specific passive and/or active assisted movements by the therapist to the horse, to manage and/or alter pain and dysfunction of the articular, neural and muscular systems. Manual therapy techniques are based on a wide range of methods and theories related to the intervertebral and peripheral joint complexes, myofascia and the neuromuscular system.

Passive mobilizations and manipulations are applied at different amplitudes, velocities and directions determined by the assessment procedure and biomechanics of the joint complex (Goff & Stubbs, 2007). Figure 17.8 shows an active assisted direct modified 'Maitland' mobilization technique into end of range of motion (Maitland et al., 2000). In this technique, the therapist facilitates lateral bending and dorsoventral flexion to attain end range of motion of the thoracolumbar spine by applying pressure to one side of the hindquarters (pressure from the middle of the medial gluteal to the base of the sacrum). The position is maintained while applying a lateral flexion and rotation oscillating mobilization to the lateral dorsal spinous process at the desired amplitude and frequency. This technique, if modified appropriately, can become what is termed in the human literature a 'Mulligan mobilization-with-movement

Fig 17.8 Visual demonstration of an active assisted direct modified 'Maitland' mobilization technique into end of range of motion (Maitland et al., 2000). The therapist facilitates lateral bending and dorsoventral flexion to attain end range of motion of the thoracolumbar spine by exerting pressure to one side of the hindquarter (pressure from the middle part of *gluteus medius* to the base of the sacrum). While maintaining this position, a lateral flexion and rotation oscillating mobilization technique with lateral flexion and rotation is applied laterally to the dorsal spinous process at the desired amplitude and frequency.

technique'. These techniques have been positively reviewed in the scientific literature with regard to producing immediate and substantial pain reduction and improved function. Vicenzino et al. (2007) reviewed the clinical efficacy, effects and putative mechanisms of action of the approach, including the mechanisms and action in both biomechanical and pain science paradigms. This technique (Fig. 17.8) requires the oscillatory mobilization and response techniques to be applied simultaneously and repeated during multiple oscillations, hence both active lateral bend and dorsoventral flexion occur whilst the mobilization technique is applied. Manual passive assessment and treatment techniques directed at a joint, soft tissue or neural structure are well tolerated by the horse due to the rhythmical motion being applied at a comfortable speed as has been widely reported in people (Hurwitz et al., 1996). This may include high-velocity, low-amplitude thrust (HVLA) techniques. In the human literature it is hypothesized that the velocity may be more important than the amplitude, as demonstrated and standardized by using a mechanical 'activator' to perform the technique (Fuhr & Meke, 2005). Although the HVLA involves high speed, horses also appear to tolerate these techniques well, as they take place in a very short period of time, in conjunction with what is theorized as a rebound parasympathetic reaction and thus relaxation (Haussler, 2000; Pickar, 2002; Triano, 2005; Haussler et al., 2010).

The effect of manual therapy in horses in relation to equine back pain has been evaluated (Haussler et al., 1999a, 2007; Faber et al., 2003; Colborne et al., 2004; Wakeling et al., 2006; Gomez-Alvarez et al., 2008). These studies highlight the difficulties in conducting manual therapy research, especially across time. There is certainly a lack of randomized clinical trials. Methodological limitations are primarily due to limited subject numbers, variations within and between horses and practitioners, and the difficulty in the differential diagnosis and monitoring of back pain. Even with modern motion analysis systems there are inherent difficulties in measuring intervertebral motion accurately and non-invasively (see Chapters 2 and 10), and in measuring pain objectively. In spite of these limitations, joint mobilization and chiropractic manipulations have been shown to affect the kinematics of the back. For example, kinematic measurements following treatment showed less extension in the thoracic region and a greater symmetry of pelvic motion (Gomez Alvarez et al., 2008). Haussler, (2009) recently reviewed the scientific literature supporting manipulative therapy in the horse, where the focus of chiropractic has been on the clinical effects. In a pilot study, Haussler et al. (1999a) showed that manipulative techniques produce substantial spinal motion. In one study manipulative therapy modulated MNT, and a clinical trial using PA indicated that manual and mechanical spinal manipulation increase MNTs (Sullivan et al., 2008; Haussler & Erb, 2003). Further preliminary studies have investigated the effects of manipulative techniques on vertebral mobility and muscle tone (Haussler et al., 2007; Wakeling et al., 2006). Wakeling et al. (2006) investigated spinal (McTimoney) manipulations (Colloca et al., 2009) and reflex inhibition therapy versus a control group in 26 randomly assigned horses. Compared with controls, both treatment groups had significantly less muscle tone as measured by EMG after treatment. Collectively, these studies suggest that manipulative therapy elicits changes in TL and pelvic kinematics, and muscle tone, which are likely to be beneficial (Faber et al., 2003; Gomez Alvarez et al., 2008). However, further investigation is warranted to improve the objectivity of the methodology, decrease the number of variables, and increase sample size.

Recently Haussler et al. (2010) reported on the efficacy of dorsoventral spinal manipulation and mobilization on trunk flexibility and stiffness in 24 actively ridden horses. Passive spinal mobility was assessed once per week for 3 weeks by measuring peak vertical displacement, loading and unloading velocities, applied force and frequency of truncal oscillations induced during dorsoventral spinal mobilization at 5 TL sites. This was compared between treatment (n = 12) and control (n = 12) groups. Outcomes were measured each week pre- and post-intervention and showed significantly higher amplitudes and applied forces post intervention in the treatment group compared to the controls, with a trend for increased passive spinal stiffness. Further studies with improved objective measures of musculoskeletal dysfunction are needed to assess the effectiveness of manual therapies (Haussler, 2009).

Evaluation of information on exercise and facilitation techniques

Exercise-based treatment techniques: motor control

In the human rehabilitation literature much emphasis is placed on functional assessment and objective measurements in relation to *neuromotor control*. As described in Chapter 4, locomotion can be viewed as an emerging pattern within a complex system initiated by spinal central pattern generators. Locomotion involves central neural structures, peripheral organs and interactions with the environment (Latash, 2008). In equestrian sports, the rider must be included (Peham et al., 2004; Valentin et al., 2010). Dynamic control involves a spectrum of control strategies during locomotion, ranging from muscular co-contraction causing stiffening, to more dynamic control strategies that involve carefully timed muscle activity and movement. Multiple factors influence selection of the appropriate dynamic control strategy: load, movement, predictability, proprioceptive function and error-tolerance or robustness (Hodges & Cholewicki, 2007). An essential element of motor control is accurate internal and external receptor activity, especially regarding proprioceptive feedback on joint position during locomotion, which can be altered due to pathology. In the last two decades, much of the research in human PT and sports medicine in relation to musculoskeletal disorders has focused on the neurosciences including neuromotor control and pain associated with musculoskeletal conditions, as well as the inter-relationship between pain and function. This complements work in biomechanics and kinematics. In this research, functional impairments and interventions have been studied via randomized clinical trials investigating and comparing one or more approaches.

One of the major and current areas of interest in human musculoskeletal PT is the field of neuromotor control and dynamic stability. Research in this area has allowed major advancements in the prevention and treatment of important problems in people including pelvic pain (Richardson et al., 2002) and low back pain (Hodges et al., 2003a; Hodges, 2005), as well as prevention and treatment of peripheral joint injuries (Reimann & Lephart, 2002a, b) and performance enhancement in athletes (Saunders et al., 2005). These are also key issues in equine performance and wastage (Jeffcott et al., 1982; Stubbs et al., 2010) and research in these areas for horses is clearly warranted and currently underway in a number of research facilities around the world.

For example, research in human back pain, spinal stability and control of movement is highly dependent on the contribution of the muscular system. In the past, attention focused on muscle strength alone. However, it is now recognized that the central nervous system's control of the muscular system (when and how the muscles work) is probably of greater importance to the muscle system's ability to satisfy the needs of spinal movement and stability. The central nervous system must plan suitable strategies of muscle recruitment, co-ordination, and levels of activity to meet the demands of internal and external forces and initiate appropriate responses to unexpected disturbances of movements and function.

Research has shown that the deep, local muscles of the TL region (for example, the *transversus abdominis* and the segmental lumbar *multifidi*) play key roles in modulating the stiffness of the lumbar spinal segments and pelvic joints during limb and lumbo-pelvic movements (Indahl et al., 1997; Richardson et al., 2002; Hodges et al., 2006; Kalichman et al., 2009; Mok et al., 2011). It has also been shown that the central nervous system pre-programs activity in certain trunk muscles in preparation for limb movement. For instance, the *transversus abdominis* and *multifidi* activate prior to limb movement, regardless of direction. This serves to increase segmental stiffness for spinal segmental support prior to loading (Hodges & Richardson, 1997, 1999; Hodges et al., 2003b; Holm et al., 2002; MacDonald et al., 2010). Back pain patients display delayed activation of the *transversus abdominis* and *multifidi*, depriving the painful and injured spinal segments of timely support (MacDonald et al., 2009). Findings to date indicate that the horse follows the same sequence of events (Stubbs et al., 2010). Further research into the activation patterns in normal horses and those with back pain is necessary and currently underway.

Until recently relatively little was known about other epaxial and hypaxial muscles in normal horses or those with back pain. In the human literature there is a vast body of evidence (>80 peer reviewed research papers: Pubmed), with *in vivo* and *in vitro* observations of the role of *transversus abdominis* and *multifidus* muscles in controling intervertebral motion. The *multifidi* provide intersegmental stabilization and stiffen the spine, contributing two-thirds of the total increase in spinal stiffness imparted by muscular action (Wilke et al., 1995). *In vivo* studies in pigs confirmed that the *multifidi* are also a major stabilizer of lumbar intersegmental motion in quadrupeds (Kaigle, 1995). Morphological changes occur in the *multifidus* muscle in association with low back pain. In both acute and chronic low back pain, reduced CSA of *multifidus* was observed within 24 h of injury at the same intervertebral level and on the same side as the spinal pathology (Hides et al., 1994, 1996; Hodges et al., 2006; 2009). In a recent study, a decrease in density of *multifidus/erector spinae* was found in association with facet joint osteoarthritis, spondylolisthesis and disc narrowing (Kalichman et al., 2009). This also occurs within 3 days after a unilateral experimental lesion to an intervertebral disc in pigs (Hodges et al., 2006).

Another interesting finding is that *multifidus* does not automatically resume its normal function following recovery from or resolution of an episode of acute back pain (Hides et al., 1996). Specific physiotherapeutic interventions (exercises) are required to restore the size and function of *multifidus* after an episode of acute back pain in people and these interventions reduce the rate of recurrence of injury from 84% in untreated controls to 30% (Hides et al., 2001) in patients who received specific interventions. In horses, generalized secondary atrophy of the epaxial muscles, especially *longissimus dorsi* and *gluteus medius* have been reported in horses with back pain (Jeffcott et al., 1982; Quiroz-Rothe et al., 2002). Changes in *multifidus* CSA associated with ipsilateral osseous pathology in the horse has been reported (Stubbs et al., 2010). Furthermore, the muscles hypertrophy in response to regular performance of dynamic mobilization exercises (Stubbs et al., 2011).

Knowledge gained from ultrasonographic research in relation to changes in neuromotor control associated with back pain has translated to the development of new rehabilitation strategies for the lumbo-pelvic muscles in human back pain patients. This is an example of anatomical and biomechanical research creating a framework for future neuromotor control research in the horse along the same lines as the human research model. MacDonald and colleagues (2006) recently reviewed the evidence of these treatment strategies in clinical practice. Rehabilitation in this context using ultrasonography-guided feedback places emphasis on motor relearning to optimize motor control for spinal dynamic stability. The rehabilitation first uses the end organs of the neuromotor system, the muscles, with the aim that cognitive, repeated contractions of the muscles and correct movement patterns will result in a transition to automated use (i.e. skill training) (O'Sullivan et al., 1998). Initially, the deep muscles such as *transversus abdominis* and lumbar *multifidus* are repeatedly activated in the relearning process during rehabilitation. Movement patterns and strategies for all trunk muscles are then re-educated to retrain painless and controlled functional activities. Progressively the stability system is functionally challenged with load (static and dynamic exercises) as control improves. Most importantly there is growing evidence that this exercise approach can reduce low back pain and possibly reduce its recurrence rate (O'Sullivan et al., 1997; Hides et al., 2006; MacDonald et al., 2006). Specific physiotherapeutic intervention in people with *multifidus* dysfunction following an episode of acute back pain reduced the rate of recurrence of injury to 30% in the PT intervention group compared with a recurrence rate of 84% in controls (Hides et al., 2001).

The human motor control model has been applied in investigations of the equine *multifidus* muscle (Stubbs et al., 2006, 2011) revealing striking similarities in structure and function across species. The equine *multifidus* has similar morphological orientation; therefore, its biomechanical activity is comparable to man, with the primary function being to stabilize intervertebral motion. *Sacrocaudalis dorsalis lateralis* forms the caudal continuation of *multifidus* in the equine sacro-caudal spine (Stubbs et al., 2006) (Figure 17.5). *Multifidus* CSA is largest in the lumbosacral region, which is the area with the greatest amount of motion (Townsend et al., 1983; Stubbs et al., 2006).

Anatomical variations in the equine lumbosacral region occur in at least a third of horses (Haussler et al., 1999b). The predominant variation is divergence between the dorsal spinous processes of L5 and L6, with L6 being a transitional vertebra and functioning as part of the lumbosacral joint (Stubbs et al., 2006). These variations may affect range of motion and performance.

In people with back pain, the deep spinal stabilizer *multifidus* is inhibited ipsilaterally leading to muscle atrophy, asymmetry in CSA and loss of its function leading to intervertebral instability. Specific physiotherapeutic exercises are required to reactivate *multifidus.* This information has influenced the management of back pain in humans (MacDonald et al., 2006, 2009). In horses, Stubbs et al. (2011) applied these physiotherapeutic and motor control principles to the horse in a study that assessed the effects of dynamic mobilization exercises on size and symmetry of *multifidus* in the equine caudal thoracic and lumbar spine. Eight horses performed dynamic mobilization exercises (three cervical flexions, one cervical extension, and three lateral bending exercises to the left and right sides) with five repetitions/exercise/day on 4–5 days/week for 3 months during which time they were not ridden (Fig. 17.9). These exercises are widely used in clinical practice with the aim of increasing 'core' muscle activation (Stubbs & Clayton, 2008). Left and right *multifidus* CSA was measured ultrasonographically at 6 levels from T10–L5 at the start (initial evaluation) and end (final evaluation) of the 3-month study. Changes in CSA of the left and right *multifidi* and symmetry of *multifidus* CSA on the right and left sides between the two evaluations were sought using analysis of variance ($p < 0.05$). Between the initial evaluation and final evaluations *multifidus* CSA increased significantly at all six spinal levels on both right and left sides. Asymmetries in *multifidus* CSA between the right and left sides decreased significantly between the initial and final evaluations at all six spinal levels indicating the dynamic mobilization exercises are effective in activating the equine *multifidus* (Stubbs et al., 2011).

Clayton et al. (2010a, 2012) reported the intervertebral angulations in the end position of the dynamic mobilization exercises performed in flexion and lateral bending, respectively. Most of the movements occurred at the cranial and caudal cervical joints with less motion in the mid neck. The results were interpreted in the context that articulations at the cervicothoracic junction are primarily responsible for raising, lowering and turning the neck while the cranial cervical joints position the head relative to the neck, which is important with regard to proprioceptive input.

Regular performance of dynamic mobilization exercises may also have neuromuscular training effects as a consequence of the activation, recruitment, and strengthening of the deep dynamic segmental stability muscles in the neck and back (*longus colli, intertransversarii,*

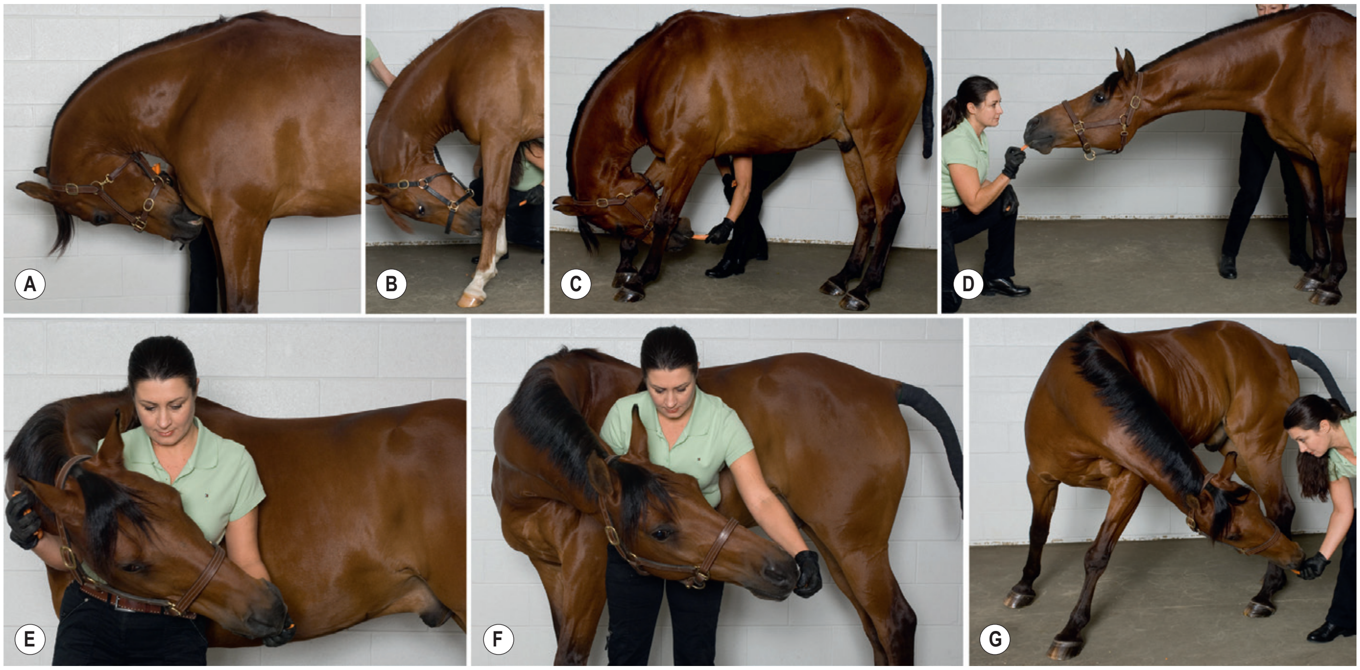


Fig 17.9 Dynamic mobilization exercises (baited stretches) performed in flexion–extension (top row): (A) chin to chest, (B) chin between carpi, (C) chin between fetlocks, and (D) cervical extension; and in lateral bending (bottom row): (E) chin to girth/ribcage, (F) chin towards stifle, and (G) chin towards hock.

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multifidi); the thoracic sling (primarily *serratus ventralis thoracis*); the hypaxial musculature (abdominals, *iliopsoas* complex); and the pelvic dynamic stabilizers (superficial and medial gluteals, *tensor facia latae, biceps femoris*). It is believed that the horse develops more appropriate dynamic control strategies as a consequence of performing these exercises. It is further suggested that, as the horse's dynamic stability and strength improve, the exercises should be made more challenging, for example, by deliberately having the horse stand in a slightly unbalanced position or by teaching the horse to perform the exercises with one leg raised off the ground. It is important for the therapist to assess each horse's compensation strategies and to always encourage horses to use the appropriate dynamic control.

Research into the biomechanics and neuromotor control of the human sacroiliac joint (SIJ) has also contributed to clinicians' ability to diagnose sacroiliac disease (SID) in humans. It has been shown that non-invasive, manual SIJ provocation tests are as predictive for SIJ being the source of pain as diagnostic joint blocks (van der Wurff et al., 2006). These pain provocation tests compress the SIJ articular surfaces and/or stress the extra-articular structures of the joint. Manual tests based on the examiner's impression of the amount of motion (hypo/hypermobility) and quality of motion (the status of the neuromotor system) at the SIJ are also used clinically to assess the functional status of the SIJ. This includes assessment of the amount of movement of the SIJ during application of manual force and, specifically, analysis of sacral movement relative to the pelvis in weight bearing through specific motion tests, such as the one leg flexion test in standing or the 'stork test' (Gillet test) (Lee, 2004). Diagnosis of equine sacroiliac disease using manual tests similar to those used in the human literature has been eluded to (Haussler, 1999b, 2003a, b; Varcoe-Cocks et al., 2006; Goff & Crook, 2007). Motion between the sacrum and ilium (dorsal sacroiliac ligament provocation test) during the application of manual force has been reported and the direction and amount of movement of the ilium relative to a fixed sacrum in response to manual pressure has been measured in an *in vitro* model (Goff et al., 2006). The sacroiliac joint lies at an angle of 30° to the horizontal (Dalin & Jeffcott, 1986), which is conisitent with the finding that the direction of greatest movement is in the lateral and oblique planes (Goff et al., 2006). In conclusion, research to date supports the use of manual provocation tests for SID in horses.

Facilitation-based exercise therapy

In conjunction with direct manual therapy techniques, facilitation techniques may be utilized to cause the horse to move through a desired range of motion. These techniques and exercises encompass many forms of direct and indirect mobilizations with/through movement techniques/exercises, which clinically have been seen to be very effective, especially in relation to functional motor control. Altered motor control (neuromuscular function) may be a result of an underlying lesion in the spine and/or peripheral joint disease with pain and inflammation causing reflex inhibition of motor neurons, resulting in weakness and atrophy of associated muscles (Young, 1993). Many of these mobilization techniques/exercises are reported to use neuromuscular reflexive responses along with muscular facilitation and inhibition. In horses, these techniques are based on similar theoretical principles to those used in human manual therapy, including *muscle energy* techniques to gain motion that is limited by restrictions of neuromuscular structures and restore or normalize motor control. The human patient is asked to contract and relax specific muscles in a given range of motion and often resistance is applied to the body part. In theory these techniques promote muscle relaxation by activating the Golgi tendon reflex (DiGiovanna et al., 2005) via the principles of reciprocal inhibition and post-isometric relaxation. Reciprocal inhibition uses the body's antagonist–inhibition reflex to induce relaxation of a muscle. Conversely, other techniques use the antagonist–inhibition reflex to incrementally restore range of motion, whereby a muscle is stretched immediately following an isometric contraction due to the neuromuscular apparatus becoming briefly refractory or unable to respond to further excitation.

Although these techniques have not yet been investigated scientifically, it is the author's opinion that many of these applied techniques/exercises are very useful in the majority of rehabilitation cases to maintain and improve mobility, strength and dynamic stability, especially in regions where the affected joint complexes are inaccessible due to the horse's morphology such as the horse's cervicothoracic region and back. The intention is not only to increase joint mobility but also to activate and strengthen muscles that move the horse's body to the desired position, promote intersegmental joint stability, and restore functional locomotion and sport specific motion. Indirect mobilization techniques can be utilized clinically to mobilize the cervicothoracic junction, whereby a muscle reflex/response occurs in response to applying constant pressure between the index finger and the thumb while they are wrapped around the distal third of the *brachiocephalicus* muscle, producing flexion in this region. The brachiocephalic response can be coupled with ventral pressure to the sternum to mobilize the joint complexes by stimulating flexion in the cranial thoracic region. This may be combined with lifting of one forelimb to progress the technique (Fig. 17.10).

Many combinations of mobilization, core strengthening and stability/balancing exercises have been described in the clinical literature (Stubbs & Clayton, 2008; Goff, 2009; Paulekas & Haussler, 2009; Stubbs et al., 2011). These often use food as an incentive or bait (such as a carrot) to encourage the horse to move into the desired posture, with the end range of motion posture being maintained for a period of 3–10 s. The exercises that move the chin to the chest or between carpi/fetlocks stimulate flexion, whereas movement of the chin toward the girth, flank or hock is achieved using coupled lateral bending and axial rotation. The aim of these exercises is not only to mobilize both the axial and appendicular skeleton, but also to facilitate core muscle activity (thoracic sling, hypaxial/epaxial and pelvic musculature), improve neuromuscular control and strengthen the active musculature, which is a key concept in rehabilitation and sports medicine.

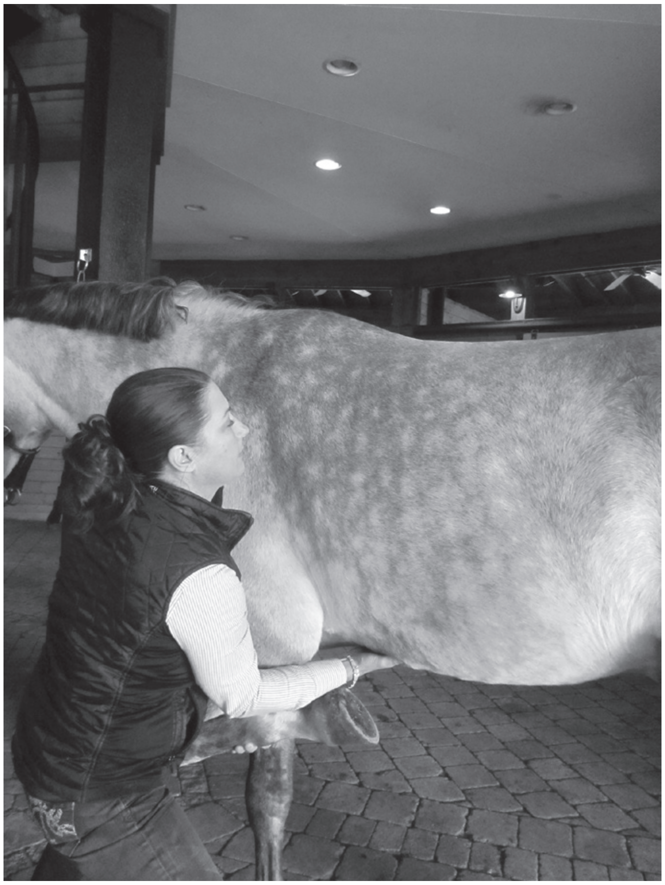

Fig 17.10 Combined facilitation technique used to assess and treat dynamic stability in the cervicothoracic and thoracic sling regions. The first step is to perform a 'sternal lift' or 'rounding response' by pressing upward on the sternum. The horse responds to the noxious provocation by flexing the cervicothoracic spine with the flexed position being maintained for 3–5 s. A progression of the exercise is to lift one forelimb off the ground while performing the sternal lift.

The human scientific literature indicates that core stability exercises improve neuromotor control in back pain patients to aid recovery and prevent further reccurrence (Hides et al., 2001, 2006). It seems likely that core training exercises as described in horses by Stubbs & Clayton (2008) will have similar therapeutic applications in horses that are rehabilitating from neck and back pain. Furthermore, regular use of the exercises may help to prevent the occurrence or recurrence of equine neck and back pain. Further studies in equine neck and back pain patients are needed to test this hypothesis.

A vital aspect of musculoskeletal and neurological rehabilitation and performance enhancement is related to motor control and motor-skill retraining, not only with respect to pain management but directly related to and mediated by proprioceptive and mechanoreceptive afferent feedback from joints, tendons, ligaments, fascia and skin, which modulate efferent neuromuscular control. As stated previously, the overall aim of rehabilitation is to restore the appropriate neuromuscular pathways, and strengthen the musculature to allow the horse to return to perform to its athletic potential.

Sensory integration is a form of facilitation-based exercise therapy that involves tactile stimulation during exercise. These techniques have clinically (Goff & Stubbs, 2007; Stubbs & Clayton, 2008; Goff, 2009; Paulekas & Haussler, 2009) and scientifically (Ramon et al., 2004; Clayton et al., 2008, 2010b, 2011a,b) been reported to be useful tools in the treatment of the horse. The aim of these techniques is to alter the horse's kinesthesia (proprioception and joint position sense), which ultimately influences static and dynamic posture. Static and dynamic position senses are dependent on feedback from peripheral receptors that determine joint angulations in all planes and their rate of change. Peripheral receptors include cutaneous mechanoreceptors, nociceptors, Golgi tendon organs, muscle spindles and capsular receptors, which relay information to the central nervous system via type Ia and type II afferent fibers, to modulate and coordinate locomotion (Loeb, 2005). Sensory integration is very effective because the horse has a heightened cutaneous mechanoreceptive system, in conjunction with the underlying myofascial attachments of *cutaneous trunci* to the skin. Theoretically, tactile stimulants including adhesive tape, exercise bands, loose-fitting tactile limb bracelets (55 g), or tactile cues can be applied to the skin over targeted regions including the limbs or specific muscles, with the aim of altering mechanoreceptive and proprioceptive feedback, which alters motor control. There is a vast body of literature to support the application of these techniques in people (Seki et al., 2003; Rose & Scott, 2003).

A series of studies has explored the effects of sensory integration techniques in horses (Clayton et al., 2008, 2010b, 2011a,b). The first study determined the short-term habituation to the effects of lightweight (55 g) stimulators consisting of a strap with seven double stranded oval brass links that were 7 cm in length. The straps were loosely attached around the pastern. Trials were conducted under three conditions: no stimulators, stimulators attached to the pasterns of both forelimbs and stimulators attached to the pasterns of both hind limbs, with 10 consecutive trails collected for each condition (Clayton et al., 2008). Eight sound Arabians (450 ± 56.1 kg) were trained by an experienced handler to trot in a straight line at a consistent velocity. Kinematic data were collected using an automated motion analysis system (eight cameras; data collection volume 5 × 3 × 2 m) with reflective markers attached to the head, trunk (T10 and L6), tuber spinae scapulae, tuber coxae, and each hoof. Velocity did not vary significantly across all trials (± 0.4 m/s) and hoof height in the control condition did not differ significantly across the 10 trials. As determined by the slope of the regression lines, the effect on peak hoof height was largest immediately after the application of the fore and hind stimulators and decreased over time. Peak hoof height was significantly greater than the control across the first six trials for the forelimbs and for all 10 trials for the hind limbs with extrapolation of the regression line estimating that hind hoof elevation would no longer be significant after the 14th trial. There was, however, considerable individual variation in the rate of habituation of different horses. It was suggested that habituation may be more rapid in the forelimbs due to the inherently higher extensor tone of the forelimbs and the influence of ascending neurological inhibition from the hind limbs to the forelimbs (De Lahunta, 1983). Crossover effects between the limbs were observed (Clayton, unpublished). The effects of longer-term habituation and the response to repeated applications of the stimulators have not yet been investigated. It is theorized that there may be a potential effect on training due to altering kinesthesia and joint position sense, thus modulating the central pattern generators via the extrapyramidal system and alteration of the horse's gait over time, which may be an ultimate goal during the rehabilitation process.

In a different study, swing phase kinematic and kinetic effects of the same tactile stimulators (55 g) loosely attached to the hind pasterns were investigated in nine sound horses during four trials at trot compared with a control condition, with the two conditions applied in random order (Clayton et al., 2010b). Peak height of the flight arc and peak flexion angles were measured, and net positive and negative work performed across each joint were calculated using inverse dynamics analysis and compared pairwise (tactile stimulant versus control). Speed and stride duration did not change but the lightweight tactile stimulators were associated with a reduction in hind stance duration. The flight arc was higher as a result of a significant increase in flexion at the stifle, tarsus, metartarsophalangeal and distal interphalangeal joints. Interestingly, the pattern of the flight arc changed shape from biphasic to monophasic as a result of increased muscular work across the limb joints. Negative work (eccentric contraction) increased across the stifle, MTP and DIP, and positive work (concentric contraction) in the tarsal musculature but not the hip musculature. No changes in hip flexion or in the range of limb protraction/retraction were found.

Another study evaluated the response to weighting the hind pasterns, which has previously been investigated by Wennerstrand et al. (2006). Swing phase kinematics and kinetics were measured at trot (Clayton et al., 2011a) in six horses to compare control/no weight condition with firmly attached leg weights (700 g). The two conditions were applied in random order. Peak height of the flight arc was significantly higher with leg weights due to increased flexion at the stifle, tarsus and metatarsophalangeal joints. Positive (concentric) work increased in the tarsal and hip flexors in early swing to lift the hoof and protract the limb and in the tarsal and hip extensors in late swing to lower the hoof and retract the limb. There was also increased negative (eccentric) work across the stifle and metatarsophalangeal joints. The increased work was needed to overcome the additional inertia of the leg weights. In a rehabilitation setting, a weight firmly attached to the pastern may be a useful method of facilitating and strengthening the musculature of the hip, stifle and hock. The authors concluded that 'increased muscular activity occurs without an increase in hip flexion suggesting that it will not improve hind limb engagement though the concurrent increase in tarsal flexion may give the impression of greater hind limb activity' (Clayton et al., 2011a).

Another in this series of studies made direct comparisons of the biomechanical effects of different types of stimulation devices applied to the hind pasterns of trotting horses (Clayton et al., 2011b). Eight sound horses were tested under the following conditions applied in random order: no stimulators, loose straps (10 g), loose lightweight tactile stimulators (55 g), leg weights (700 g) and leg weights with tactile stimulators (700 g). Peak hoof height was lowest for the control (5.42 ± 1.38 cm) and loose straps (6.72 ± 2.19 cm), significantly higher for lightweight tactile stimulators (14.13 ± 7.33 cm) and leg weights (16.86 ± 15.93 cm) and significantly higher again for leg weights plus lightweight tactile stimulators (24.35 ± 13.06 cm). The shape of the flight arc of the hind hooves changed with loss of the biphasic shape as hoof height increased (Fig. 17.11).

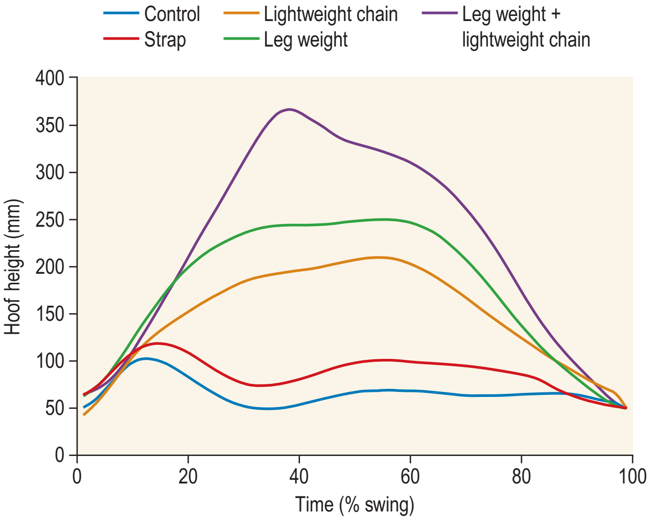

Fig 17.11 Flight arc of right hind hoof without stimulators and with four types of stimulators attached around both hind pasterns. Each curve represents one trial with all trials being from the same horse.

Compared with no stimulators, peak joint flexions increased significantly at the stifle, tarsal and fetlock joints when using the combination leg weights plus tactile stimulator and tarsal flexion increased with the tactile stimulator (Table 17.4). There were large differences in the response of individual horses that affected the ability to detect significant differences even with large changes in mean peak flexion values across conditions. Net energy generation increased at the tarsal joint and net energy absorption increased at the stifle joint for lightweight chains, leg weights and leg weights plus lightweight chains but only the two weighted conditions were associated with increased net energy generation across the hip joint (Table 17.4).

In conclusion, this series of studies has determined that both the type and weight of tactile stimulators can alter the magnitude of the kinematic and kinetic variables in the swing phase. The results suggest that the effects of tactile stimulation of the hind pasterns on joint motion and muscle activation may be used in PT and rehabilitation to restore or increase flexion of the hind limb joints with the exception of the hip joint. The authors suggest that 'rehabilitation after an orthopedic injury should progress from lightweight tactile stimulators that restore range of motion by facilitating stifle and tarsal musculature, to weighted stimulators that also strengthen the hip musculature'. The ability to stimulate concentric activity of the tarsal musculature may have therapeutic applications in conditions such as toe dragging (Clayton et al., 2010b). Lameness is also often associated with reduced joint ranges of motion, even after the lameness resolves. Clinically this is often associated with degenerative joint disease or as a result of a period of immobilization. Van Harreveld et al. (2002) reported long-term reduced joint range of motion in sound horses after being cast for 7 weeks, even following a progressive 8 week exercise program that included trotting on a treadmill. This could be a result of altered mechanical properties of the articular and periarticular structures (Akeson et al., 1987; Michlovitz et al., 2004; Katalinic et al., 2009) or alterations in neuromotor control (Jerosch & Prymka, 1996; Cowan et al., 2001). In the human literature there is evidence of

Table 17.4 **Effects of four types of hind limb stimulators on swing phase kinematics at trot**

Type of stimulator	None	Strap	Tactile stimulator	Leg weight	Leg weight + tactile stimulator
Peak hoof height (cm)	5.4 ± 1.4^{a,b,c}	6.7 ± 2.2^{d,e,f}	14.1 ± 7.3^{a,d,g}	16.9 ± 15.9^{b,e,h}	24.4 ± 13.1^{c,f,g,h}
Peak flexion angle (degrees)					
Hip	73.2 ± 9.6	74.6 ± 6.4	72.2 ± 9.6	71.1 ± 11.0	71.3 ± 9.9
Stifle	118.3 ± 10.2^{a,b,c}	117.7 ± 6.1^{d}	104.5 ± 15.8^{a}	95.9 ± 21.2^{b}	95.2 ± 13.8^{c,d}
Tarsus	116.5 ± 5.0^{a,b}	114.6 ± 2.5^{c}	96.0 ± 15.1^{a}	87.7 ± 21.7	84.8 ± 13.5^{b,c}
Fetlock	133.8 ± 8.7^{a}	131.2 ± 9.0^{b}	116.7 ± 18.1^{c}	107.8 ± 20.8	101.5 ± 15.4^{a,b,c}
Net joint energy (J/kg)					
Hip	0.160 ± 0.099^{a,b}	0.259 ± 0.026^{c}	0.246 ± 0.046	0.367 ± 0.029^{a,c}	0.320 ± 0.016^{b}
Stifle	−0.141 ± 0.057^{a,b,c}	−0.184 ± 0.018^{d}	−0.211 ± 0.030^{a,e}	−0.320 ± 0.036^{b,d,e}	−0.312 ± 0.043^{c}
Tarsus	0.052 ± 0.024^{a,b,c}	0.066 ± 0.006^{d,e}	0.088 ± 0.16^{a,f}	0.145 ± 0.051^{b,d}	0.146 ± 0.038^{c,e,f}

Values in the same row with the same superscript are significantly different from each other ($p < 0.05$).

Reprinted with permission from Clayton et al., 2011b.

underlying neuromotor control problems in human patients with back and knee pain, including abnormal knee joint position sense, altered joint proprioception (Baker et al., 2002), altered electromyographic (EMG) firing patterns of *vastus medialis obliquus* and *vastus lateralis* that contribute to maltracking of the patella (Cowan et al., 2001; Owings et al., 2002), reduced knee flexion in early stance due to the delay in onset of eccentric activity in *vastus medialis obliquus* (Crossley et al., 2004) and significantly decreased strength in the more proximal musculature including hip external rotators and abductors (Ireland et al., 2003) in patients with patellofemoral pain syndrome. Similar neuromotor control problems may occur in the horse and confound many gait abnormalities and disease processes, as shown by subtle, and often related, changes in lameness patterns and back kinematics (Gomez-Alvarez et al. 2007a,b, 2008) due to altered neuromotor control. The use of tactile stimulation as a form of sensory integration may be a valuable tool to facilitate restoration of normal locomotor function by activating and strengthening specific muscle groups, with a training effect over time.

Clinically it has been reported that other forms of sensory integration are useful during training but further investigation is needed to confirm their value. These include the use of different materials such as bandages, such as Vetrap or 'body wrap', and exercise-bands wrapped around the horse's hindquarter, abdomen and/or chest (Goff & Stubbs, 2007). It is the authors' opinion that exercise bands are the most useful of these techniques in a clinical setting as they appear to increase the horse's body awareness (kinesthesia) and the ability to use the core muscles when exercised in hand, on the longe or under saddle (Fig. 17.12).

Another effective technique for sensory stimulation in a clinical setting is the 'functional proprioceptive taping technique', which is widely used in human rehabilitation, sports medicine and athletic performance. In the veterinary literature, Ramon et al. (2004) reported that 'rigid mechanical athletic taping' of the fetlock did not alter the kinematics of the forelimb during stance, but did limit fetlock flexion in the swing phase. There was also a decrease in peak vertical ground reaction force, which may have been due to an increased proprioceptive effect. The authors concluded that reduced vertical force may be beneficial in preventing or reducing the risk of injury and might be useful for tendinous or ligamentous rehabilitation in equine patients.

Different effects may be seen when using a functional, rather than mechanical, taping technique to facilitate increased muscle activity. This type of taping is commonly used in human athletes and is known as kinesiology taping. In theory, the effects are achieved through tension that increases the kinesthetic awareness along the fibers of a muscle or muscles when a facilitatory effect is desired. The horse performs specific exercises with the tape attached, including sport-specific activities under saddle, which leads to alteration of neuromotor function over time. The author has used taping techniques with clinical success to facilitate activity of the core dynamic stability musculature, more specifically *biceps femoris* and the abdominal complex (Fig. 17.13). Further investigation into these sensory facilitation techniques is definitely warranted given the clinical improvements observed.

These sensory integration techniques may be combined with many forms of in-hand and ridden exercises that have been described in the clinical literature (Paulekas & Haussler, 2009; Steiner & Bryant, 2003; Tellington-Jones & Burns, 1988). The exercise protocol should be individually tailored and monitored by the therapist, as there are vast individual variations in responses from the horse to these therapeutic strategies. A skilled handler/trainer is required to perform the exercises on a daily basis. The exercise protocol should follow the principles of conditioning (Clayton, 1991), with ongoing re-assessment of the horse's motion to ensure that compensatory strategies are minimal and the desired effects are evident. Considerations should include exercise time, gaits, transitions, direction, surfaces and gradients/slopes, with constant monitoring for signs of fatigue.

Hydrotherapy

There is limited evidence in the literature regarding the musculoskeletal benefits of equine hydrotherapy. Irwin & Howell (1980) suggested several indications for and some observations of swimming horses. Kato et al. (2003) determined the effects of immersion in warm spring-water (38–40°C) on autonomic nervous system activity in horses. Variations in heart rate (HR) were evaluated from the power spectrum in terms of low-frequency (LF) and high-frequency (HF) power as indices of autonomic nervous activity. They found that an increase in HF power, indicative of parasympathetic nervous activity, occurred during immersion in warm spring-water, which may thus provide a means of relaxation for horses. Kohn et al. (1999) proved that active cooling by washing with cold (15.6 ± 0.6°C) water is a safe, effective means of facilitating heat dissipation of horses after exercise in a hot, humid environment.

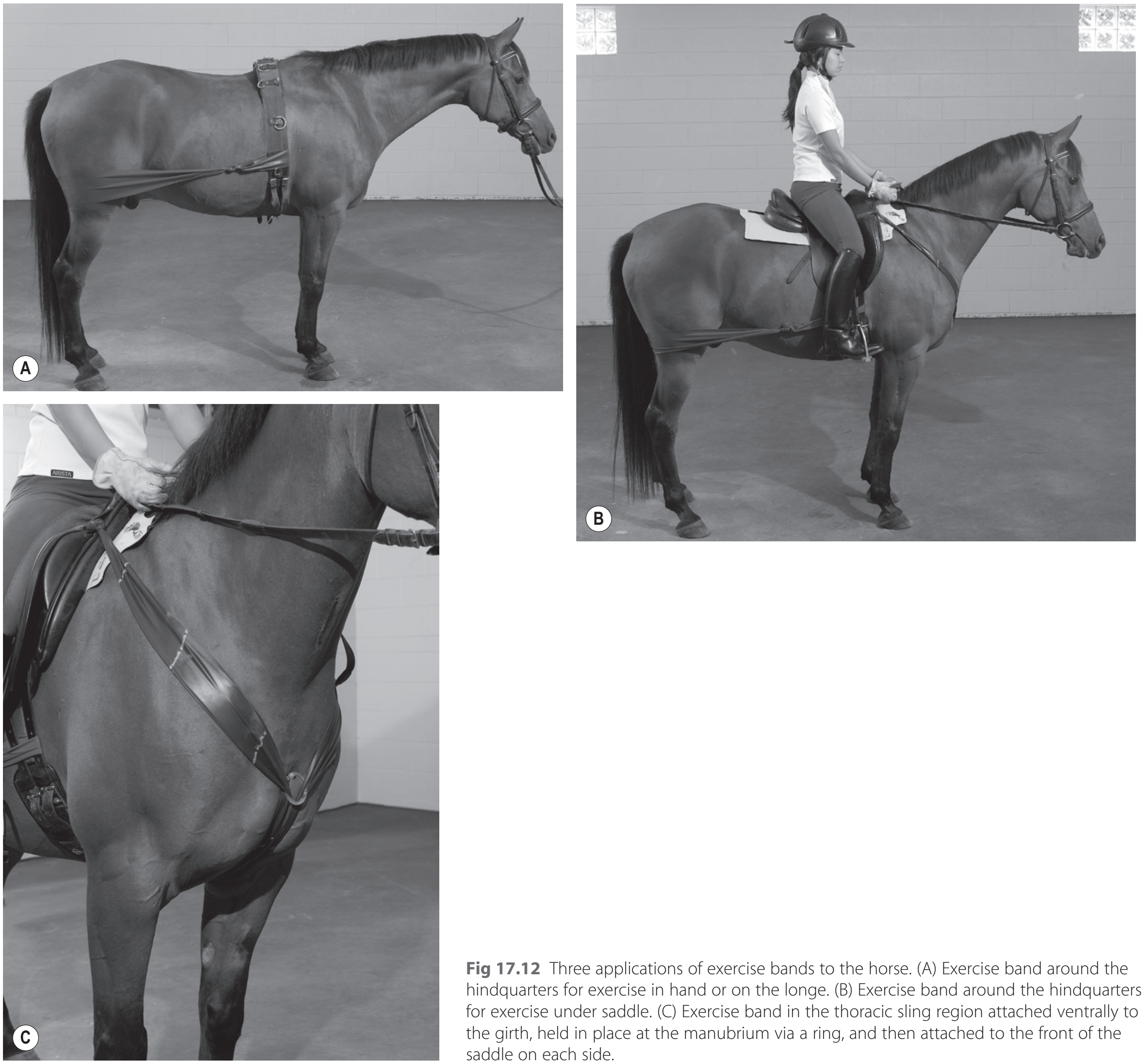

Fig 17.12 Three applications of exercise bands to the horse. (A) Exercise band around the hindquarters for exercise in hand or on the longe. (B) Exercise band around the hindquarters for exercise under saddle. (C) Exercise band in the thoracic sling region attached ventrally to the girth, held in place at the manubrium via a ring, and then attached to the front of the saddle on each side.

Evaluation of information on mechanical and electro-physical intervention

It is beyond the scope of this chapter to define and describe all the electromodalities and biophysical agents that are used in PT and rehabilitation to alter and/or accelerate tissue healing or to minimize the effects of disuse atrophy, immobilization and denervation. Readers are encouraged to search the human literature for further information because studies in the human field are more numerous and extensive than those in the veterinary field where many questions need to be addressed. In horses, the clinical efficacy of therapeutic ultrasound and optimal methods of application are uncertain, with no peer reviewed studies to date. Factors to consider that can alter penetration and absorption are the horse's coat (which needs to be shaved to apply therapeutic ultrasound) and thickness of the skin, fascia and subcutaneous fat.

It is well established in the human literature that cryotherapy is an effective method of modulating pain and inflammation in the acute phase of healing following injury (first 48 h), if the tissue temperature is reduced to therapeutic threshold of 10–19 °C at depths of 1–4 cm (Michlovitz, 1996). In the horse there has been considerable research on using cryotherapy in the distal limbs, where it has been shown to markedly reduce the severity of acute laminitis due to the reduction of enzymatic mediators (Van Eps & Pollitt, 2010). The most effective form of cryotherapy in the equine limb is ice water immersion (Kaneps et al., 2000), which is a common practice in many forms of equestrian sports post-exercise, such as eventing (Fig. 17.14). Horses are able to stand immersed in ice below the carpi or tarsi for extended periods of time, but on other parts of the horse's body it is suggested that the human recommendations for cryotherapy should be adhered to. Wet ice applications (wet towel with crushed ice) are best applied for up to 20 min, every 2–4 h, to avoid tissue damage and cold-induced vasodilation ('hunting response'). Tissue damage has been shown to occur in humans if the tissue temperature is reduced by more than 10 °C.

Superficial heat therapy (hot packs and hot water hosing) may be less useful in the horse. A study by Kaneps et al. (2000) showed that subcutaneous and deep tissue temperatures never reached the

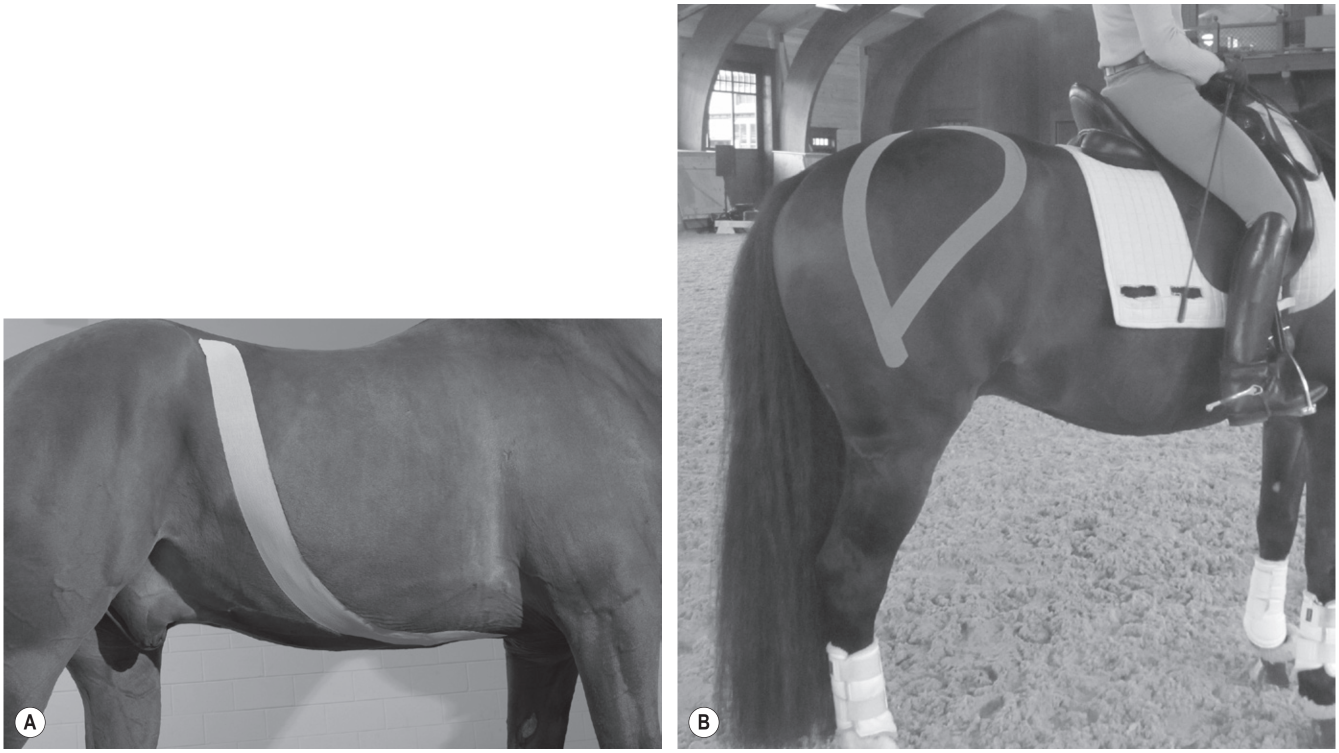

Fig 17.13 Examples of functional proprioceptive taping techniques using kinesiotape. (A) The abdominal complex is taped to facilitate activity of transversus abdominis, internal oblique and rectus abdominis. (B) Taping technique to facilitate activity of the pelvic stabilizer muscles including: *biceps femoris, gluteus superficialis* and *medius,* and *tensor fascia latae*.

Fig 17.14 Event horse after returning to its stable following the cross-country phase at an international competition. The horse is standing in boots filled with a slush of ice and water and has a wet ice towel placed along its back.

therapeutic threshold of 41 °C in the metacarpal region. It is not known whether other anatomical regions might be different.

Therapeutic ultrasound is another modality commonly used in people to heat tissue (3–5 cm depth) and increase fluid motion around cell membranes, but evidence of a therapeutic effect is still lacking (Paulekas & Haussler, 2009).

Electrotherapy entails the introduction of electrical currents to the body to gain therapeutic effects. These modalities utilize various types and frequencies of current, dependent on the desired effect. In the human, transcutaneous electrical nerve stimulation (TENS) has been well documented to provide temporary pain relief by central release of endogenous endorphins and opioids, and/or by stimulation of inhibitory inter-neurons at the spinal level (Watson, 2008). Even though there is no evidence that TENS is effective in horses, it is the authors' experience that it is a well-tolerated and clinically useful modality to complement other treatment strategies.

Neuromuscular electrical stimulation (NMES) is a useful electromodality in cases of muscle atrophy due to disuse, immobility and/or nerve damage in people. When a patient is unable to voluntarily contract the muscle(s), NMES can be applied to generate 80–90% of the maximal voluntary contraction to assist in maintaining neuromuscular control and muscle development (Paulekas & Haussler, 2009). In denervated muscle the findings are inconsistent though there is some evidence of a delay in denervation atrophy (Watson, 2008). To date there are no equine studies, but it is the authors' opinion that, if the horse will tolerate it, NMES is a useful adjunct to assess and treat horses with muscle dysfunction and/or atrophy. Cases in which NEMS may be useful include suprascapular and radial nerve lesions.

Anecdotal reports suggest beneficial effects from a variety of treatment modalities (e.g. Bromiley, 1999; Porter, 2005). However, objective evidence to support their use is not available. Extrapolation from the human field is complicated by the fact that there are differences in skin resistance, pigmentation, energy transmission and absorption between equine tissue and the tissues of people or research animals that the modalities have been tested on. Consequently, therapeutic regimes are recommended by the manufacturer rather than being based on scientific evidence.

Acupuncture

Acupuncture is a part of the traditional Chinese medicine (TCM) dating back to 1500 BC. In addition to acupuncture, TCM also uses herbal medicine, massage, breathing exercises and others. The word acupuncture is formed by the combination of the Latin words *acus*, 'needle', and *pungere*, 'prick'. Typically, acupuncture involves inserting needles at specific acupuncture points (acupoints), although the points may be stimulated by other methods including electro-acupuncture, laser acupuncture and acupressure (massaging of acupuncture points). Since the formation of the International Veterinary Acupuncture Society (IVAS) in 1974, acupuncture has become more popular as a therapy in animals. There are some indications of a positive clinical effect (Xie et al., 2001; Martin & Klide, 1987), but literature reviews indicate insufficient evidence to accept or reject the effectiveness of acupuncture for certain problems in both veterinary and human medicine (Cherkin et al., 2003; Habacher et al., 2006; Johnston et al., 2008). Prospective, randomized, double blind, clinical trials are necessary to determine whether acupuncture has more than a placebo effect (Sluijs, 2000). This section will highlight objective evidence for the use of acupuncture in the treatment of horses suffering from chronic back pain (Ridgway, 1999; Martin et al., 1987; Xie et al., 2005).

The philosophy is based on the Yin-Yang principle, which explains that everything in nature is constantly subject to change. Yin and Yang are each other's opposites but on the other hand they complement each other. Diseases can also be divided into Yin or Yang. Yin diseases are chronic conditions in which the pain decreases by applying warmth and movement. Yang diseases are inflammations, which usually show redness, swelling, heat and a sharp pain. Yang pain decreases by applying rest and cold. Yin and Yang are parts of the life energy, called Qi or Chi, which is present everywhere, but researchers have not been able to quantify or measure Qi. Qi circulates through 12 channels, called meridians, each of which is connected to a certain organ or organ system. Most of the acupuncture points are located on the meridians (Van der Molen, 1999).

Trigger points are used in Western medicine for making a diagnosis and for treatment of pathological pain (Simons et al., 1999). They can be recognized as painful, hard nodular structures within a muscle or fascia. Sometimes they can be localized subcutaneously or in the periosteum. Trigger points can occur anywhere on the body, but mostly they appear on stable, anatomically described points (Janssens, 1992). There is a correlation between the location of trigger points and the location of acupuncture points, which were discovered independently in Eastern and Western medicine, respectively. Pressure applied to a trigger point can produce pain in the trigger point itself, or referred pain in myofascial or visceral structures.

It is generally perceived that by applying pressure to a painful point on the body, the pain decreases. Physical therapists use this information during therapy (Simons et al., 1999). Instead of applying pressure, acupuncturists insert needles into these points (Melzack et al., 1977). Acupoints are located at specific locations of the body where the skin has a localized decrease in electrical resistance. Needle insertion influences the energy in the meridian and in the corresponding organ. The theory of acupuncture therapy is to restore the balance of energy (Qi) in the body (van der Molen, 1999; Xie et al., 2005). Besides the specific acupoints described in manuals and atlases, every point on the body can be used as an acupoint. Points that are painful on palpation, so called Ah Shi points, can be stimulated by any form of acupuncture. Insertion of an acupuncture needle causes micro trauma, which produces a local inflammatory reaction (Ridgway, 2005) and always has a degree of afferent sensory stimulation (Skarda et al., 2002). The use of a twitch in horses is based on the same principle as acupuncture; stimulation of the receptors in the skin of the nose produces analgesia (Lagerweij et al. 1984; Macgregor and von Schweinitz, 2006). The effect of the twitch and of acupuncture can be blocked by naloxon, a specific opioid antagonist (Xie et al., 2005), which indicates that opioids play a role in the pain transmission (Veeneklaas, 1999; Han, 2004). A significant increase of β-endorphins in plasma and cerebrospinal fluid has been found following acupuncture treatment in horses (Xie et al., 2001). Electro-acupuncture produces a greater β-endorphin release in the cerebrospinal fluid than needle acupuncture (Skarda et al., 2002). Besides the β-endorphin release, acupuncture is also thought to act via the gate control theory in which pain in the central nervous system is inhibited by stimulation of sensory receptors (by needle insertion) in the same innervation area (Veeneklaas, 1999; Ammendolia et al., 2008).

In human research there is a correlation between activation and deactivation of specific areas in the brain by stimulation of acupuncture points compared to stimulation of sham points (points that are not described as being acupuncture points, but which are located nearby the used acupuncture points and are innervated by the same spinal segment). Some brain areas are activated and deactivated by both acupuncture points and sham points (Yan et al., 2005; Hsieh et al., 2001). Stimulation by acupuncture needles at the vertebral level of the pathological process gives better analgesia in the short term than stimulation distal to the pathological process (Skarda et al., 2002). In research on the effect of acupuncture in people with back pain, a positive effect has been described. The largest positive effect was found when acupuncture was compared to a negative control group or when acupuncture was used as a complementary therapy. There are conflicting results from studies that compare acupuncture with needling of sham points with insufficient evidence to prove that the effect of acupuncture is greater than the effect of needling sham points (Ammendolia et al., 2008).

Acupuncture points in horses originate from two sources. One system used human acupuncture points and 'translated' them to the equine model, using corresponding anatomical landmarks. Western acupuncturists generally use the transpositional atlas in equine acupuncture (Fleming, 2001). Two articles are found with relevant data on the effect of acupuncture in horses with chronic back pain. Xie et al. (2005) used fifteen horses with TL pain that were randomly assigned to one of the three treatment groups. The pain-relieving effect of acupuncture in horses with back pain was compared with phenylbutazone treatment and with a control group in which the horses received 0.9 % NaCl per os. Group 1 (four horses) received electroacupuncture every 3 days for five treatments. Group 2 (seven horses) received phenylbutazone 2.2 mg/kg, PO, q 12 h for five days. Group 3 (four horses) was the control group which received 0.9% NaCl 20 ml, PO, q 12h for 5 days. The horse owners and trainers were not informed as to what treatment their horse had received. TL pain score (TPS) was evaluated before, on days 1, 4, 7, 10 and 13 during treatment and on days 7 and 14 after the last electroacupuncture treatment. The mean score of 2 TPS investigations was used because of the subjective nature of behavior with one TPS score being evaluated from videotape of the examinations. After a washout period of 4 weeks, the measurements were repeated, but for unexplained reasons group 3 (control) was not included and horses in this group were reallocated to one of the other groups. The results showed that after two treatments there was no significant difference in pain scores between the three groups. After treatment 3 until 14 days after the final treatment, the group treated with acupuncture had a significantly decreased pain score compared to the other groups. Between the NaCl and phenylbutazone group there was no significant difference. The article concluded that the decrease in TPS scores for the acupuncture group occurred after three treatments and could last at least 14 days after the fifth treatment. Deficiencies in the study include the lack of a negative control group during the second phase and the fact that treatment duration in the three groups was different. Phenylbutazone and NaCl were administered for 5 days, but acupuncture therapy was continued for 15 days (once every 3 days for five treatments). Furthermore, it is not clear if the person investigating the TPS scores was blinded to the given treatment.

Martin and Klide (1987) used 15 horses that were referred to a university clinic by other veterinarians. All horses showed signs of chronic back pain, which existed for 2–24 months and had not improved with previous therapies. Hind limb lameness, poor saddle fit and poor riding technique were ruled out as causes of the back pain. All horses were treated by injecting 1 mL of saline at the same nine acupoints once a week for 7–12 weeks with an average of nine treatments. Signs of back pain (clinical signs, behavioral signs, performance changes) were evaluated by the investigators, rider/trainer and referring veterinarian on three occasions: before, during and after the treatment period. Response to treatment was classified as alleviation of signs or no change. The horses were classified as having their signs alleviated only if all three evaluators agreed that the horse's performance was normal, there were not clinical signs of back pain and the owner/rider thought the horse could perform normally. Signs were alleviated in 13/15 horses. Six to twelve months after the final treatment, 11/13 horses that returned to normal performance were still competing without signs of back pain and the other two were no longer competing for reasons unrelated to back pain. The nomenclature of the acupoints used in this study is different from the traditional and transpositional points, which are commonly used worldwide. No explanation is given on why different points were used. No control group was included in the study, which makes it impossible to rule out a placebo effect. The exact moment of evaluation of back pain signs is not made clear in the report and the method of classification of the horses is not described. Because the classification of the horses was not performed objectively, the outcome has a high risk of being subjective.

Other studies have shown further systemic effects. Cheng et al. (1980) found that electro-acupuncture elevated blood cortisol levels in naive horses whereas sham treatment did not. Bossut et al. (1984) noted production of cutaneous analgesia by electroacupuncture in horses, with variations in response due to sex of subject and locus of stimulation. Steiss et al. (1989) used electroacupuncture to treat lameness in horses and ponies with chronic laminitis (n = 10) or navicular disease (n = 10) and assessed the degree of lameness by: 1) a grading scheme, 2) measurement of stride lengths and 3) analysis of weight distribution using a force plate. Though the majority of horses improved (60% with chronic laminitis, 70% with navicular disease) there were no statistically significant differences between treatment and control groups. Skarda et al. (2002) found that electroacupuncture was more effective than acupuncture in stimulating the spinal cord to release β-endorphins into the CSF of horses. Both methods provided cutaneous analgesia in horses, measured by use of skin twitch reflex latency without adverse cardiovascular and respiratory effects.

A considerable body of literature on acupuncture in human and veterinary alternative medicine is available, but there is a lack of good-quality study designs. Patient groups are often relatively small, negative controls are not included, and blinding is difficult. Articles have described some of the effects of acupuncture, like endorphin release or improvement of performance. Controversial outcomes are given in articles comparing acupuncture with sham treatment. It is unclear if specific acupuncture points are of greater value than a specific needling of the painful area. Further studies with larger sample sizes and relevant control groups are necessary to obtain scientific evidence to accept or reject the effectiveness of acupuncture.

Conclusions

The use of rehabilitation strategies and PT in equine veterinary medicine is rapidly expanding; to date there is a relatively small body of scientific evidence of their applications and benefits. However, the existing data are extremely promising, highlighting the beneficial effects of complementary and alternative medicine, particularly from a manual therapy and motor control approach as an adjunct to traditional medical management in the prevention, treatment, and rehabilitation of sport horses. Equine researchers should evaluate the human literature to develop research strategies, paying particular attention to therapeutic research that has used quadrupeds as an animal model for human interventions. In clinical practices that are widely used including acupuncture, electromodalities and biophysical agents including therapeutic ultrasound, magnetic field therapy, laser therapy, hydrotherapy (swimming pools, spas, underwater treadmills) and thermotherapy. These modalities are reported in the lay literature to have beneficial effects (Bromiley, 1999; Porter, 2005) but objective evidence and scientific indications for their use are not yet clear in horses. Moreover, many of these treatment techniques are still the subject of scientific dispute in the human literature. TENS and NMES, although not proven effective in the horse, are supported by many studies in relation to pain modulation and muscle tissue stimulation. Increasing evidence is appearing in the equine scientific literature to support the implementation of manual therapy and exercise-based therapies derived from scientific motor control principles. These include intervertebral joint mobilizations/manipulations, dynamic mobilization exercises and proprioceptive sensory integration techniques.

Although research and documented clinical experiences are still necessary to complement the adaptation of scientific-based principles presented in this chapter, it is the authors' opinion and clinical experience that rehabilitation/PT strategies can be successfully incorporated in conjunction with traditional veterinary medicine. A team approach with the necessary clinical reasoning skills is vital to choose the appropriate rehabilitation strategy, PT technique and objective monitoring of the patient's progress and protocol. Constant reassessment and, where possible, the use of objective measures to validate the outcome of the interventions are indicated for successful treatment strategies involving PT and rehabilitative techniques.

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CHAPTER 18

Metabolic energetics

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Introduction

The horse is a superb athlete, the result of the evolutionary adaptations required to live as a species on open landscapes. These adaptations resulted in speed, to escape predators, and endurance, necessary in the search for nutrition. Selective breeding by humans has further modified these evolutionary traits.

Domesticated horses have been selected for certain characteristics depending on the intended use. Heavy breeds were selected for draft or military work whereas lighter horses were chosen because of their speed and endurance. This has resulted in myriad breeds and capacities of each. For example, Thoroughbreds can achieve speeds of >65 km/h when racing over 800–7000 m, Standardbreds trot or pace at up to 55 km/h for up to 4000 m, Quarter Horses sprint over 400 m (1/4 mile) at speeds approaching 90 km/h, yet endurance horses (of Arabian breed) can cover 160 km at average speeds of ~25 km/h. In contrast, a pair of draft horses pull a sled weighing >2000 kg over specific distances from 3.7 to 8.5 m, whereas breeds such as Warmbloods may participate in eventing, show jumping and dressage competitions.

The athletic capacity of horses results from physiologic properties. These may be innate and as such are not affected by training, for example respiratory capacity. In contrast other variables do respond to training, including skeletal muscle respiratory capacity and blood volume. Overall, particularly when compared to humans, the noteworthy athletic ability of horses can be attributed to:

- High maximal aerobic capacity.
- Large intramuscular stores of energy, particularly glycogen.
- High respiratory capacity of skeletal muscle.
- Splenic contraction, which results in the oxygen-carrying capacity of blood increasing by up to 50% soon after the onset of exercise.
- Highly efficient and adaptable gait(s).
- Well-developed capacity for effective thermoregulation (Hinchcliff et al., 2004).

The maximal aerobic capacity of horses is over 2-fold greater than that of similarly sized cattle. This is due to many of the adaptations outlined in the previous paragraph. Substrate is required to support these high metabolic rates during exercise. Substrate to support exercise is generally either carbohydrate or fatty acids. In most species oxidation of fatty acids, although highly efficient in terms of energy yield, is limited, and is likely to reach capacity when work rate requires ~50% of the maximal oxygen consumption. Above this exercise intensity substrate is provided by the oxidation of carbohydrates, predominantly glycogen. Athletic species such as horses and dogs have high intramuscular concentrations of glycogen relative to humans. This locally available source of substrate is critical as the flux of glucose from the circulation during exercise is limited and is likely to provide no more than ~10% of the energy used during intense exercise. Mitochondria produce the energy for muscle contraction. It is not surprising therefore that skeletal muscle of horses contains approximately twice the concentration of mitochondria found in humans, sheep and cattle. These factors combined with the profound cardiac output and oxygen carrying capacity of horses permits this species to have a higher whole animal maximal aerobic capacity when compared to less athletic domestic species (Hinchcliff et al., 2004).

The circulation is responsible for transport of oxygen from the lungs to exercising muscle and other tissues. Cardiac output and oxygen-carrying capacity of blood are key determinants in this process. As stated earlier horses achieve rapid increases in the oxygen-carrying capacity of blood via exercise-induced splenic contraction. This epinephrine-induced contraction (autoinfusion) results in substantive increases (~50%) in blood hemoglobin concentrations without concomitant increases in plasma volume.

The limbs of horses are long and their associated muscles have relatively low power outputs when compared to smaller athletic species. However, despite this, horses have adapted such that their gait is energetically efficient. This results from the fact that up to 50% of the muscular work occurring during galloping is stored as elastic energy in muscle and tendon units. This mechanism is of such magnitude that it has been estimated that in the forelimb of horses, energy storage and subsequent release means key muscles of the forelimb are substantially smaller than if this process were not available (Hinchcliff et al., 2004).

Vertebrate locomotion requires the controlled integration of numerous physiological and metabolic pathways that have an impact on the musculoskeletal system to provide the organism with mobility. Perhaps the most important pathways are those concerned with the production of energy, for without energy muscles cannot contract and mobility is not achieved. One of the major survival mechanisms for the wild equid is swift retreat from threatening circumstances. Consequently, the horse has an efficient locomotor system designed to move a relatively large mass with great speed and endurance.

Muscular movement requires the transformation of chemical energy stored in metabolic fuels to the kinetic energy of muscular contraction. All pathways integral to energy supply are concerned with the ultimate production of adenosine triphosphate (ATP), the final carrier of energy ‘packages’ utilized by muscle for contraction. Muscular contraction involves coupling of thin actin and thick myosin filaments to form cross-bridges and then these filaments slide relative to each other by a change in orientation of the cross-bridges (Guyton, 1986). Energy is necessary for the change in orientation of the cross-bridges to occur. Cleavage of a high-energy phosphate bond from ATP results in adenosine diphosphate (ADP),

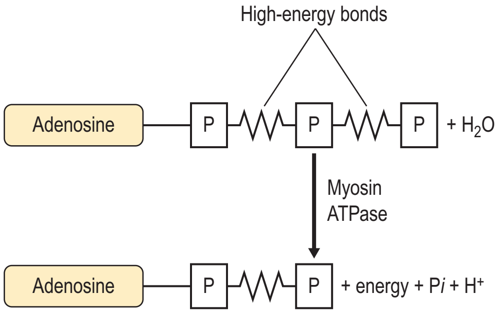

Fig 18.1 Hydrolysis of ATP to ADP by the enzyme myosin ATPase, with the release of energy for use by working muscle. P, phosphate; P*i*: orthophosphate.

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free phosphate, a proton and the release of energy. This hydrolysis reaction of ATP occurs at the head of each myosin filament and is catalyzed by the enzyme myosin ATPase (Fig. 18.1). The energy released is utilized by the working muscle (Cain & Davies, 1962).

In addition, ATP is the source of energy required to restore the contracted muscle to a relaxed or resting state via the distribution of calcium ions (Åstrand & Rodahl, 1986). Under normal conditions there is a finite store of ATP within muscle, sufficient to maintain muscular activity for only a few seconds (Lindholm, 1979; Åstrand & Rodahl, 1986). Therefore to perform continuous muscular exertion it is necessary to resynthesize ATP and this is performed by the pathways of aerobic (oxidative) and anaerobic phosphorylation.

Production of energy

Aerobic phosphorylation

Production of ATP via aerobic pathways occurs within the inner membrane of mitochondria in a series of single oxidation reactions known as the *electron transport* or *respiratory chain*. *Oxidation* is the donation or loss of electrons (often in the form of hydrogen) from an atom or molecule, while *reduction* is the acceptance of electrons (hydrogen) by an atom or molecule. When electrons are donated, considerable chemical energy is liberated and a portion of this energy is captured for the rephosphorylation of ADP to ATP, with the remainder being lost as heat energy (Guyton, 1986). Nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) act as hydrogen carriers (acceptors) during glycolysis, β-oxidation and the tricarboxylic acid (TCA) cycle and therefore are reduced to NADH and $FADH_2$. These coenzymes are essential for aerobic and anaerobic phosphorylation but their concentrations within the muscle are low. Therefore, NADH and $FADH_2$ must be reoxidized to NAD^+ and FAD via the electron transport chain. Specific mitochondrial enzymes incorporated in the electron transport chain catalyze the oxidation through a process of dehydrogenation. The donated hydrogen atoms provide the electrons that are transported from one enzyme complex to another by electron carriers, e.g. *cytochrome c*. The importance of oxygen (O_2) in this whole process is that it acts as the final hydrogen acceptor to form water. The energy released by the step-by-step transfer of electrons from NADH or $FADH_2$ to O_2 via the electron carriers is used to pump protons from the inner matrix of the mitochondrion into the outer chamber between the inner and outer mitochondrial membranes. This creates a strong transmembrane electric potential. Energy for the phosphorylation of ADP to ATP is obtained as the protons flow back through an inner membrane enzyme complex called *ATP synthetase* (Guyton, 1986; Stryer, 1988).

The availability of O_2 to the exercising muscle is the rate-limiting step for oxidative phosphorylation. Oxygen immediately available to the muscle at the onset of exercise, from myoglobin within the muscle (MbO_2), hemoglobin within the circulatory system (HbO_2) or O_2 dissolved in the body fluids, is in sufficient quantities for only a few seconds of exercise. Therefore the delivery of O_2 to the exercising muscles via the cardiorespiratory system is crucial for the capacity to continuously produce energy via aerobic means.

The two major electron donor substrates for aerobic phosphorylation are carbohydrates (CHO) and fatty acids. Glucose is the main CHO and if it is not used for immediate energy production, it is stored as glycogen, mostly in skeletal muscle and to a lesser extent in the liver (Lindholm, 1979; Hodgson et al., 1983, 1984). Adipose tissue constitutes the largest store of fatty acids (FA) (Robb et al., 1972; Stryer, 1988). Adipocytes store fat within their cytoplasm as triglycerides. Triglyceride storage also occurs to a much lesser extent in muscle (Lindholm, 1979).

Aerobic glycolysis

The importance of CHO as a substrate for energy production increases as exercise intensity increases (Hodgson, 1985; Lawrence, 1990). Glucose diffuses into the muscle cell cytoplasm from the circulation facilitated by the glucose transporter 4. Glucose transport in mammalian skeletal muscle is almost exclusively mediated by the glucose transporter 4 (GLUT-4). Insulin and muscle contraction are two potent stimuli for GLUT-4 translocation and both recruit GLUT-4 from intracellular storage sites. In equine muscle GLUT-4 is predominantly seen in the cytosol of fast type 2B fibers (Lacombe et al., 2003; van Dam, 2004). Following uptake, CHO is phosphorylated to glucose-6-phosphate (G-6-P) in a reaction catalyzed by the enzyme *hexokinase* (HK) and requiring one ATP molecule. Glucose-6-phosphate is then transferred into the glycolytic pathway for immediate energy production or reversibly converted to glucose-1-phosphate (G-1-P) and then glycogen for storage. Glycogen stores provide most of the glucose required for energy production during exercise. In the glycolytic pathway, G-6-P is phosphorylated to fructose-6-phosphate (F-6-P). Fructose-6-phosphate is then phosphorylated to fructose-1,6-bisphosphate (F-1,6-BP) in a reaction catalyzed by *phosphofructokinase* (PFK) and at the expense of one ATP molecule. Fructose-1,6-bisphosphate is subsequently split into the triose phosphate isomers, glyceraldehyde-3-phosphate (Gl-3-P) and dihydroxyacetone-phosphate (DiH-P). Dihydroxyacetone-phosphate is readily converted into Gl-3-P by *triose phosphate isomerase* (TPI). So one molecule of glucose or glycogen gives 2 molecules of Gl-3-P. Glyceraldehyde-3-phosphate then proceeds through a series of reactions with the end result being the production of pyruvate, ATP, NADH, water and hydrogen ions. The net reaction for the glycolytic pathway utilizing glucose is:

$$\begin{aligned}&\text{Glucose} + 2\text{Pi} + 2\text{ADP} + 2\text{NAD}^+\\&\quad \rightarrow 2\ \text{Pyruvate} + 2\ \text{ATP} + 2\ \text{NADH} + 2\text{H}^+ + 2\text{H}_2\text{O}\end{aligned}$$

Under aerobic conditions the hydrogen atoms are transferred to the electron transport chain and pyruvate is transported into the mitochondrial matrix as a substrate for acetyl coenzyme A (acetyl CoA). Acetyl CoA then enters the TCA cycle by combining with oxaloacetate to form citrate. The normal function of the TCA cycle requires 3 NAD^+ and 1 FAD to accept hydrogen atoms during the oxidative conversion of citrate back to oxaloacetate. When O_2 is available, the NADH and $FADH_2$ are then reoxidized back to NAD^+ and FAD in the electron transport chain, thus replenishing the adenine dinucleotide stores and producing ATP (Fig. 18.2). The complete aerobic utilization of one mole of glucose generates 36–38 ATP. When O_2 is not available, pyruvate is converted to lactate as described later.

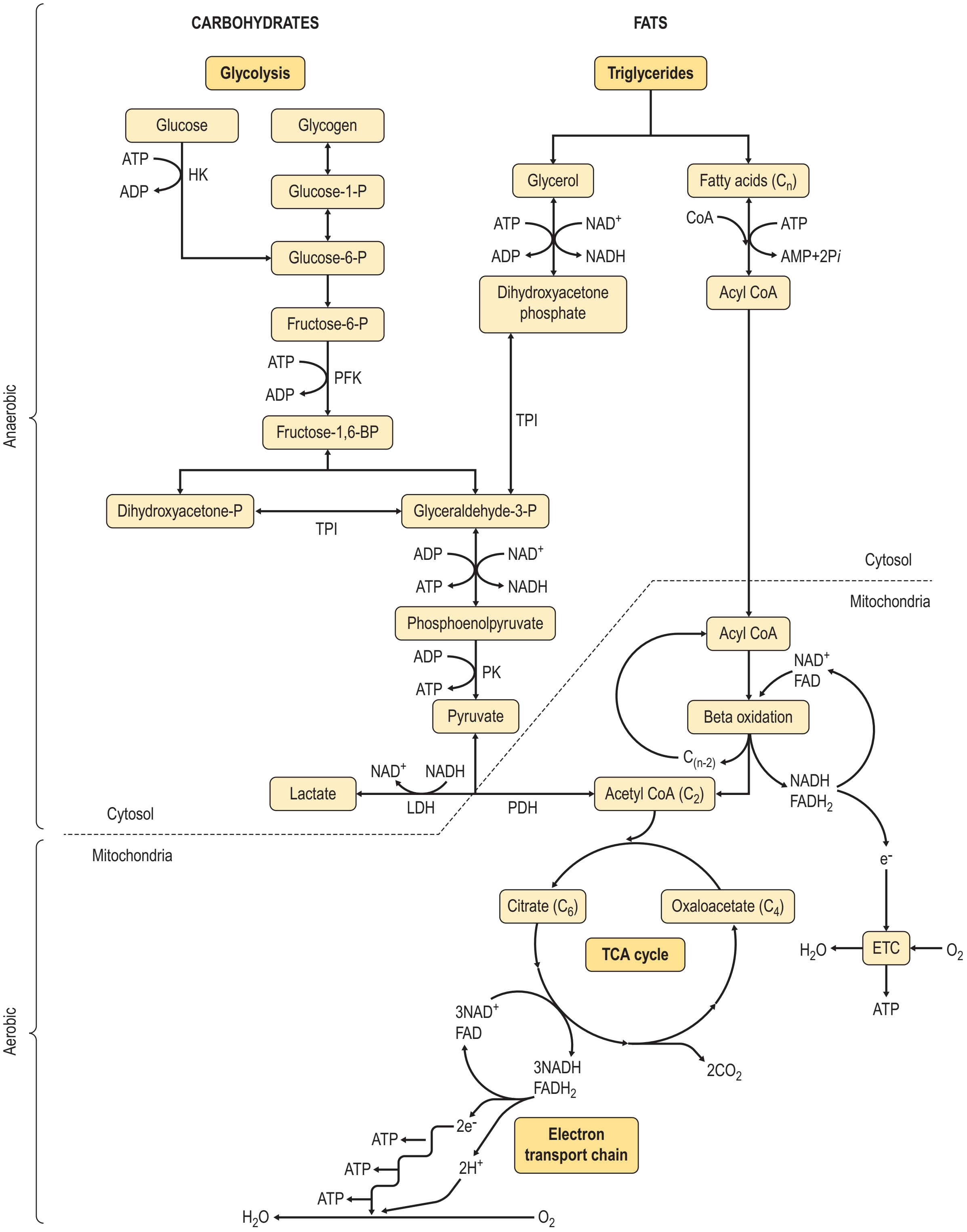

Fig 18.2 Schematic representation of the principal components of glycolysis, fatty acid oxidation, the tricarboxcylic acid (TCA) cycle and the electron transport chain (ETC) in a muscle cell. ATP, adenosine triphosphate; ADP, adenosine diphosphate; BP, bisphosphate; C, carbon; CS, citrate synthase; FAD, $FADH_2$, flavin adenine dinucleotide; HK, hexokinase; LDH, lactate dehydrogenase; NAD^+, NADH, nicotinamide adenine dinucleotide; P, phosphate; PDH, pyruvate dehydrogenase; PFK, phosphofructokinase; PK, pyruvate kinase; TPI, triose phosphate isomerase.

Fatty acid utilization

Following lipolysis, non-esterified fatty acids (NEFAs) are released into the circulation and are subsequently available as hydrogen donors for energy production in skeletal muscle. NEFAs likely diffuse into muscle cells down a concentration gradient (Hodgson, 1985) as well as being actively transported across the cell membrane. The latter is facilitated by a membrane-associated protein called membrane fatty acid translocase (FAT/CD36). This membrane fatty acid translocase resides in intracellular membrane fractions and translocates to the plasma membrane of skeletal muscle cells also after insulin or contraction stimuli and is seen intracellularly in equine muscle exclusively in type 1 fibers (van Dam, 2004). At the cytoplasmic surface of the outer mitochondrial membrane, the NEFAs are esterified (activated) enzymatically forming long-chain acyl CoA molecules. The acyl CoA molecules are then linked to carnitine and shuttled across to the matrix side of the inner mitochondrial membrane. In the mitochondria the acyl CoA molecules undergo a series of four reactions known as *β-oxidation*. With each cycle of β-oxidation two-carbon (C_2) units are sequentially removed from the acyl CoA molecule and acetyl CoA, NADH and $FADH_2$ are produced (Fig. 18.2). NADH and $FADH_2$ subsequently donate their electrons in the electron transport chain generating ATP and being reoxidized to NAD^+ and FAD in the process. Acetyl CoA is utilized in the TCA cycle as previously described. The splitting of C_2 units from the parent acyl CoA molecule is repeated until the whole chain has been cleaved into the acetyl CoA molecules. The number of carbon atoms in the parent FA chain will determine the net energy yield from β-oxidation. Complete oxidation of one palmitic acid molecule produces 129 molecules of ATP.

Anaerobic phosphorylation

The pathways of anaerobic phosphorylation occur solely in the muscle cell cytoplasm, with no reactions in the mitochondria as there are for aerobic phosphorylation. However, in general mitochondria are no longer the once-thought uniform ATP-producing organelles, identical in all organisms, but are rather diverse and adapted to distinct conditions. Next to the classical aerobic mitochondria, which contain a respiratory chain and use oxygen as a final electron acceptor, anaerobically functioning mitochondria were identified that also contain a respiratory chain and perform oxidative phosphorylation, but do not use oxygen as a terminal electron acceptor. The energy metabolism in anaerobic mitochondria differs from that in aerobic mitochondria, as no external final electron acceptors are used (Tielens & van Hellemond, 2007).

With the initiation of exercise there is a lag period before oxidative energy production becomes an important source of ATP. During this time rapid supplies of ATP must still be available if muscular contraction is to continue. Stores of ATP in skeletal muscle are limited (4–6 mmol/kg wet muscle) and contribute little to the total energy supply (Lindholm & Piehl, 1974; McMiken, 1983). Until aerobic phosphorylation makes a substantial contribution to energy supply, rapid regeneration of ATP must occur in the absence of O_2. The anaerobic phosphorylation of ADP is achieved by three pathways: the phosphocreatine reaction, the myokinase reaction and anaerobic glycolysis. The former two pathways may be described as anaerobic alactic reactions because no lactate is produced as it is in the latter process (Clayton, 1991).

Phosphocreatine reaction

In this pathway the enzyme *creatine kinase* catalyzes a reversible reaction where creatine phosphate (CP or phosphocreatine) donates its high-energy phosphate to ADP producing ATP:

$$\text{CP} + \text{ADP} \rightarrow \text{Creatine} + \text{ATP}$$

In the *gluteus medius* muscle of Standardbreds, the size of the CP pool is estimated to be 15–20 mmol/kg wet muscle (Lindholm & Piehl, 1974; Lindholm, 1979). This source of ATP replenishment would support maximum intensity exercise for no more than a few seconds (Åstrand & Rodahl, 1986; Clayton, 1991).

Myokinase reaction

The *myokinase* enzyme catalyzes the synthesis of ATP and adenosine monophosphate (AMP) from two ADP molecules:

$$\text{ADP} + \text{ADP} \rightarrow \text{ATP} + \text{AMP}$$

At rest, this reaction proceeds at an approximately equal rate in both directions with little net ATP being produced. In working muscle, *AMP-deaminase* reduces AMP concentration by converting it to ionosine monophosphate (IMP) and ammonia. This provides the driving force for the myokinase reaction towards the production of ATP (McMiken, 1983). Again this pathway only has the capabilities of providing small amounts of ATP.

Anaerobic glycolysis

The anaerobic production of two molecules of pyruvate from one molecule of glucose or glycogen is identical to that described for aerobic glycolysis. In the absence of available O_2, pyruvate accepts hydrogen atoms from NADH and is converted to lactate, rather than being converted to acetyl CoA and entering the TCA cycle. The reaction is catalyzed by *lactate dehydrogenase* and the regeneration of NAD^+ during the reduction of pyruvate to lactate sustains glycolysis under anaerobic conditions (Fig. 18.2). The net result of anaerobic glycolysis is the production of three molecules of ATP from one molecule of glycogen or two molecules of ATP from one molecule of glucose. This form of energy production is relatively rapid compared to aerobic glycolysis but yields a significantly lower amount of ATP and substrates are limited.

Regulation of aerobic and anaerobic pathways

At all exercise levels both systems of energy supply are active; however, one will predominate, depending in particular on the intensity and duration of the activity. A complex method of metabolic regulation controls the input of each pathway. Substrate and enzyme availability, end product concentrations and various feedback mechanisms contribute to pathway dynamics.

Oxygen supply to muscle and the ratio of ATP:ADP are the most significant regulators of the energy producing pathways. When adequate O_2 is available aerobic phosphorylation persists, providing a driving force for substrate to enter the TCA cycle and produce high concentrations of citrate. Citrate retards the activity of PFK, the enzyme responsible for the irreversible conversion of F-6-P to F-1,6-BP in the glycolytic pathway. This has the effect of inhibiting glucose and glycogen metabolism. Accumulation of glycolytic intermediates before the PFK step, including G-6-P, inhibits the activities of HK and phosphorylase, thus also dampening the glycolytic pathway. High cellular concentrations of ATP (i.e. a high ATP : ADP ratio) also inhibits PFK activity. *Pyruvate kinase*, the third control site in glycolysis, is inhibited by ATP and activated by F-1,6-BP. When the relatively slow production of energy by oxidative phosphorylation is unable to meet the demands for ATP, the ATP : ADP ratio swings in favor of ADP and this in turn stimulates PFK and enhances glycolysis and the utilization of glucose and glycogen stores. The pyruvate produced is metabolized to lactate and this allows the reoxidization of NADH to NAD^+ for continued electron acceptance in the glycolytic pathway.

Control of the TCA cycle starts with regulation of the irreversible oxidative decarboxylation of pyruvate to acetyl CoA by *pyruvate dehydrogenase* (PDH). Acetyl CoA, NADH and ATP inhibit PDH activity. Once acetyl CoA is formed, its combination with oxaloacetate to produce citrate is inhibited by high concentrations of ATP. At least two other sites in the TCA cycle have regulatory mechanisms that respond to the cellular concentrations of ATP. Overall the rate of the TCA cycle is reduced when abundant ATP is present but it should also be remembered the TCA cycle operates only under aerobic conditions because of the constant need for NAD^+ and FAD.

The rate of oxidative phosphorylation is regulated by the cellular ADP concentration. This is known as *respiratory control*. For electrons to flow through the electron transport chain to O_2 the simultaneous phosphorylation of ADP to ATP is usually required. When ATP is utilized ADP concentrations increase and therefore the rate of oxidative phosphorylation increases, assuming an adequate O_2 supply is available. So oxidative phosphorylation is coupled to ATP utilization via the relative ADP concentration.

Enzymes in the β-oxidation pathway are inhibited by NADH and acetyl CoA; however, the rate of FA oxidation is determined greatly by substrate availability.

Energy pathway contributions in the exercising horse

The duration and intensity of exercise determine the metabolic requirements of muscle. At any given time the most effective combination of the various energy-producing pathways will occur and, again, it should be emphasized that no form of exercise by the horse is entirely aerobic or anaerobic in nature.

At the initiation of exercise, the immediate source of energy is locally available ATP (McMiken, 1983). As previously noted, this supply of ATP is limited and rapidly depleted, so for exercise to continue ATP must be replenished by other processes. Creatine phosphate and the phosphocreatine pathway provide the next rapidly available ATP source; however, this energy supply is also of limited capacity. The myokinase reaction provides a further means of regenerating ATP but it is restricted to certain muscle fiber types and is used in anaerobic exercise only when these fibers are recruited (Meyer et al., 1980). The myokinase reaction (and associated NH_3 production) is believed to have a minor role in energy production overall.

The glycolytic pathway with the production of pyruvate and lactate provides the main ongoing ATP source and reaches peak metabolism within about 30 s of the onset of exercise (McMiken, 1983). The delay in maximal glycolytic output is possibly due to the multiple and complex reactions required (McMiken, 1983). The large stores of glycogen in equine muscle (Lindholm & Piehl, 1974; Lindholm et al., 1974; Lindholm, 1979; Nimmo & Snow, 1983; Hodgson et al., 1984) allow this pathway to provide an early consistent source of energy, but still there is a finite limit to this substrate. On the other hand, this large store of glycogen in equine muscle might explain the fact that ketogenesis is a very limited pathway of energy production in the equine species (van der Kolk, 1995).

Aerobic mechanisms for ATP replenishment represent the most efficient means of substrate production. However, it is the slowest pathway to respond to exercise demands, owing to the cardiovascular lag in supplying O_2 to the cells and the intricacy of the reactions. Oxidative processes are in full production approximately 1 min after the onset of exercise and then muscular energy is more likely to be dependent on the rate of oxygen transport to the cells rather than substrate availability (McMiken, 1983).

At rest and during low-intensity exercise (walking and trotting), aerobic pathways provide most energy requirements after the initial lag period (Åstrand & Rodahl, 1986). At this exercise intensity the ratio of ATP to ADP will be high; PFK will therefore be inhibited and β-oxidation of fatty acids will provide the main method for ATP regeneration (Hodgson, 1985; Lawrence, 1990). Such is the case during endurance rides where it is well recorded that blood concentrations of NEFA increase and the glycogen utilization rate is low (Lucke & Hall, 1980; Snow et al., 1982; Hodgson et al., 1983; Hodgson, 1985) (Tables 18.1 and 18.2).

Table 18.1 Rates of glycogen utilization in horses performing various types of athletic activities

Type of exercise	Average speed (m/min)	Glycogen utilization*
Endurance ride		
40 km	187	1.47
110 km	173	0.41
160 km	180–135	0.69
3-day event		
Cross-country phase (23.1 km)	293 (range 220–690)	4.08
Trotting		
4 h	300	0.50[†] (2.0)
1 h	500	0.175[†] (7.0)
5 min	750	15.0[†] (6.0)
Racing		
506 m	870	149.4
800 m	920	191.9
1025 m	846	129.3
1200 m	960	126.5
1600 m	756	66.5
3620 m	684	18.8

Note: At speeds greater than 500–600 m/min, intensity of exercise is such that aerobic phosphorylation is unable to meet all the energy needs of the working muscle; therefore anaerobic glycolysis plays a major role in the supply of energy. As a result, glycogen utilization increases dramatically at these and faster speeds.

*Millimoles glucose units per kg muscle per min (dry weight).

[†] Millimoles glucose units per kg muscle per min (wet weight). Approximate figures for dry weight values are presented in parentheses.

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As exercise intensity increases, ADP accumulates and this stimulates anaerobic glycolytic energy production with a dramatic increase in the use of CHO substrates (see Table 18.1). Galloping and bursts of intense exercise, such as during polo and jumping, rely heavily on anaerobic energy supply. The self-limiting nature of anaerobic power output (substrate exhaustion) means the horse can only maintain maximal speed for about 600–800 m. After this distance, energy supply falls back to the slower aerobic pathways, necessitating a reduction in speed of exercise (McMiken, 1983; Hodgson, 1985).

Energy substrates

Scientific data on the relationship between nutrition and equine performance has occupied the attention of many researchers; however, it is difficult to design controlled experiments that isolate

Table 18.2 Mean plasma non-esterified fatty acid (NEFA) concentration in horses performing various athletic activities

Type of exercise	Mean plasma NEFA concentration (μmol/L)
80 km endurance ride	
Pre-exercise	47
Post-exercise	1254
3-day event cross-country with phases A, B, C and D	
Pre-exercise	156
After steeplechase and roads and tracks section	586
After cross-country section	324
Galloping (1.2 km)	
Pre-exercise	246
Post-exercise	279

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Table 18.3 Estimation of energy stores for a 500-kg horse with a muscle mass of 206 kg (approximately 55 kg being locomotor muscles), adipose tissue of 25 kg and a liver of 6.5 kg

Fuel	Energy	
	kJ	kcal
ATP	38	9
Creatine phosphate	188	45
Glycogen	75 300	17 988
Fat	640 000	152 889

Adapted and reprinted from McMiken, D.F. (1983) An energetic basis of equine performance. Equine Vet. J. 15 (2), 123–133, with permission from the Equine Veterinary Journal.

nutritional influences on performance. Subtle, yet important effects of nutritional alterations may go undetected partly because the power of statistical studies is limited by the small numbers of horses often used in experiments (Hintz, 1994). The relationship between energy and exercise is complex and inseparable. The amount of energy required depends on the type and duration of activity and the horse's body weight. Maintenance digestible energy (DE) requirements are linearly related to body weight (Pagan & Hintz, 1986a). During submaximal exercise energy expenditure is exponentially related to speed and proportional to the body weight of the riderless horse or the combined weight of the horse plus rider (Pagan & Hintz, 1986b). The method used by Pagan and Hintz (1986b) for calculating energy requirements was based only on the amount of work performed and may not account for any follow-on demands for energy in recovery that the work bout stimulates (Lawrence, 1990).

The stores of major fuels in the horse for muscular contraction are outlined in Table 18.3 as calculated by McMiken (1983). It is clear that 'fast' energy stores (i.e. ATP, creatine phosphate and glycogen) are limited despite the high capacity for glycogen storage in equine muscle. The primary dietary sources of energy stores for the horse are soluble and fiber CHOs and fats. Protein is considered to play a minor role as an energy source.

Carbohydrates

Absorbed CHO is immediately available as an energy source in the form of blood glucose. Muscle and liver provide the reservoirs for excess CHO where it is stored as glycogen. Numerous studies have documented the depletion of muscle glycogen stores that occurs with exercise in the horse (Lindholm et al., 1974; Lindholm, 1979; Hodgson et al., 1983; Nimmo & Snow, 1983). The rate of, and percentage, depletion that results is a function of the intensity and duration of exercise. Muscle glycogen utilization/min is greatest at the faster speeds over shorter distances (Nimmo & Snow, 1983; Hodgson et al., 1984) (Table 18.1) but the total percentage of glycogen depletion increases with increasing duration of exercise (Snow et al., 1981, 1982; Hodgson et al., 1983). Liver glycogen stores are also depleted significantly during exercise (Lindholm et al., 1974; Lindholm, 1979). Restoration of depleted muscle glycogen stores takes up to 48–72 h in the horse (Davie et al., 1995; Lacombe et al., 2004), which is 2–3 times slower compared to man (up to 24 h). Recent research suggests that the low rate of glycogen synthesis in horses may be due to a reduced rate of absorption of CHO from the gastrointestinal tract, combined with reduced skeletal muscle glucose uptake compared to man (Waller & Lindinger, 2010). The rate of skeletal muscle glycogen uptake is determined by several factors among them the amount of initial muscle glycogen, carbohydrate availability, glucose transport into muscle and activity of glycogen synthase (GS).

In man, glycogen synthesis in muscle post exercise occurs in two phases. During the first hour of recovery, there is a rapid insulin independent phase stimulated by glycogen depletion and contraction stimulated GLUT-4 translocation, followed by a slower insulin dependent phase with marked increased muscle insulin sensitivity up to 48 h (Price et al., 1994). Post exercise increases in insulin sensitivity facilitate rapid muscle glycogen synthesis after glycogen depleting exercise in man. However, in the horse no increase in insulin sensitivity could be found 24 h after a single bout of exercise in trained horses (De Graaf-Roelfsema et al., 2006; Pratt et al., 2007). In addition, no increase in crude muscle membrane GLUT-4 content was found after exercise inducing 40–50% glycogen depletion (Pratt et al., 2007; Nout et al., 2003).

Glycogen synthase (GS) is activated by insulin binding to its cell surface receptor and the rate of GS synthesis is inversely proportional to muscle glycogen in contraction- and insulin-stimulated muscle in horses (Pratt et al., 2007) although less marked than in man.

Although single bouts of exercise does not seem to influence glycogen replenishment rate, training and overtraining have been shown to influence peripheral insulin sensitivity. Several studies describe an increase in insulin sensitivity after training horses for a short period (Pratt et al., 2006, Stewart-Hunt et al., 2006). Also overtrained horses have been shown to increase insulin sensitivity (De Graaf-Roelfsema et al., 2012). The underlying mechanisms are not completely understood yet.

Fat

Assimilated fats are stored as triglycerides (uncharged esters of glycerol) in adipose tissue and muscle. Quantitatively, adipose tissue constitutes the largest energy store in the body (see Table 18.3). Triglyceride concentrations in muscle are considerably less than in fat (Lindholm, 1979). The triglycerides are highly concentrated stores of energy because they are reduced and anhydrous (Stryer, 1988). The initial event in the utilization of triglycerides as an energy substrate is their hydrolysis by lipases to glycerol and free fatty acids (FFA). Lipolysis is stimulated by epinephrine,

Starch/glucose → ↑ insulin → ↓ catecholamines → ↓ lipolysis → ↑ glycogenolysis → ↓ endurance and speed?

Fats → ↑ citrate → ↓ phosphofructokinase → ↓ glycogenolysis

Glucose during exercise → ↑ glycemia, extends endurance time?

Fig 18.3 Effect of consumption of carbohydrate or fat immediately before or during exercise on energy metabolism.
Reprinted from Frape, D.L., (1988) Dietary requirements and athletic performanceof horses, Equine Vet J, 20 (3), 163–172, with permission from the Equine Veterinary Journal.

norepinephrine, glucagon and adrenocorticotrophic hormone and inhibited by insulin via hormone sensitive lipase. Glycerol is converted in a number of steps to Gl-3-P, which is an intermediate in both the glycolytic and gluconeogenic pathways. The FFAs undergo β-oxidation and enter the TCA cycle as previously described. Oleic, palmitic and linoleic acids (Robb et al., 1972; Westermann, 2008a) as well as 3-OH-butyric and 3-OH-iso-butyric acid (Westermann, 2008a) represent the major FAs in the equine species.

Fat has been shown to be the major energy substrate during low-intensity exercise. This is best evidenced by a decrease in the respiratory exchange ratio (R) (McMiken, 1983; Pagan et al., 1987; Rose et al., 1991) and an increase in plasma NEFA concentrations (Lindholm, 1979; Rose et al., 1980; Essén-Gustavsson et al., 1991) that occurs with prolonged submaximal exercise. R is calculated by dividing the volume of carbon dioxide (CO_2) expired by the volume of O_2 consumed during exercise. R values around 0.7 indicate fat utilization whereas for CHO utilization the value is 1.0. Values within this range reflect various mixtures of FA and CHO metabolism. When anaerobic metabolism predominates R values will exceed 1.0 because lactate production is high, thereby adding to the CO_2 load to be eliminated. In addition, in the equine species carnitine forms esters predominantly with short- and medium-chain fatty acids in plasma. Submaximal exercise in Standardbreds mainly affected concentrations of short-chain acylcarnitines (Westermann, 2008a).

Protein

Digested protein is absorbed from the small intestine as amino acids and small peptides. When amino acids are available in excess of the animal's requirements they may be broken down to provide energy. Degradation by deamination or transamination reactions occurs mostly in the liver, with the final product being acetyl CoA for utilization in the TCA cycle. Leucine, a branched-chain amino acid, may undergo oxidation directly in muscle (Lawrence, 1990). The contribution of amino acids to energy production during exercise is minor compared to that of CHO and FA (Åstrand & Rodahl, 1986), perhaps in the range of 1–15% (Lawrence, 1990). High protein diets (up to 16%) were once thought necessary to sustain the performance of mature equine athletes but now it is considered that approximately 10% protein in the diet is adequate (Snow, 1994). The main amino acids in equine plasma are serine, glutamine, proline, glycine, alanine, and valine. Training of Standardbreds reduced plasma concentrations of aspartic acid (Westermann, 2010).

Effects of dietary alterations on energy substrate utilization

Many published reports have described the effect that altering components of the normal diet has on substrate utilization and performance in the horse. The consumption of large amounts of digestible CHO within a few hours of strenuous activity may depress the performance of that exercise (Åstrand & Rodahl, 1986). This is possible because insulin-stimulated uptake of blood glucose results in hypoglycemia and a greater dependence on muscle glycogen and therefore earlier onset of fatigue. Free FA mobilization is also inhibited by insulin. Frape (1988) summarized the effects of consumption of CHO or fat before or during exercise on metabolism, as depicted in Figure 18.3.

On the other hand, a lack of available CHO during submaximal exercise can also limit performance and there is strong evidence supporting the use of high CHO diets by humans for endurance exercise (Lawrence, 1990). In humans, muscle glycogen loading was achieved by performing intense exercise and then consuming a CHO-rich diet (Lindholm, 1979). Current practice is to combine a program of decreased activity with increased CHO consumption a few days before competition to achieve a glycogen load. Glycogen loading in horses has been accomplished but no obvious improvement in work performance has been demonstrated (Topliff et al., 1983, 1985; Frape, 1988; Lawrence, 1990; Snow, 1994). Intravenous, but not oral, glucose supplementation has increased glycogen repletion rates after exercise (Snow et al., 1987; Davie et al., 1994, 1995; Snow, 1994). Although glycogen loading is not recommended in the horse adequate CHO intake must still be ensured (Hintz, 1994). A low CHO diet and regular exercise leads to glycogen depletion and decreased performance in horses (Topliff et al., 1983, 1985). In a study where fit Standardbreds were exercised strenuously for 3 consecutive days to achieve a 55% depletion of the muscle glycogen store, anaerobic, but not aerobic, capacity was impaired (Lacombe et al., 1999). However the association between glycogen depletion and impaired anaerobic metabolism is not conclusive as confounding effects of other exercise-induced changes on performance could not be eliminated (Lacombe et al., 1999). When muscle glycogen was depleted by 22% there was no significant effect on performance of Thoroughbreds exercising at high intensities (Davie et al., 1996).

A CHO supplement taken an hour or two before exercise does not seem to benefit endurance performance but intake of glucose during exercise may supplement waning plasma concentrations and delay onset of fatigue (Lawrence, 1990) (see Fig. 18.3).

The beneficial effects of feeding high-fat diets to horses remains shrouded in controversy. Differences in the condition of the horses, type of exercise, the length of the adaptation period to the diets, the type of fat used as the supplement, and the level of fat supplemented, particularly in relation to CHO, make comparing the published results difficult (Lawrence, 1990; Hintz, 1994). Many variations in study designs influence results obtained. Feeding an increased level of fat is suggested to cause metabolic adaptations like increase in equine heparin-released lipoprotein lipase activity (Geelen et al., 2001) that permits horses to preferentially utilize fat and spare glycogen during exercise but the evidence to support such a proposal is inconclusive (Lawrence, 1990; Hintz, 1994; Snow, 1994; Geelen et al., 2000). Furthermore, it should be realized that dietary soyabean oil depresses the apparent digestibility of fiber when substituted for an iso-energetic amount of cornstarch or glucose (Jansen et al., 2002).

It has been suggested that improvements in oxidative capacity can be brought about by certain amino acid supplements (Lawrence, 1990; Hintz, 1994). Higher than necessary protein diets are often fed to performance horses but studies to indicate that this practice enhances exercise capabilities are lacking (Lawrence, 1990). On CHO-rich and fat-rich diets, plasma concentrations of glucose, ammonia, lactate, alanine and the muscle concentrations of G-6-P and lactate were higher at the end of exercise compared to normal diets (Essén-Gustavsson et al., 1991). Higher pre-exercise muscle glycogen concentrations and FFA concentrations were present in the horses fed a CHO-rich diet when compared to the fat-rich and normal-diet fed periods. No significant difference in performance during trotting at submaximal intensity on a horizontal treadmill was detected between the three diets (Essén-Gustavsson et al., 1991) with the average time to fatigue being 51–56 min. Whether or not the diets would alter performance in shorter or longer exercise periods remains unanswered. The effects on protein metabolism need to be further investigated as both the CHO-rich and the fat-rich diets were associated with significant increases in branched-chain amino acids in the plasma during and at the end of exercise compared to the normal diet (Essén-Gustavsson et al., 1991). The resting plasma concentration of the branched-chain amino acids was increased 26% on the fat-rich diet but only 8% on the CHO-rich diet.

A 9% (control) or 18.5% (high) crude protein diet had no effect on hepatic or muscular glycogen utilization and did not affect exercise performance in Quarter Horses exercising at submaximal intensities (Miller-Graber et al., 1991). Performance of Arabian endurance horses was not augmented by excessive protein in their diet (Hintz, 1983). In contrast, Standardbreds fed a high-protein diet (20%) or high-fat diet (15% soybean oil) showed greater muscle and liver glycogen utilization during prolonged exercise compared to when fed a control diet of 12% crude protein (Pagan et al., 1987). During higher-intensity, shorter-duration exercise, glycogen utilization was less when horses were fed the high-protein or high-fat diets. Of interest, there was no difference in concentrations of various plasma amino acids in overtrained Standardbreds and age-matched controls (Westermann, 2010).

The timing of feeding and what to feed before exercise has considerable influence on the metabolic and physiological responses to exercise (Lawrence et al., 1995; Harris & Graham-Thiers, 1999). In one study, it was concluded that feeding only hay shortly before exercise would not adversely affect performance but feeding grain would, and that therefore grain should be withheld (Pagan & Harris, 1999).

Of course, many other nutritional components not discussed in this chapter may play roles in equine performance (Marlin & Nankervis, 2002; Hinchcliff et al., 2004). These include water, electrolytes, acid–base balance, minerals and vitamins.

Energy expenditure

Aerobic power

Oxygen uptake

The oxygen consumed by the body at a given time is a measure of the body's total aerobic metabolic rate and is termed the oxygen uptake ($\dot{V}O_2$). Units of measurement are usually milliliters of oxygen per kilogram of body weight per minute (mL/kg/min) or liters per minute (L/min), therefore representing a rate of consumption and not a finite capacity. The maximum rate of oxygen uptake is called the $\dot{V}O_{2max}$. Oxygen consumption by the body is principally a function of the cardiorespiratory system to supply oxygen and the capacity of end organs to utilize oxygen. The sequence of events is described as the *oxygen transport chain* (Fig. 18.4). It is influenced by the O_2 concentration in the air, ventilation of the lungs, diffusion of O_2 through the alveolar wall, circulatory perfusion of the lungs and affinity of hemoglobin (Hb) for O_2, distribution of O_2 to the periphery by the circulation, extraction by the end organ (muscle) and, finally, O_2 utilization by the mitochondria. A large number of physiological variables contribute to the capacity of the oxygen transport chain.

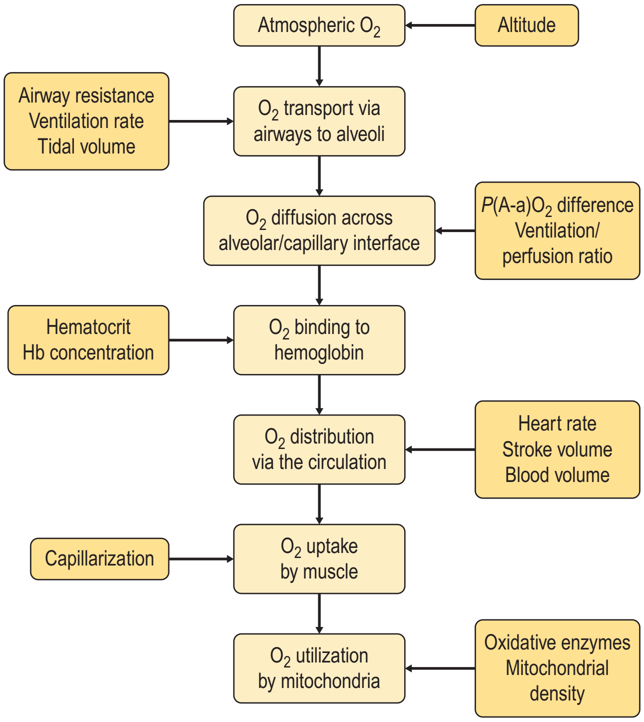

Fig 18.4 The oxygen transport chain, indicating the steps in the transfer of oxygen from the inspired air to the final utilization by the mitochondria. Physiological variables that will influence the capacity of the oxygen transport chain are listed beside each step they affect. Hb, hemoglobin; P(A–a)O_2, alveolar – arterial oxygen pressure.

Oxygen uptake at rest and during submaximal exercise

At rest, $\dot{V}O_2$ is in the order of 3–5 mL/kg/min or 1.5–2.5 L/min for a 500-kg horse (Thornton et al., 1983; Eaton, 1994). It can be difficult to accurately obtain a basal $\dot{V}O_2$ prior to exercise as often horses are excited in anticipation of impending activity. Therefore a resting $\dot{V}O_2$ level of 2 mL/kg/min may be more realistic (Eaton, 1994).

During submaximal exercise a number of factors will influence the level of $\dot{V}O_2$, including speed of exercise, load being carried, degree of incline on which exercise is being performed, duration of exercise, thermoregulation and track surface.

There is a well-established linear relationship between $\dot{V}O_2$ and the speed of exercise at submaximal intensities in horses (Hoyt & Taylor, 1981; Hörnicke et al., 1983; Evans & Rose, 1987, 1988a; Rose et al., 1990a; Eaton, 1994) and humans (Åstrand & Rodahl, 1986). When speed increases such that $\dot{V}O_{2max}$ is approached, this linear relationship is lost as $\dot{V}O_2$ plateaus and anaerobic sources of energy production become significant. In addition, if horses exercise at unnatural (extended or restricted) gaits the linear relationship will be lost due to a loss in economy of locomotion (Hoyt & Taylor, 1981; Eaton, 1994; Preedy & Colborne, 2001; Wickler et al., 2001; Griffin et al., 2004).

Few equine sports are performed without the horse carrying an extra load in the form of a rider or driver. Oxygen consumption (or energy expenditure) increases in proportion to the load carried (Taylor et al., 1980; Pagan & Hintz, 1986b; Thornton et al., 1987; Gottlieb-Vedi, et al., 1991).

Taylor and colleagues (1980) reported that when a 10% load was added to the horse when trotting, $\dot{V}O_2$ increased approximately 10% and this direct proportionality was consistent for loads between 7% and 27% of the horse's body mass. A direct proportionality between load and $V.O_2$ was also demonstrated for trotting rats, trotting and galloping dogs and running humans (Taylor et al., 1980). As a consequence, small animals use more oxygen and expend more energy to carry each gram of a load a given distance than do large animals, be it their own body mass or an additional load carried. Pagan and Hintz (1986b) demonstrated that a 450-kg horse with a 50-kg rider would expend the same amount of energy as a 500-kg horse. Thornton and colleagues (1987) found no significant difference in the oxygen cost per kilogram per meter traveled between loaded and unloaded horses. The increase in $V.O_2$ due to load is achieved largely by an increase in ventilation until maximum tidal volume is approached (Thornton et al., 1987) and this is readily explained by the close and linear relationship between $V.O_2$ and pulmonary ventilation (Hörnicke et al., 1983; Gottlieb-Vedi et al., 1991).

The implications for racing performance should be considered. A horse of less mass will expend proportionally less total energy to move the same distance when compared to a heavier horse.

The degree of incline on which exercise is being performed has a significant impact on $V.O_2$. For Standardbreds, trotting on a 6.25% inclined treadmill at an average speed of 5.2 m/s, $V.O_2$ increased from a mean of 17.7 L/min on the flat to 31.1 L/min on the slope (mean change of 13.4 L/min; 76%, p <0.001) (Thornton et al., 1987). The addition of a load when doing the inclined exercise did not significantly add to the oxygen cost of the exercise. Thoroughbreds exercising on a treadmill at speeds of 1–13 m/s also showed a substantial increase in $V.O_2$ when the treadmill slope was elevated from 0–5% and 10% (Eaton et al., 1995a). Exercising on a 10% slope can double the energy expenditure at some speeds.

When trotting on an inclined treadmill over a range of speeds, $V.O_{2max}$ is higher during inclined than level running (McDonough et al., 2002) and a greater volume of muscle would have to be recruited to generate an equivalent force for body support, which is reflected in significant increases in the EMG intensity (IEMG) of muscles (Wickler et al., 2005). In addition, normal training in Standardbreds resulted in a significant adaptation of quantitative needle electromyography (QEMG) parameters. Compared with normal trained controls, intensively trained Standardbreds showed a stronger adaptation (e.g. higher amplitude, shorter duration and fewer turns) in QEMG variables resembling potentially synchronization of individual motor unit fiber action potentials (Wijnberg et al., 2008).

Wickler et al. (2004) found that the costs of swinging the limbs in the horse are considerable and the addition of weights to the distal limb can have a profound effect on not only the energetics of locomotion but also the kinematics, at least in the hind limb. Thus, they proved that the use of weighted shoes, intended to increase animation of the gait, increases the metabolic effort of performance horses a disproportionate amount. The additional mass also increases the joint range of motion and, potentially, the likelihood of injury.

The terrain of endurance rides and cross-country tracks in three-day events ensure that much work up and down gradients will be performed and this will play a large role in determining energy expenditure. Little investigation has been done regarding the effect of a downhill gradient on energy expenditure in horses but in humans the energy cost of moving down a slope decreases up to a certain steepness and then becomes more expensive compared to level exercise (Åstrand & Rodahl, 1986).

The effect that duration of exercise has on $V.O_2$ has not been frequently investigated. Rose and Evans (1986) monitored cardiorespiratory and metabolic alterations during 90 min of submaximal exercise in Standardbreds. The horses trotted on a slope of 2% at 3 m/s. Many of the respiratory variables measured, including $V.O_2$, reached a steady state within 5 min of the start of exercise and remained stable for the duration of the exercise period. Oxygen consumption from 5 min onwards did not alter significantly until a slight decrease was identified at 90 min. It was proposed that fluid and electrolyte losses in the sweat, contributing to thermoregulatory and circulatory problems, would be key factors in the horse's ability to perform endurance activity (Rose & Evans, 1986). Naturally, the intensity of exercise will be a determinant of the duration of any activity.

The effect of temperature on $V.O_2$ will be a consequence of any impedance that altered thermoregulation may have on energy demands. Redistribution of cardiac output to skin for heat dissipation, fluid shifts and metabolic disturbances may all contribute to a less-efficient oxygen transport chain and therefore diminished performance. The optimum temperature range for oxygen utilization has yet to be established.

Track surfaces may affect the economy of locomotion due to altered stride patterns (change in frequency and length of stride) in slippery, uneven or 'heavy' conditions. Quantifying track effects on energy expenditure is difficult but Thoroughbreds and endurance horses have longer race times in heavy conditions (Eaton, 1994). Different treadmills also influence the energetic cost of locomotion: it costs less energy for horses to walk, trot or canter on a stiffer treadmill than on a more compliant treadmill (Jones et al., 2006).

It has been reported that major horse race times and records improved by 5–7% around 1900 when jockeys adopted a crouched posture. When animals carry loads, there is a proportionate increase in metabolic cost, and in humans this increase in cost is reduced when the load is elastically coupled to the load bearer. Pfau et al., (2009) showed that jockeys move to isolate themselves from the movement of their mount, which would be difficult or impossible with a seated or upright, straight-legged posture. This isolation means that the horse supports the jockey's body weight but does not have to move the jockey through each cyclical stride path. This posture requires substantial work by jockeys, who have near-maximum heart rates during racing.

Maximum aerobic power

When $V.O_2$ no longer increases despite an increase in workload, the horse is defined as having reached $V.O_{2max}$. This value represents the 'gold standard' measure for maximum or peak aerobic power. Thoroughbred horses have mean $V.O_{2max}$ values around 150–170 mL/kg/min (Evans & Rose, 1987; Rose, et al., 1990a), easily twice the values for elite human athletes (69–85 mL/kg/min), 1.5 times those of greyhounds (100 mL/kg/min) and 3 times those of racing camels (51 mL/kg/min) (Derman & Noakes, 1994). Oxygen consumption can be calculated by the following equation:

$$V.O_2 = CO \bullet (a\text{-}v)O_2$$

where CO = cardiac output (heart rate • stroke volume) and (a-v) O_2 is the arterio-mixed venous oxygen difference.

The horse's tremendous ability to achieve a higher $V.O_{2max}$ than other athletic species is related to its massive heart rate response and ability to substantially augment its circulating red blood cell mass, and therefore oxygen-carrying capacity, during exercise (Thomas & Fregin, 1981). Trends indicate that top human athletes (e.g. runners, cyclists and cross-country skiers) will generally have higher $V.O_{2max}$ values; however, there is considerable variation between athletes of similar ability (Derman & Noakes, 1994). In horses, a positive correlation between running speed and $V.O_{2max}$ has been described and this correlation became stronger as the distance ran increased with an increase in distance run (Harkins et al., 1993). It was suggested that faster horses utilize more oxygen during maximal exercise intensity.

Anaerobic power

Anaerobic energy supply becomes significant when exercise intensity is at a level beyond that which aerobic pathways can accommodate alone. The faster glycolytic pathways may be recruited under

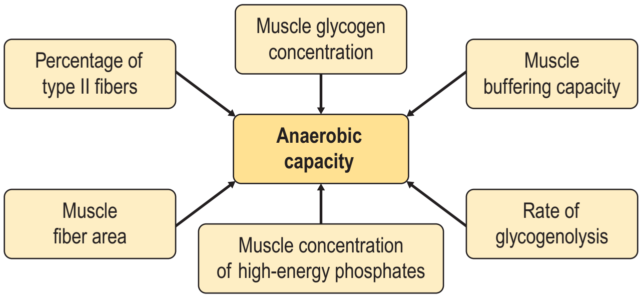

Fig 18.5 Major factors contributing to anaerobic capacity.

two conditions: when energy demand increases so rapidly that the slower aerobic systems cannot match the supply rate required; or when the total energy demand exceeds what the aerobic pathways are capable of supplying at peak capacity. Workloads at intensities beyond that provided for by V.O$_{2max}$ have been referred to as *supramaximal* intensities. This level of energy utilization is experienced by racing Thoroughbreds, Standardbreds and Quarter Horses during competition. Shorter duration races, e.g. Quarter Horse 400-m sprints, rely predominately on the rapid supply of energy by anaerobic means (Eaton, 1994). Anaerobic power is considered a finite capacity and not a rate because the supply of substrates for anaerobic phosphorylation is limited. Factors that influence anaerobic capacity are depicted in Figure 18.5.

Theorizing that anaerobic capacity is a function of the area of type II fibers in the locomotor muscles, McMiken (1983) stated that to measure maximal anaerobic capacity one should calculate the type II fiber area and the activities of anaerobic pathway enzymes in the muscle. *Maximum accumulated oxygen deficit* (MAOD) has been investigated as a measure of anaerobic capacity in horses (Eaton et al., 1992, 1995b; Eaton, 1994) following preliminary studies indicating its usefulness in humans (Mebø et al., 1988; Scott et al., 1991).

Oxygen deficit refers to the deficiency in V.O$_2$ that occurs at the commencement of exercise until the responding cardiorespiratory system meets the oxygen demand of the tissues (Åstrand & Rodahl, 1986). The total oxygen deficit that accumulates during exercise at supramaximal intensities is the MAOD and this is the difference between the oxygen demand and the actual V.O$_2$ achieved. The O$_2$ demand is calculated by extrapolating from the linear relationship between V.O$_2$ and speed at submaximal intensities (Fig. 18.6). To determine MAOD, horses on a treadmill are rapidly accelerated to speeds equivalent to supramaximal intensities (defined as a percentage of V.O$_{2max}$ measured in a previous exercise test and extrapolated from the V.O$_2$ versus speed plot) (Rose et al., 1988; Eaton et al., 1995b). The V.O$_2$ is measured at frequent intervals until the horse fatigues. The area between the O$_2$ demand and the V.O$_2$ curve is the MAOD (Eaton et al., 1995b) (Fig. 18.6).

For exercise intensities requiring 105–125% V.O$_{2max}$ the MAOD was similar at 31 mL O$_2$ equivalents per kg of bodyweight but the proportion of energy supplied by anaerobic processes increased from 14 to 30% (Eaton et al., 1995b). V.O$_{2max}$ was not correlated to MAOD, suggesting that anaerobic capacity is unlikely to be dependent on the rate of oxygen uptake. Eaton and colleagues (1995b) proposed from their results that anaerobic energy supply would contribute less than 30% of the total energy input in Thoroughbred and Standardbred races, which is considerably lower than previously suggested (Bayly, 1985). Using peak blood or plasma lactate concentrations as an indicator of anaerobic capacity appears limited because of the many variables like function of monocarboxylate transporters (MCT) as lactate carriers (Koho et al., 2006) that affect lactate concentrations including rates of flux between fluid compartments.

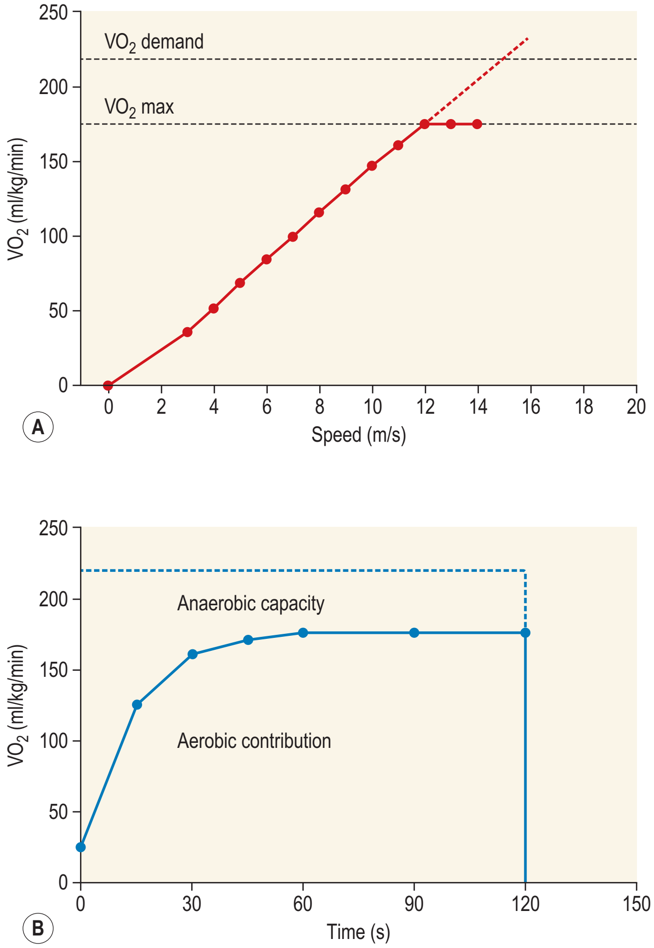

Fig 18.6 Determination of maximum accumulated oxygen deficit (MAOD). (A) Initially, the V.O$_2$ versus speed plot is generated by performing a standardized incremental exercise test on an inclined treadmill. The V.O$_{2max}$ is 175 mL/kg/min, and for this horse to exercise at an intensity of 125% of V.O$_{2max}$, by extrapolation it can be seen that the V.O$_2$ demand would be 219 mL/kg/min. To exercise at this supramaximal intensity the horse would need to run at 15 m/s. (B) This figure demonstrates the relationship between V.O$_2$ and time for the horse exercising at 125% of V.O$_{2max}$. The previously calculated O$_2$ demand is drawn in as the dotted line at 219 mL/kg/min. At the onset of the exercise there is a lag in V.O$_2$ but it quickly reaches V.O$_{2max}$. The exercise ceases when the horse can no longer keep pace with the treadmill. The difference in the O$_2$ demand and the actual oxygen uptake is defined as the MAOD and is a measure of the anaerobic capacity.

Adapted from Eaton (1994).

In humans, the power vs time-to-fatigue (P:TTF) relationship has been used as an accepted method for assessing anaerobic work capacity and this relationship has now been investigated in horses (Lauderdale & Hinchcliff, 1999). In humans, the relationship is best described by the hyperbolic equation:

$$t = W9/(P2\text{Ø}_{PA})$$

where t is the time to fatigue (s); P is power (watts); Ø_{PA} is power asymptote, or critical power, which represents the maximum sustainable power output or anaerobic threshold, and W9 is a constant representing anaerobic capacity or the finite amount of work that can be performed above Ø_{PA} (Fig. 18.7). Similarly to humans, the P:TTF relationship in Standardbreds is best represented by a hyperbolic function; however, the technique needs to be validated against the more traditional MAOD measure of anaerobic capacity before its usefulness in horses as a predictor of fitness and anaerobic

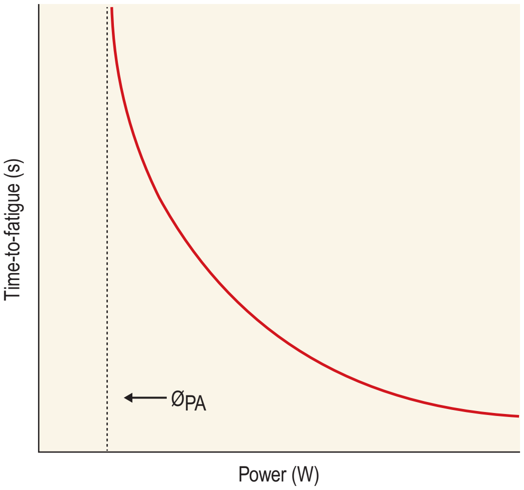

Fig 18.7 Schematic of the hyperbolic relationship between power (*P*) and time-to-fatigue (*t*) represented by the equation $t = W'/(P2Ø_{PA})$. W′, anaerobic capacity; $Ø_{PA}$, critical power; power units = watts (W).

capacity can be investigated (Lauderdale & Hinchcliff, 1999). The P:TTF does not require collection of respiratory gases or blood for its calculation and this may be an advantage over the more intensive effort required to measure blood lactate concentrations or determine MAOD. However, currently a high-speed treadmill and multiple high-intensity exercise tests are still a prerequisite, as the ability to calculate the P:TTF relationship in field trials is yet to be determined.

For any measure of anaerobic capacity in the horse, it remains to be examined what relationship exists between performance and anaerobic capacity.

Anaerobic threshold

Anaerobic threshold is defined as the level of work or $V.O_2$ consumption just below that at which metabolic acidosis and the associated changes in pulmonary gas exchange occur (Wasserman et al., 1973). It represents the transition when anaerobic means of energy supply becomes important during exercise. In humans, this level of work has been correlated with a blood lactate concentration of 4 mmol/L (Åstrand & Rodahl, 1986). As exercise intensity increases, lactate accumulation in the circulation rises in an exponential manner. Hence the anaerobic threshold has also been described as the *onset of blood lactate accumulation (OBLA)*. The velocity or intensity of work at which a blood lactate concentration of 4 mmol/L (V_{LA4}) is reached has been used to assess the relative fitness of horses and humans and their response to training (Persson, 1983; Thornton et al., 1983; Rose et al., 1990a; Auvinet, 1996). The V_{LA4} increases with training (Thornton et al., 1983; Eaton et al., 1999) and in general, the higher the V_{LA4} the fitter the horse (Rose & Hodgson, 1994a).

Anaerobic threshold and OBLA are determined during an incremental exercise test. Anaerobic threshold is identified by the point of non-linear increase in respiratory variables such as minute ventilation and carbon dioxide production (Wasserman et al., 1973). It is assumed that this point is highly correlated with the OBLA but this may not be the case (Åstrand & Rodahl, 1986).

Postexercise oxygen consumption

At the cessation of exercise, O_2 continues to be consumed above basal rates as it declines in an exponential manner to resting levels. This is referred to as *excess postexercise oxygen consumption* (EPOC) or *oxygen debt*. The EPOC may only account for a small fraction of the net total oxygen cost (NTOC) of exercise. In humans exercising at 30–70% of $V.O_{2max}$ for up to 80 min the EPOC was only 1.0–8.9% of the NTOC of the exercise (Gore & Withers, 1990). In the only comprehensive study to date in horses, Rose and colleagues (1988) measured oxygen debt as the area under the O_2 recovery curve following a bout of exhaustive exercise at an intensity equivalent to 120% of $V.O_{2max}$. Oxygen debt represented nearly 52% of the NTOC, which is dramatically higher than that in the previously quoted study of humans. This can be attributed in part to the very different exercise intensities performed in the two studies and the relative fitness of the subjects.

EPOC is considered to have an initial fast phase and then a slower phase. In the horse these phases were complete by 1.4 and 18.3 min, respectively, after supramaximal exercise (Rose et al., 1988). The fast phase is associated with the resaturation of myoglobin and hemoglobin and the replenishment of the high-energy phosphagen pool (CP and ATP). Perhaps less than 1.5% of the EPOC was required to restore the muscle CP pool in the horse and this occurred at a slower pace than may have been expected (Rose et al., 1988). Post-exercise tachycardia and tachypnea would also contribute small components to the EPOC because of increased consumption of O_2 by the myocardium and respiratory muscles until resting levels are reached. The slow phase is associated with the oxidation of lactate that accumulates during exercise. However, not all the lactate that is metabolized is accounted for by the EPOC and some is utilized in gluconeogensis and amino acid synthesis. A poor relationship existed between the restoration of muscle metabolites to pre-exercise levels and the recovery of $V.O_2$. Muscle and plasma lactate concentrations remained elevated after 60 min of recovery whereas $V.O_2$ had returned to near pre-exercise levels (Rose et al., 1988).

A number of other factors considered associated with EPOC, including exercise-induced hyperthermia, have not been quantified in the horse.

Economy of locomotion

The *economy of locomotion* refers to the net energy cost in mL O_2 per kg of body weight per meter traveled (mL O_2/kg/m). It is independent of speed and load (or body weight) (Eaton, 1994). There are conflicting reports on the values for economies of locomotion but the importance of gait in these studies needs to be recognized (Eaton, 1994). Horses on treadmills may be forced to work at defined speeds, and in doing so, utilize extended or restricted gaits that might alter the true cost of locomotion they would otherwise naturally incur if allowed to control their own pace. Thornton and colleagues (1987) have reported values of 0.122 mL O_2/kg/m for speeds of 4.5–6.25 m/s and 0.124 mL O_2/kg/m for speeds of 6.5–8.14 m/s obtained on a horizontal plane. These results are similar to the 0.133 mL O_2/kg/m that can be derived from the results of Taylor and coworkers (1980) for a 119-kg pony working at 3.11 m/s. Eaton and colleagues (1995a) recorded a range of 0.10–0.16 mL O_2/kg/m at speeds of 5–13 m/s on a horizontal treadmill. Exercising on a positively inclined treadmill will increase the oxygen cost of work about 2–2.5 times that measured on a flat plane, depending on the steepness of the slope (Thornton et al., 1987; Eaton et al., 1995a). When averaging a range of speeds for each gait, Hörnicke and colleagues (1983) reported higher values for the walk (0.21 mL O_2/kg/m) and for the trot and gallop (0.19 mL O_2/kg/m) for horses exercising on the track. By averaging the economies of a number of speeds, a higher oxygen cost can be expected as values will include less-efficient gait velocities than that at which the horses may be required to exercise (Hörnicke et al., 1983).

It is well documented that horses will choose a gait at any speed that results in the least possible expenditure of energy (Hoyt & Taylor, 1981; Eaton, 1994; Preedy & Colborne, 2001; Wickler et al., 2001; Griffin et al., 2004). Ponies (110–170 kg) were trained to walk, trot and gallop, and to extend their gait on command on a

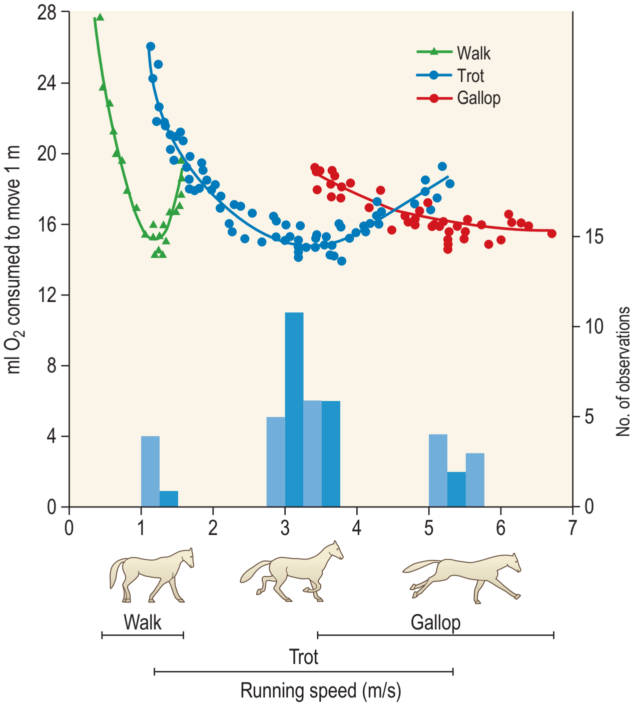

Fig 18.8 Economy of locomotion. The oxygen cost to move a unit distance (rate of oxygen consumption divided by speed) declined to a minimum and then increased with increasing speed in a walk and trot. It also declined to a minimum in a gallop but the treadmill did not go fast enough to observe any increase at higher galloping speeds. The minimum oxygen cost to move a unit distance was almost the same in all three gaits. The histogram shows gaits when a horse was allowed to select its own speed while running over ground. The three speeds chosen coincided with the energetically optimal speed for each gait.

From Hoyt, D.F., Taylor, C.R., Gait and the energetic of locomotion in horses. Reprinted by permission from Macmillan Publishers Ltd, Nature Publishing Group, ©1981.

treadmill. Rates of oxygen consumption increased curvilinearly with speed for walking and trotting. The maximum speed of the treadmill prevented sufficient data from being obtained for galloping velocities. Gait transitions occurred at speeds when the oxygen consumption was similar for the two gaits, but when the ponies were forced to exercise at an extended gait beyond the normal range of speeds, oxygen consumption was higher (Hoyt & Taylor, 1981). Thus, there was a speed for each gait where the energy cost of locomotion was minimal and this cost was similar for the walk, trot and gallop (Hoyt & Taylor, 1981) (Fig. 18.8). So, at the optimal speed of each gait, the amount of energy consumed to move a given distance is much the same. When a horse was allowed to move at its natural pace, it did so by selecting speeds within each gait around the most energy efficient speed (Hoyt & Taylor, 1981). The optimal value for economy was similar to the 0.122–0.133 mL O$_2$/kg/m values derived elsewhere for flat treadmill exercise (Taylor et al., 1980; Thornton et al., 1987).

Griffin et al. (2004) found that the absolute walk–trot transition speed increased with size, but it occurred at nearly the same Froude number. In addition, horses spontaneously switched between gaits in a narrow range of speeds that corresponded to the metabolically optimal transition speed. These results support the hypotheses that the walk–trot transition is triggered by inverted-pendulum dynamics and occurs at the speed that maximizes metabolic economy. Of interest, some overtrained Standardbreds made a transition to canter rather than continue trotting during a standardized exercise test (De Graaf-Roelfsema et al., 2009). Nevertheless, Hoyt et al. (2006) found it is confusing to distinguish between walking and running by the duty factor (DF). When changing from pendulum to spring mechanics, there is a change in the slope of metabolic rate (MR) vs. speed. At the trot–gallop transition, where quadrupeds are hypothesized to change from spring mechanics to some combination of spring and pendulum mechanics, there is a change in slope of MR vs. speed in horses but not in other species. Stride frequency (SF) is a logarithmic function of walking speed in all species, a linear function of trotting/running speed, and nearly independent of speed in galloping. In humans and horses there is a discontinuity in SF at the walk-trot (run) transition. The slope of time of contact vs. speed does not change with mechanics in most species, but it does in humans. In horses and humans, there is a discontinuity at the walk-trot (run) transition and data for other species do not permit generalization. Duty factor (DF) in humans is >0.5 in walking (pendulum mechanics) and <0.5 when running (spring mechanics). However, this is not true in many species that have DF >0.5 at the lowest speeds where they use spring mechanics, including horses performing the tölt (Biknevicius et al., 2006). Apparently, different energy-conserving mechanics (i.e. pendulum and spring) used in different gaits reflected in differences in energetics and/or stride parameters.

The effects of training and athletic activities on the economy of equine locomotion need to be considered. Endurance horses forced to use extended gaits for prolonged periods may fatigue more rapidly than if they were to move at their natural speed for each gait. Clearly, it becomes a matter of achieving the right balance of speed and energy consumption to complete the distances and be successful in such events. Standardbred trotters and pacers may be able to work at a wide range of speeds using a single gait without any loss of economy (Thornton, et al., 1987; Eaton, 1994).

Fatigue

Fatigue is a complex and intricate physiological response to exercise, leading to the inability to sustain further activity at the current intensity. Fatigue can be categorized as structural, acute or chronic. Structural fatigue refers to biomechanical failure of tissues, for example tendons, ligaments and bone, which inadequately adapt to the stresses placed upon them. Chronic fatigue is a function of prolonged conditions such as chronic anemia and starvation. Acute fatigue is directly related to energy production in the muscle and occurs in events requiring maximal work effort for short periods, e.g. Thoroughbred or Standardbred racing. It has been labeled *anaerobic fatigue* (McMiken, 1983) and has different causal factors to those that limit aerobic performance in endurance type events. Fatigue appears to involve central (psychologic/neurologic) and peripheral (muscular) contributions (Hodgson & Rose, 1994a). Overtrained horses can become listless and 'sour' with a decline in performance that may be partly a manifestation of psychological fatigue. Rivero et al., (2008) differentiate overtraining syndrome (OTS) from over-reaching, a term used for horses that, after suffering a loss of performance without an obvious clinical reason, recover their performance within 1 or 2 weeks. When inadequate training stress is applied and recovery time is insufficient, performance reduction and chronic maladaptation occurs. Overtraining syndrome (OTS) is known as a complex condition, which often afflicts horses in top training. Peripheral causes of fatigue have been studied more widely as they are easier to define. Recently, De Graaf-Roelfsema et al., (2009) induced overtraining (performance decreased nearly 20% compared with controls and did not improve after 4 weeks of detraining) by intensified training and found that endocrinological and behavioral alterations occurred before peripheral adaptations for example in the muscles (De Graaf-Roelfsema et al., 2009).

Fatigue in response to high-intensity exercise is likely due to a combination of factors including depletion of the phosphagen pool (ATP and CP), decreased intracellular pH, and possibly accumulation of lactate (McMiken, 1983; Hodgson, 1985; Hodgson & Rose, 1994a; Essén-Gustavsson et al., 1999). The main event appears to be a reduction in the concentration of ATP. Acidity can impair the respiratory capacity of muscle and have a direct effect on the contractile apparatus. In addition, acidosis and increased muscle temperature could be associated with impaired sarcoplasmic reticulum function. Finally, altered electrolyte gradients (potassium and calcium) will add to the overall deleterious effects on muscle metabolism.

During prolonged, submaximal exercise, hyperthermia, altered fluid and electrolyte balance, and fuel depletion have all been considered as contributors to fatigue during this type of exercise (Lucke & Hall, 1980; Snow et al., 1982; Hodgson, 1985; Hodgson & Rose, 1994a). Performance capacity or onset of fatigue in horses and humans has been correlated with a depletion in glycogen stores in working muscle (Snow et al., 1981, 1982; McMiken, 1983; Åstrand & Rodahl, 1986). A decline in extracellular glucose concentrations may also be important. However, fatigue or reduced muscle power occurs before the complete depletion of any substrate and it is the rate of ATP production that appears crucial. Neural fatigue in short events is considered very unlikely but may be important in endurance events (McMiken, 1983). However, in supramaximal exercise lasting only a few seconds, fatigue may be related to an inability of the neuromuscular junction to maintain the propagation of excitatory action potentials into the muscle fibers, possibly leading to early musculoskeletal damage (Leach & Sprigings 1979). Racehorses that were being whipped as they were progressing through the field were at much greater risk of falling compared to horses that were not being whipped and that had no change in position or lost position through the field (Pinchbeck et al., 2004).

Training programs

The implications of the various energy supply pathways are far-reaching in terms of specific training programs for horses competing in different athletic events. An understanding of the patterns of energy substrate supply and utilization in different athletic events allows tailored training strategies to be adopted to maximize the adaptations in various body systems. Although no activity is exclusively aerobic or anaerobic in nature, aerobic energy production is vital in all cases. Hence an emphasis on establishing a good 'aerobic foundation' is considered paramount in any training program (Rivero et al., 2008).

Even today, there is probably more desire to use training methods that have 'stood the test of time' over many years and have been passed on from generation to generation, than to develop a training program based on current scientific knowledge. Naturally, the successful training of any athlete relies on far more than simple physiologic adaptations to exercise. The maintenance of motivation, the skill of predicting a horse's tolerance levels and the fostering of that psychogenic factor, 'the will to win,' are vitally important and unquantifiable. The ability to train a horse to its limits without causing it to 'break down' is necessary. These 'human factor' components of any training program separate the elite trainers from their average peers.

Training may be of a continuous or intermittent nature. Continuous training, also known as endurance training, refers to exercise performed in a single bout that can vary in intensity and duration. Intermittent or interval training implies a series of intense work sessions interspersed with rest periods of varying duration. The intensity and duration of training are two variables that must be considered in any training program. It seems that the shorter the race the more consideration should be given to the intensity of training and the longer the race the more important endurance training becomes (Bayly, 1985). A basic model of training incorporates three phases (Derman & Noakes, 1994; Evans, 1994):

1. A foundation phase
2. A cardiovascular or aerobic phase
3. An anaerobic interval phase.

The foundation phase is considered continuous or endurance-type training and is vital for the cardiovascular and musculoskeletal systems to make early adaptations to the stresses placed upon them. Subsequent phases include more intense, shorter runs.

Improvement in $\dot{V}O_{2max}$ is independent of submaximal training intensity when horses are exercised for the same distance (Knight et al., 1991; Eaton et al., 1999) and as little as 10–14 days of training is all that is required to achieve an increase in aerobic capacity (Knight et al., 1991; Geor et al., 1999). Geor and colleagues (1999) reported an 8.9% increase in $\dot{V}O_{2max}$ after 10 days of moderate-intensity training at 55% $\dot{V}O_{2max}$ for 60 min each day. Concurrent metabolic studies revealed a decrease in muscle glycogenolysis and anaerobic metabolism but no concomitant increase in muscle oxidative enzyme activities. So, although there was improvement in the aerobic capacity of the horses the mechanisms underlying it were not clear (Geor et al., 1999). In contrast, normal training in Standardbreds resulted in decreased muscle hexokinase activity (Wijnberg et al., 2008). Guy and Snow (1977) reported an increase in muscle glycogen content and an increase in aerobic and anaerobic enzymes in response to training.

Various conditioning programs studied by Gansen and colleagues (1999) revealed significant increases in muscle glycogen storage in Haflinger stallions after low-intensity, long-duration exercise but not after higher-intensity, shorter-duration exercise. This adaptation in the middle gluteal muscle fibers was only noted at 6-cm depth and not at 2-cm depth, demonstrating the variable response of different regions of muscle fibers to training.

Few scientific studies comparing conventional and interval training techniques for Thoroughbreds have been reported. In one study it was concluded that interval training led to higher lactate production and increased plasma lactate clearance during a 1000-m sprint compared to conventionally trained horses and this was equated with greater anaerobic capacity (Harkins et al., 1990). An earlier study failed to identify significant differences in the response to conventional and interval training techniques but the total slow- and fast-work distances undertaken were the same in both training schedules (Gabel et al., 1983).

The various physiologic adaptations that occur in response to training in the horse have been extensively reviewed elsewhere (Hodgson & Rose, 1994b; Rivero et al., 2001, 2007; Marlin & Nankervis, 2002; Hinchcliff et al., 2004; Rivero et al., 2007).

Measuring energy expenditure

Until the 1980s, some veterinarians and horse trainers relied on the complete blood count and the plasma or serum biochemistry panel in an attempt to assess clinical and subclinical disease in performance horses. Evaluation of resting and/or post-exercise hematology and biochemistry to assess fitness capacity or response to training is of limited use.

A range of equipment to determine various performance indices has now been available and extensively used for the last decade and a half, including treadmills, heart rate meters and rapid lactate analyzers.

Treadmills

The first use of a high-speed equine treadmill for experimental purposes was in 1960 in Stockholm, Sweden (Fredricson et al., 1983; Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999). Early studies focused on metabolic variables with locomotor studies becoming more common in later years (Barrey et al., 1993; Gottlieb-Vedi & Lindholm, 1997; Couroucé et al., 1999). Equine treadmills have been installed in many university veterinary colleges and equine research centers for ongoing studies of exercise physiology and for the diagnosis of poor performance conditions, in particular dynamic upper airway obstructions. In addition, treadmills are now commonly used in training stables as a complementary training tool and by stud farms to walk and trot yearlings for conditioning prior to sale.

Most current knowledge concerning the physiologic response of the horse to exercise has come from numerous treadmill-based studies. Cardiovascular, respiratory, metabolic, hematologic, thermoregulatory, hormonal, musculoskeletal and locomotory changes in the horse, exercising over various intensities and durations, have been thoroughly examined.

Treadmill exercise is not equivalent to track exercise (Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999). The effects of air movement, track surface and rider impact are not duplicated on the treadmill and horses have no forward momentum on the treadmill because the moving belt provides the driving force (Rose & Hodgson, 1994b). So the amount of work performed by a horse on the treadmill is quantitatively different from work on the track. For a track exercise test, horses require only a short habituation period and can be worked in their standard manner, often with the usual rider or driver (Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999). Nevertheless, there are clear advantages to studying responses to exercise on the treadmill. A consistent exercise surface, controlled environmental conditions, precise control over intensity of exercise and ease of measuring physiologic variables to monitor fitness are all strong indications to pursue treadmill-based studies (Rose & Hodgson, 1994b; Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999). By positively inclining the treadmill, a horse can be exercised at its maximum power output at a relatively slower speed than if it were on a flat plane (Sexton & Erickson, 1990). This potentially reduces the risk of musculoskeletal injury because speeds above 12–13 m/s are unnecessary, but the steeper the slope the greater the effects on gait and mechanics. It is suggested that muscles may be recruited differently when the horse is exercised on a slope versus the flat (Sloet van Oldruitenborgh-Oosterbaan & Barneveld, 1995). A slope of 10% (5.71°) is recommended for treadmill testing as most horses will reach their maximum oxygen uptake at speeds of 10–12 m/s compared with 14–15 m/s on the flat (Rose & Hodgson, 1994b). It is desirable to standardize the incline that exercise tests are performed on, to allow better comparison between studies from different institutions (Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999).

Significant differences in locomotor and metabolic variables have been reported in studies comparing track versus treadmill exercise (Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999) and future research may continue to elucidate the etiology of these differences. Currently, treadmill tests are preferable for most research purposes but track tests may be of greater importance when examining locomotor variables and fitness of sport horses (Sloet van Oldruitenborgh-Oosterbaan & Clayton, 1999).

Oxygen consumption

The measurement of $V.O_2$ by the exercising body is the single most important step in the evaluation of exercise capacity. In the horse, various mask systems have been investigated and an open-flow mask without valves is the currently accepted apparatus. Bayly and colleagues (1987) compared flow-through mask systems with valved masks and found a funnel-shaped, valveless flow-through system to have the least impedance on airway function at flow rates of 6300 L/min. Evans and Rose (1988b) investigated a valved mask system and showed a negative influence on arterial blood gases, namely an exacerbation of exercise-induced hypercapnea and hypoxemia. Respiratory frequency was lower when the mask was worn but arterial acid–base tensions and heart rate were minimally affected. The respiratory effects were attributed to alveolar hypoventilation (Evans & Rose, 1988b). The most appropriate exercise test to determine $V.O_{2max}$ is a standardized rapid incremental test on a 10% treadmill incline (Rose et al., 1990b) and the repeatability of results is good (Evans & Rose, 1988a; Seeherman & Morris, 1990). Oxygen uptake can improve quickly with the onset of training but relative training intensity, when kept constant and submaximal, does not appear to affect the rate of change of $V.O_{2max}$ (Knight et al., 1991).

Lactate analysis

Response to training and the relative intensity of an exercise session can be assessed by the simple measurement of blood or plasma lactate, during or after exercise (Milne et al., 1977). Lactate increases at an exponential rate with increasing workload, and fitter horses show a slower accumulation during submaximal exercise. The V_{LA4} is often calculated to compare fitness between horses and response to training. Classically, the V_{LA4} has been considered to approximate the anaerobic threshold, mirroring the metabolic transition from predominantly aerobic to anaerobic energy sources, and this calculated value increases with improved fitness (Hodgson & Rose, 1994b). Plasma lactate values are 30–50% higher than whole blood lactate (Rose & Hodgson, 1994b). However, because of great inter-individual variation in lactate distribution between plasma and red blood cells (RBCs) after exercise and in the rate of lactate influx into RBCs, there is no consistent relationship between the two lactate reservoirs (Pösö et al., 1995; Väihkönen & Pösö, 1998). Recent evidence suggests that whole blood lactate concentrations should be measured when estimating the accumulation of lactate from exercising muscle, to minimize variation due to factors that influence transport of lactate from plasma into RBCs (Väihkönen et al., 1999). If whole blood is to be used, the sample should be immediately deproteinized to halt post-collection production of lactate within the RBC (Ferrante, 1995); however, storage at 0°C for up to an hour before deproteinization does not affect the lactate concentration (Ferrante & Kronfeld, 1994).

Whether plasma or whole blood lactate is assessed, one method should be adhered to by the laboratory or investigator, to reduce variability in measurements. Post-exercise blood and plasma lactate concentrations were significantly correlated with race performance for Thoroughbreds undergoing a submaximal treadmill exercise test (Evans et al., 1993). Harkins and colleagues (1993) found the V_{LA4} to be one of the best correlates of running speed for Thoroughbreds. This was a negative correlation, indicating that faster horses attained a plasma lactate of 4 mmol/L at a lower velocity than did slower horses. The faster horses also had the highest peak lactate concentrations, implying that plasma lactate concentrations of faster horses rise more rapidly and to higher levels than do those of slower horses. However, no correlation was found between performance and post-exercise blood or plasma lactate concentrations taken after maximal activity during a field trial (Evans et al., 1993).

Recent research (Lindner et al., 2010) defined the maximum lactate at steady state (maxLASS) in horses based on the definition by Heck et al. (1985) and showed that not V4 but V2 most closely resembles the maxLASS in horses. They defined maxLASS as the maximal speed at which the [LA] does not change by more than 1 mmol/L between the 5th and the 25th min of exercise at a constant pace. More research is needed to confirm this conclusion, though it has already been shown that training of endurance horses at V2 for 4 weeks was able to significantly improve the V4 during standardized exercise tests (Trilk et al., 2002).

Heart rate

Heart rate is measured to monitor exercise intensity on the basis that there is a linear relationship between heart rate and work performed in the range of 120–210 beats per min (bpm) (Persson, 1983). The velocity at a heart rate of 200 bpm (V_{200}) has been used to assess fitness and response to training but care should be taken when evaluating this variable (Rose & Hodgson, 1994a). Conflicting reports on the correlation between V_{200} and $V.O_{2max}$ have been published (Evans & Rose, 1987; Rose et al., 1990a) but this is attributed to the dissimilar numbers of horses tested in each study and it is accepted that the two variables are significantly positively correlated. The usefulness of V_{200} to assess response to training in the field using Thoroughbreds has been confirmed (Kobayashi et al., 1999). A number of heart rate meters are available with generally good accuracy (Evans & Rose, 1986; Rose & Hodgson, 1994b; Holopherne et al., 1999). Telemetered electrocardiography is the favored technique in treadmill laboratories. To achieve accurate heart rate values good electrode contact with the skin is required, and this can be difficult to maintain in the galloping horse. Electrode gels can enhance contact and glue adhesives can hold electrode casings firmly on the skin (Hill et al., 1977; Rose & Hodgson, 1994b).

Blood gases

Respiratory disorders that may interfere with the transport of oxygen from the atmosphere to the pulmonary vasculature can be assessed for their significance by measuring arterial blood gas tensions. Arterial blood samples are normally collected from a catheterized transverse facial artery during a treadmill exercise test. Values should be corrected for central venous blood temperature. Hypoxemia and hypercapnea are recognized responses to high-intensity exercise (Bayly et al., 1983, 1987) and the severity of hypoxemia increases with training (Christley et al., 1997). There is a strong negative correlation between minimal arterial oxygen content and VO_{2max} in trained horses, indicating the importance of assessing both variables before interpreting blood gas data (Christley et al., 1997). Horses with functional airway obstructions may have a greater degree of hypoxemia or hypercapnea when approaching, and at, maximal exercise intensities compared to normal horses (Rose & Hodgson, 1994a). The degree of hypoxemia in normal Thoroughbreds performing a standardized treadmill exercise test was not correlated with their running speed on an 800 m track (Harkins et al., 1993).

Blood volume

The Evans blue dye technique of measuring the plasma volume (PV) in horses was first described by Persson in 1967. It is a simple and highly reproducible technique with a coefficient of variation of 3–4%. To ensure an accurate assessment of the plasma volume, the splenic erythrocyte pool must be mobilized either by intense exercise or an epinephrine injection. A post-exercise hematocrit is preferred and is typically measured for blood volume calculations. A major determinant of the oxygen-carrying capacity of the horse is the red cell volume (RCV), which can be calculated from the hematocrit and PV. Evaluation of the hematocrit alone as an indicator of RCV can be misleading due to variations in PV. Plasma volume increases in response to training in all species studied (Oscai et al., 1968; Persson, 1968; McKeever et al., 1985, 1987). Total blood volume (TBV) has been positively correlated with fitness level and may be a useful measure of such as long as variations due to body size, age, sex and breed of horse are taken into account (Persson, 1968). A significant positive correlation has also been found between TBV and racing performance in Standardbred trotters (Persson, 1968). During a single high-intensity exercise bout TBV increases substantially in the horse mainly due to the release of red cells from the splenic reservoir. It remains to be elucidated whether PV or RCV can be used to predict performance in horses.

Muscle biopsy

Needle biopsy of skeletal muscle was first described in the horse more than 35 years ago by Lindholm and Piehl (1974). The middle gluteal muscle was used as the preferred site of sampling and continues to be favored today although other muscles, e.g. the semitendinosis, biceps femoris, and lateral vastus have been examined. The latter muscle has the advantage to be able to compare muscle histochemistry and histopathology with quantitative needle electromyography (QEMG) parameters in the conscious horse (Wijnberg et al., 2008) as for instance the gluteal muscle has very poor basal motor unit action potentials (MUPs). Examination of muscle tissue has allowed fiber typing and evaluation of responses to exercise and training, particularly alterations in substrate utilization and the oxidative capacity of muscle. One concern with the use of muscle biopsies is the degree of variation in samples from very similar sites. A standardized approach to the muscle biopsy procedure in French trotters has been described, incorporating anatomical landmarks, age, sex and hip width of the horses (Valette et al., 1999). Interestingly, muscle fiber composition has been correlated with locomotor patterns in horses (stride frequency and stride length) (Rivero & Clayton, 1996, Rivero et al., 2006) and therefore may indirectly influence the economy of locomotion. Furthermore, epaxial muscle biopsy characterized histopathologically and by electron microscopy is a good option in diagnosing back problems in horses when clinical examination and imaging techniques do not provide a precise diagnosis (Quiroz-Rothe et al., 2002) (Fig. 18.9). In addition, urinary excretion of organic acids, glycine conjugates and acylcarnitines (Westermann et al., 2008b), needle electromyography (EMG) (Wijnberg et al., 2002, 2003, 2008) and proteomics (Bouwman et al., 2010) are attractive additional tools to evaluate myopathy besides increased plasma muscle enzyme activities (like CK) and histological evaluation of muscle biopsies.

Using modern cDNA microarrays, Barrey et al., (2006) showed that genes are modulated in leucocytes in relationship with performance and clinical status of the horses. It appeared that the gene ontology classification showed that more genes were up-regulated in successful than in disqualified endurance horses. More genes

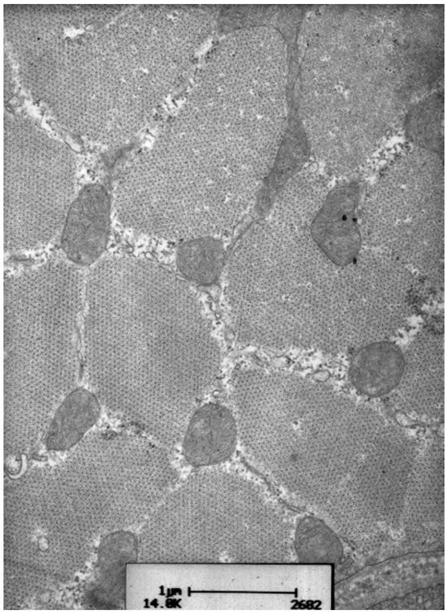

Fig 18.9 Electron micrograph of lateral vastus muscle transverse section from a 12-year-old Warmblood mare illustrating normal mitochondria. Mitochondria are no longer the once-thought uniform ATP-producing organelles, identical in all organisms, but are rather diverse and adapted to distinct conditions. Next to the classical aerobic mitochondria, which contain a respiratory chain and use oxygen as a final electron acceptor, anaerobically functioning mitochondria were identified.

were down-regulated in the disqualified horses. Some genes were expressed in relationship with the clinical phenotype observed in the disqualified horses: rhabdomyolysis and hemolysis. Recently, Eivers et al., (2010) investigated the adaptive changes in mRNA expression to training in equine skeletal muscle biopsies by real-time qRT-PCR for a panel of candidate exercise-response genes following a standardized incremental-step treadmill exercise test in a group of untrained Thoroughbred horses. Significant differences in gene expression were detected for several genes 4 h after exercise. Investigation of relationships between mRNA and velocity at maximum heart rate and peak postexercise plasma lactate concentration revealed significant associations with postexercise gene expression, and between plasma lactate concentration and basal gene expression. These findings highlight the roles of genes responsible for the regulation of oxygen-dependent metabolism, glucose metabolism, and fatty acid utilization in equine skeletal muscle adaptation to exercise.

Hormone profile

In general, stress occurs when body homeostatic balance is disturbed (Sapolsky et al., 2000; Selye 1951). When the body experiences environmental or internal stressors it responds by secreting a whole array of hormones to reestablish homeostatic balance. Regenerative processes continue after restoration of homeostatic balance such that, if the same stressor were imposed again, the homeostatic mechanisms would not be displaced to the same extent, resulting in overcompensation (Selye, 1951). The overcompensation is seen as positive stress.

The hormonal events during reestablishment of homeostasis due to (exercise) stress can be divided into two phases. Initially, a catabolic phase can be distinguished, with decreased tolerance of effort, characterized by reversible biochemical, hormonal and immunological changes. The two main hormonal axes activated in this phase are the sympathetic-adrenal medullary (SAM) axis and the hypothalamic-pituitary-adrenocortical (HPA) axis (Armstrong & van Heest, 2002). An anabolic phase follows with a higher adaptive capacity and enhanced performance capacity, in which both the GH-IGF-I axis as well as the gonadal-axis are activated (Urhausen et al., 1995). When homeostatic balance is not restored, the body experiences chronic stress which induces chronic activation of the endocrine system and possibly ending in a neuroendocrine disorder like the overtraining syndrome.

So far, no single diagnostic parameter has been identified for overreaching and the overtraining syndrome in humans or equines and so far a combination of different (hormonal) parameters appear to be the best indicators of overreaching/overtraining (Hug et al., 2003, Rivero et al., 2008). Standardized exercise tests are suggested to provide a way to detect subtle changes in hormonal responses in the individual, which may make an important contribution to the detection of early overtraining (Rivero et al., 2008).

Alterations in functioning of the HPA axis has been described in trained, overreached and overtrained horses. Several mechanisms underlying the alterations in functioning have been suggested, among them diminished adrenocortical sensitivity to adrenocorticotropic hormone (ACTH) and a decreased negative feedback sensitivity (Golland et al., 1999; Marc et al., 2000; Hamlin et al., 2002; Persson et al., 1980). However, so far only ACTH challenges were used to study the alterations in the HPA axis in horses during (over) training. Recently, the influences of overtraining on the function of the HPA axis using a corticotropin releasing hormone (CRH)-stimulation test were investigated (De Graaf-Roelfsema et al., 2008). The main finding was a reduction in the ACTH response to administration of CRH in the overtrained group. This finding was not accompanied by significant differences between the control and overtrained group in plasma cortisol concentrations after CRH administration. It was hypothesized that the decrease in pituitary sensitivity must have been caused by a more centrally located disorder, such as long-term increased CRH secretion raised by chronic stress or indirectly by increased secretion of an ACTH inhibitory factor that counteracts the action of CRH raised by chronic social stress as described by Alexander et al. (1996) in chronic socially stressed horses.

Pituitary growth hormone (GH) is usually secreted in an episodic manner as a result of a delicate interaction between the two hypothalamic peptides, GH-releasing hormone (GHRH) and somatostatin (SRIF). GH stimulates the liver to produce insulin-like growth factor (IGF-1), which mediates most of the effects of GH via the IGF receptor family. Defects in the function of the GH-IGF-1-axis could, in theory, be located at any level from the hypothalamus down to the target receptors in skeletal tissues. Diagnostic tests for assessing the function of the GH-IGF-1 axis include measurements of multiple serum GH concentrations, single serum IGF-1 concentration, and various endocrine challenge tests, for example, with GHRH. GH pulsatility characteristics can be determined from the GH data series by visual identification of presumptive pulses. However, this method is not very objective. Therefore, computerized algorithms have been developed in order to analyze GH hormone pulsatility and regularity (Veldhuis et al., 2008). Because monitoring the pattern of spontaneous GH secretion is labor-sensitive and difficult, challenge tests to measure GH 'secretory reserves' are often used instead. GH deficiency and GH insensitivity also influence the serum concentrations of IGF-1 and IGF-2 and their binding proteins, which makes the latter good indices of GH status. Furthermore, the serum concentrations of IGF-1 and IGF-2 are relatively constant during the day, so that stimulation tests or multiple samplings are not necessary (De Graaf-Roelfsema et al., 2011).

Effects of exogenous GH

It is well known that GH has anabolic effects, and its consequent abuse is a concern in many sports, including horse racing. The availability of reGH in Australia has attracted the attention of horse racing authorities worldwide and urged the development of methods for the detection of its abuse (De Kock et al., 2001). The availability of reGH also attracted the attention of researchers to determine the responses to administration of reGH in horses.

The biological responses to reGH administration in adult horses are similar to those common in other species: hyperglycemia, hyperinsulinemia, insulin resistance, decreased plasma urea nitrogen concentrations, increased plasma IGF-I and IGFBP-3 concentrations (De Kock et al., 2001, Julen Day et al., 1998, Malinowski et al., 1997, Popot et al., 2001, Smith et al., 1999, Thatcher and Thompson 2002).

Beneficial effects of reGH administration reported to date in adult horses include increased nitrogen retention, muscularity and granulocyte numbers in aged mares (Malinowski et al., 1997).

No effects of reGH administration were found in age-related declines in various immune parameters in adult horses (Guirnalda et al., 2001), on modulation of the *in vitro* biomechanical properties of superficial digital flexor tendon (SDFT) (Dowling et al., 2002a) or on second intention wound healing (Dart et al., 2002). Also no effects were found on aerobic capacity or exercise performance in geriatric mares (McKeever et al., 1998) or on exercise capacity or indices of fitness in young Standard bred horses in training (Gerard et al., 2002).

ReGH administration had a negative effect on the biomechanical properties of healing SDFT (Dowling et al., 2002b) and peripheral insulin sensitivity (De Graaf-Roelfsema et al., 2005). Long-term administration of reGH in foals did not influence body weight, long bone growth and other body sizes. Generally, basal glucose concentration and insulin response to glucose infusion were higher in reGH treated foals. Endogenous GH secretion in response to GH secretagogue (EP51389) was significantly reduced in treated foals. The prolactin and thyroid-stimulating hormone (TSH) responses to TRH were not altered by reGH treatment. Mean serum IGF-1 concentrations were not significantly higher in the reGH treated group. However, there was a significant increase of IGF-1 in the first 5 weeks of treatment in foals receiving reGH compared to controls. At necropsy, many internal organ weights were increased, but little effect on histopathologic characteristics was found in the same foals (Capshaw et al., 2001; Kulinski et al., 2002).

Endogenous GH responses to exercise

The GH-IGF-I response to exercise is well described in humans (Wideman et al., 2002; Birzniece et al., 2011), but not in horses. Nevertheless, some studies provide information about the acute changes in GH-IGF-I axis due to a bout of exercise (Cartmill et al., 2003; Thompson et al., 1992, 1994). To induce a significant plasma GH concentration elevation post-exercise, horses should perform exercise of at least 10 min duration with intensity above the lactate threshold (50–70% VO_{2max}) to overcome autonegative feedback. There is no indication that exercise modifies IGF-1 concentrations in plasma in trained adult horses (Popot et al., 2001; Noble et al., 2007).

De Graaf-Roelfsema et al., (2009) successfully used the resting nocturnal pulsatile growth hormone secretion pattern to detect the (over)training status of Standardbreds in an experimental setting (Fig. 18.10). The overtrained horses altered their resting pulsatile growth hormone secretion with an increase in the number of concentration peaks, a smaller peak secretion pattern with a prolonged growth hormone half-life, and an increased approximate entropy (ApEn). The increased irregularity of nocturnal GH pulsatility pattern is indicative of a loss of coordinated control of GH regulation. Longer phases of somatostatin withdrawal were hypothesized to be the underlying mechanism for the observed changes in GH pulsatility pattern. A 4-week recovery period did not normalize the pulsatile growth hormone secretion, thereby excluding overreaching as its cause.

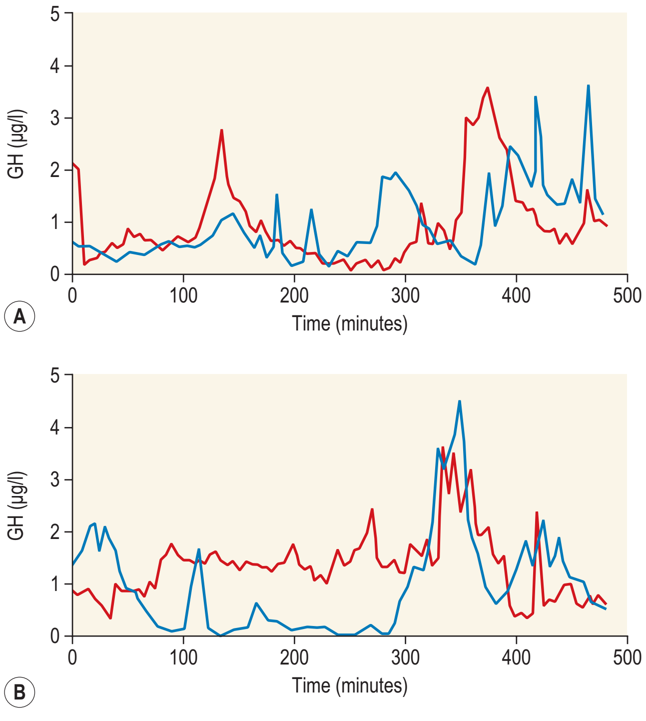

Fig 18.10 Mean nocturnal GH profiles for intensified trained (red line) horses and control horses (blue line) after the training period (A) and intensified training period (continued normal training for the control horses) (B).

Reprinted from De Graaf-Roelfsema, E., Veldhuis, P.P., Keizer, H.A., et al., 2009, Overtrained horses alter their resting pulsatile growth hormone secretion, Am J Physiol-Regulatory, Integrative and Comparative Physiology, 297 (2), R403–411, with permission from the American Physiological Society.

Thermoregulatory consequences of exercise

During the production of energy for locomotion the mechanical efficiency of the processes described above is ~20%. That is, one-fifth of the energy produced goes into exercise with the remaining 80% given off as heat. Given that the mass-specific maximal oxygen uptake of horses is at least 2-fold higher than in man, at a given workload, the metabolic heat load in horses is considerably higher. Further, relative to body mass, the surface area available for dissipation of heat in horses is approximately 50% of that in man (Hodgson et al., 1993; Hodgson et al., 1994). On the other hand, the horse's efficient thermoregulatory mechanisms provide for effective transfer of heat from contracting skeletal muscle to the environment.

Also, the horse can selectively cool the brain during exercise or heat exposure by cooling the venous blood within the cavernous sinuses during respiration (McConaghy et al., 1995). The primary physiological mechanisms driving heat loss during exercise are an increased proportion of cardiac output directed toward the cutaneous circulation and an increased rate of sweat secretion. Sweating and cutaneous evaporation are the most important heat dissipatory mechanisms in horses, accounting for 65–70% of heat loss during prolonged exercise (Hodgson et al., 1993; Hodgson et al., 1994).

Sweating rates of 20–55 $g/m^2/min$ have been measured on the necks and backs of exercising horses; for a 500-kg horse these rates correspond to sweat fluid losses of 6–15 L/h. When expressed in terms of sweating rate per unit area of skin, these rates are 2- to 3-fold greater than those reported for human subjects (McCutcheon & Geor, 2000; McCutcheon & Geor, 2004).

Unsurprisingly, the thermal responses to exercise are affected by ambient conditions. Under conditions of high heat (>30°C) and humidity evaporative heat loss is severely limited with resultant increases in the rate of heat storage and degree of hyperthermia. In horses, the rate of heat storage when exercising in hot, humid conditions can be more than twice the rate occurring during exercise at the same intensity in cool, dry conditions (Geor et al., 1995; Kohn et al.1999). Increased demands for respiratory heat loss are reflected by an increase in respiratory rate during and after exercise (Geor et al., 1995; McConaghy et al., 2002; McCutcheon & Geor, 2004).

Further, dehydration associated with profuse sweat fluid losses can further compromise heat transfer and exacerbate hyperthermia (McCutcheon & Geor, 2004). An important consequence of this impairment of heat dissipation during exercise in hot weather is a decrease in the time to attain a critical upper limit in core body temperature that results in development of fatigue (Gonzalez-Alonso et al., 1999; Nybo & Nielsen 2001). Moreover, exercise in such conditions increases the risk of developing heat-related illnesses in horses (McCutcheon & Geor, 2004).

Several factors may contribute to this decrease in performance when exercise is undertaken in hot versus cool conditions, including the effects of hyperthermia on brain and muscle function, compromise of muscle blood flow (McConaghy et al., 2002) and reduced aerobic power (Art & Lekeux, 1995). In trained human subjects, exhaustion during exercise in the heat corresponds to a core temperature of about 40°C (Gonzalez-Alonso et al., 1999; Nybo & Nielsen, 2001). The onset of fatigue at this critical upper limit may represent a mechanism to avoid heat stroke.

Measurements of central blood (pulmonary artery) temperature in horses during heavy exercise have demonstrated that fatigue occurs as blood temperature approaches 42.5–43°C. As such, horses may have greater thermal tolerance than man, perhaps in

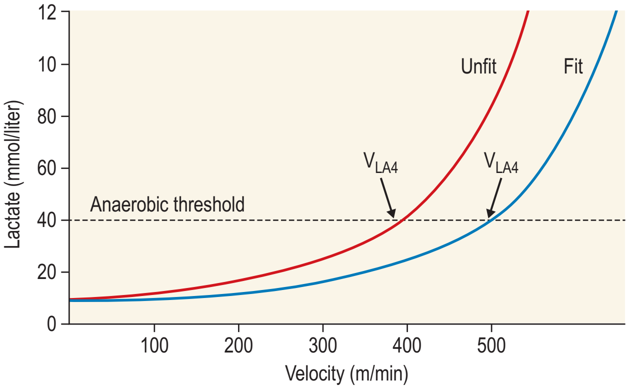

Fig 18.11 Training increases the Vla4 and moves the lactate curve to the right. Good performers have significantly higher Vla4 than poor performers, which makes it a valid parameter to assess fitness in Standardbred horses.
From Hinchcliff et al. (2004) and Lindner (2010).

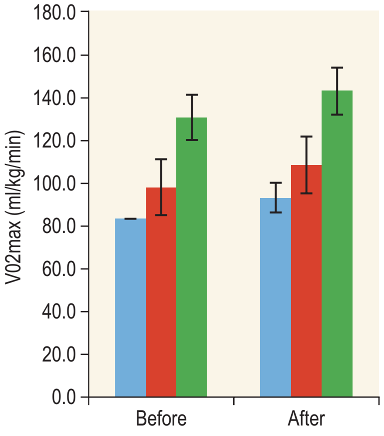

Fig 18.12 Training usually increases VO$_{2max}$ between 10 and 25%. Percentage improvement depends on the initial fitness of the horse and type of the horse. The figure shows improvement of VO$_{2max}$ after 4 weeks of aerobic training in untrained small (blue bars) and midsize (red bars) ponies, and in detrained TB. (Green bars, mean ± SEM.)
Adapted from Katz et al. (2000).

part because the selective brain cooling mechanism maintains hypothalamic temperature approximately 1°C lower than central blood temperature during exercise (McConaghy et al., 1995).

Clinical experience has indicated that poor physical conditioning, prolonged exercise (e.g. endurance races; speed and endurance test of a 3-day event) in hot environments, lack of heat acclimatization, and dehydration are factors that may increase the risk of exertional heat illnesses in horses. Horses with a history of anhydrosis are obviously at higher risk for development of exercise-associated heat illnesses.

Conclusions

It is imperative that anyone with an interest in the horse as an athlete should understand equine energy production and utilization. Both aerobic and anaerobic pathways of energy supply are necessary for all forms of exercise. Evidence suggests that the aerobic system has a much greater role to play than previously thought, in short-duration, supramaximal exercise bouts. The effect of nutrition on performance has been heavily investigated but continues to be an area of considerable controversy; comparison between studies is difficult and at this time meaningful conclusions cannot be drawn. Well-thought-out training programs tailored to the horse's particular activity are important for preparing the horse for athletic endeavors (Fig. 18.11). Every program should have an initial low-intensity foundation phase to allow body tissues to adapt to the stresses placed upon them. The economy of locomotion refers to the optimal gait at a given speed of exercise at which the energy cost is least and this gait is naturally chosen by freely moving horses. The measurement of V.O$_{2max}$ remains the single most important assessor of a horse's relative fitness (Fig. 18.12). Fundamental differences between track and treadmill exercise tests make both methods of performance evaluation attractive; however, because of more controllable conditions treadmill exercise tests continue to be favored. The emphasis is on further development and evaluation of procedures that can be readily and reliably applied to the field situation.

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CHAPTER **19**

Mechanical analysis and scaling

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Mechanical analysis

Introduction

Visual examination of equine gait has been the main clinical tool for diagnosis of lameness in horses during the past two or three millennia. Similarly, trainers and breeders routinely examine gait visually in order to predict sport performance. Recent developments in gait measurement techniques (Clayton, 1996) have made it possible to perform gait analysis in a quantitative manner, which results in better reproducibility, improved temporal and spatial resolution, and is less dependent on the experience and judgment of the clinician or trainer. The separate analysis of either movements or forces, or *kinetics* respectively, can enhance our understanding of equine gait. However, an even more powerful method is to analyze movements and forces simultaneously using Newton's laws of *dynamics*.

Kinematic variables, such as limb trajectories, joint angles and angular velocities, have been used frequently in the past two decades to quantify equine gait (e.g. van Weeren et al., 1993). These variables contain essentially the same information that is presented to the eye of a clinician, the only difference being the quantitative nature of the information and the increased spatio-temporal resolution. This resolution is important, because equine gait is very reproducible and small or fast changes in movement, invisible to the human eye, are relevant. Until now, however, automated kinematic gait analysis has not resulted in a better ability to quantify and characterize lameness, as compared to visual examination by an experienced clinician (Back et al., 1993). However, some success has been reported in prediction of performance using gait analysis (Deuel & Park, 1993; Back et al., 1995).

A different type of gait information is obtained by using *kinetic* variables. Kinetic variables are variables related to forces. Internal kinetic variables such as tendon forces (Riemersma et al., 1996) and bone strain (Hartman et al., 1984; Biewener et al., 1988) have been measured in horses. These measurements are, however, invasive and limited to research applications. For routine gait evaluation, the only non-invasive kinetic measuring device is the force platform, which measures forces between hoof and ground. After initial work by Pratt and O'Connor (1976), clinical applications were explored (Merkens & Schamhardt, 1988; Dow et al., 1991). These studies have shown that, although force plate signals do not always provide enough information for full diagnostics, they are useful to quantify lameness and to indicate the affected limb.

Isaac Newton (England, 1642–1727) formulated the basic laws of *dynamics*, establishing a relationship between force, mass and translational movement: $F = m \cdot a$. Leonhard Euler (Germany, 1707–1783) further developed these laws to describe rotation of rigid bodies, whereas Joseph Louis Lagrange (France/Italy, 1736–1813) formulated equations for linked multibody systems which are the basis of modern robotics. The laws of dynamics have proved useful to predict motion resulting from known forces (*forward dynamics*), or to estimate the forces that were the cause of an observed motion (*inverse dynamics*). Since Elftman introduced the inverse dynamics analysis in biomechanics (1939) it has been applied successfully in human movement research. Examples can be found in orthopedics (Andriacchi, 1993), in motor control (Winter & Eng, 1995) and in sport (Yeadon & Challis, 1994). It provides an opportunity for interpretation of gait that is not possible with kinematic or kinetic measurements alone. This opportunity has also been explored for basic questions on equine gait (Bartel et al., 1978; Schryver et al., 1978; Clayton et al., 1998).

Inverse dynamic analysis treats the locomotor system as a system of linked rigid segments, with hypothetical torque (or moment) motors at each joint representing the action of muscles. The analysis combines kinematic and force platform data to derive these joint moments throughout the movement cycle (Fig. 19.1). The methods have been well established in the literature, both in two dimensions (Winter, 1990) and in three dimensions (Vaughan, 1984; van den Bogert, 1994). Software to perform inverse dynamic analysis on any user-specified locomotor system, allowing for horses as well as humans, is available from the major manufacturers of gait analysis equipment.

The moment at the center of rotation of a joint is directly related to the combination of muscle forces acting across the joint. These joint moments by themselves provide useful information about movement. Even more so than the human, the horse, with its four multi-jointed limbs frequently acting as closed-chain mechanisms, may redistribute its joint moments without visual gait changes. For instance, a visually identical hind limb extension in late stance may be accomplished by only hip extensor muscles, only knee extensor muscles, or any combination of these. Inverse dynamic analysis allows us to 'see' these differences in muscle coordination. One further useful step in inverse dynamic analysis is the quantification of joint power profiles. This allows investigation of the sources of mechanical power for movement. We will show in this chapter how joint moment and joint power can be used to estimate force and power output in musculotendinous structures.

It must be stressed that results of inverse dynamic analysis are sensitive to the protocol for data collection and the methods for data analysis. Since the horse is not a set of perfect rigid body segments, and kinematic data are contaminated by measurement errors and soft tissue deformation, results can only be an approximation. This is acceptable, as long as the methodology is well understood and used consistently so that results can be compared between studies.

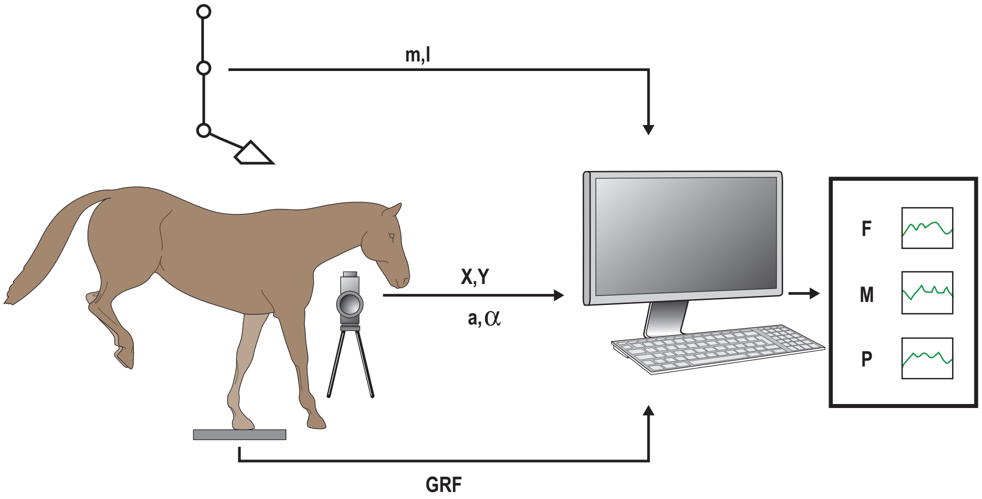

Fig 19.1 Inverse dynamic analysis uses a linked segment model, kinematics and force platform data to calculate joint moments, forces and powers. (See text for details.)

An indication of the potential applications of inverse dynamic analysis can be obtained from examples in the human literature. A well-known finding is that knee extensor moments during gait are significantly reduced after anterior cruciate ligament injury. Inverse dynamic analysis provides a tool to monitor the patient's progress during rehabilitation and decide when surgical treatment is required (Andriacchi & Birac, 1993). Using out-of-sagittal plane joint moments, it has been shown that a certain bracing method reduces the medial compartment loads in the knee joint (Lindenfeld et al., 1997). Especially noteworthy is the success of gait analysis, including inverse dynamic and joint power analysis, in surgical decision making for children with cerebral palsy (Rose et al., 1993). In research, useful information for understanding of injury mechanisms and design of joint replacements is obtained from inverse dynamic analysis of muscle and joint forces during various activities (Paul, 1971; van den Bogert et al., 1999). Similar clinical applications can be found for horses when using inverse dynamics to analyze equine gait. It has, for example, been used successfully to analyze the influence of heel wedges in horses with tendinitis (Clayton et al., 2000).

Before such applications are possible, it is imperative that valid test protocols are established and normative data are collected (Ounpuu et al., 1991). Movements of horses are remarkably planar and the function of most muscles, especially those in the distal limbs, is limited to flexion and extension in the sagittal plane. Therefore, two-dimensional analysis is sufficient for most purposes. This chapter presents in detail the procedure for inverse dynamic analysis for sagittal plane movement, with specific reference to development of protocols for equine applications. Some applications require a full three-dimensional analysis. A short introduction of this more complex analysis therefore concludes this chapter.

Inverse dynamic analysis

Linked segment model

For the inverse dynamic calculations a simplified model of the horse is used. This model is called a linked-segment model since it consists of rigid segments, which are linked to each other. The segments can rotate in the joints that link the segments. In a two-dimensional model, these joints are assumed to be ideal hinge joints: there is no friction, there is no translation possible and the only movement is a pure rotation around a fixed point, the center of rotation. Since the segment is assumed to be rigid, its length, or the distance between the joints, is constant. Furthermore the inertial properties, mass (m), location of the center of mass and moment of inertia (I), of the segments are constant (Winter, 1990). In mechanical terms the moment of inertia is the rotational equivalent to the mass. While the mass determines the resistance to linear accelerations, the moment of inertia determines the resistance to angular accelerations. The force needed for a certain (linear) acceleration equals the mass times the acceleration ($F = m \cdot a$). In a similar way the moment needed for a certain angular acceleration equals the moment of inertia times the angular acceleration ($M = I \cdot \alpha$). This moment of inertia is determined by the spatial distribution of the mass within the segment. The mass of the segment equals the total mass between the joints; it represents not only the bone but also the soft tissue surrounding it. The mass of all segments together is therefore equal to the body mass of the horse. Figure 19.2 gives a graphical representation of a linked-segment model.

The action of the muscles is represented by the moment they generate around the joint. This moment generating function is explained in Figure 19.3. If a muscle is activated it generates a tensile force at the bones. Due to this force the bones are compressed at the joint. This causes a bone-to-bone force from both bones onto each other. So, because of the muscular activity there are two forces acting on each bone: from the muscle at the attachment site and one from the other bone at the joint. Since these two forces are equal in magnitude and opposite in direction they form a couple. The moment associated with this couple equals the force times the distance between the two forces. Since the two forces are equal in magnitude and opposite in direction they cancel each other out and the muscle action can be represented by the moment (Elftman, 1939). In a similar way the forces exerted by ligaments can also be represented by moments. It should be noted that the bone-to-bone force of Figure 19.3 does not represent the complete joint contact force; it is only the part of this force that is caused by the activity of the muscle.

Inverse dynamic calculations

In inverse dynamic calculations the movement of the linked segment model is used to calculate the underlying forces (Elftman, 1939; Winter, 1990). The calculations are based on the principles of Newton's laws of motion. In order to apply these principles the linked segment model is split into separate segments. The interaction between the segments is summarized in a net joint force and a net joint moment. The net joint force is the resultant of all forces between the two segments. The net joint moment is the sum of the

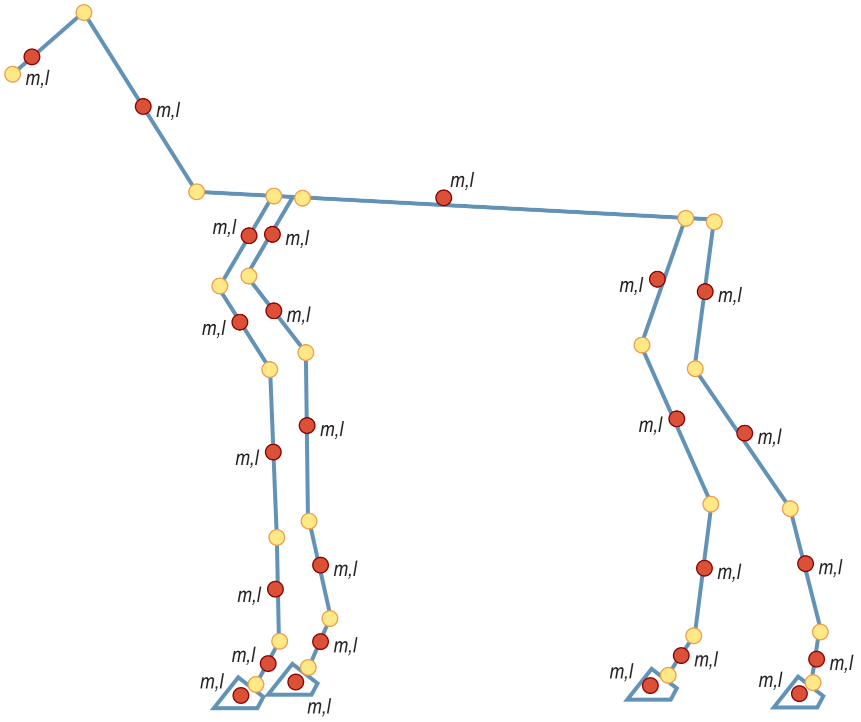

Fig 19.2 Linked-segment model of a horse (moment of inertia).

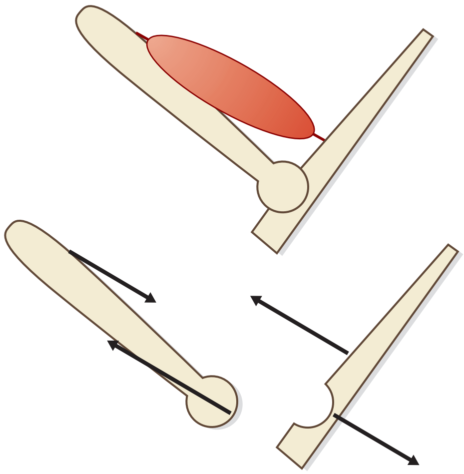

Fig 19.3 Muscle activity causes a bone-to-bone force at the joint. The muscle action can thus be represented by a moment.

moments of all muscles and ligaments crossing the joint. All moments and forces acting on each segment are depicted in a free body diagram. The moments are the net joint moments at both joints. The forces are the gravitational force, the net joint forces at both joints and, sometimes, an external force. The most important external force is the ground reaction force (GRF) acting on the hoof segment during stance. Other external forces can be the weight of a rider or the force needed to pull a load. All those external forces are measured. Furthermore, the linear and angular accelerations are calculated from the (measured) movements of the segments. The inverse dynamic calculations can then start by analyzing either the most proximal or the most distal segment.

The free body diagram of the most distal segment, the hoof segment, is drawn in Figure 19.4. The amplitude and direction of

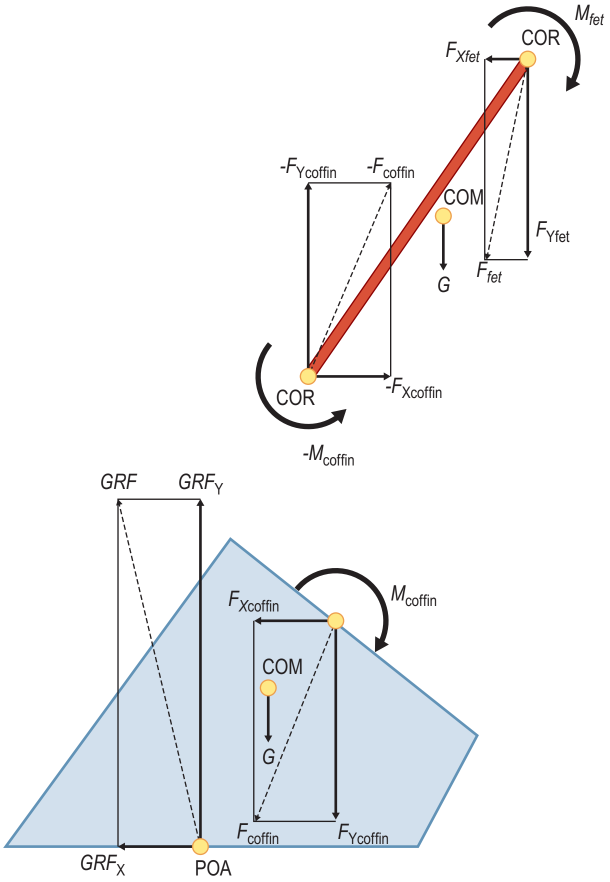

Fig 19.4 Free body diagrams of the hoof and pastern segments. POA, point of application of the COM (segmental center of mass); COR, joint center of rotation.

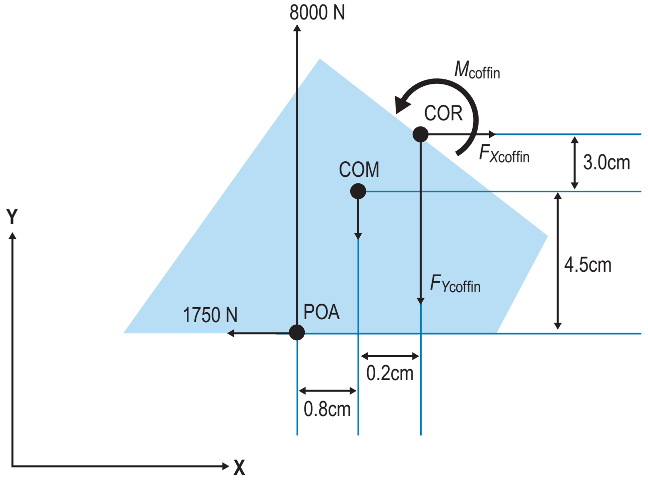

Fig 19.5 Free body diagram of the hoof segment.

the coffin joint moment and force are not yet known. They are therefore drawn in an arbitrary direction. After the calculations the real direction and magnitude will be known. According to Newton's second law the sum of all forces on the segment must equal its mass times acceleration:

$$\Sigma F_X = m_{hoof} \cdot a_{Xhoof}$$

where the subscript $_X$ denotes the horizontal components of the force (see Fig. 19.4), m_{hoof} is the mass of the hoof segment and a_{Xhoof} is the horizontal acceleration of the center of mass of the hoof. Using this equation the horizontal components of the net joint force can be calculated from measurements, as is illustrated in Figure 19.5. Complete formulas can be found below. A similar equation can be written for the vertical direction to calculate the vertical component of the net joint force at the coffin joint:

$$\Sigma F_Y = m_{hoof} \cdot a_{Yhoof}$$

where the subscript $_Y$ denotes the vertical components of the force and acceleration. Of course, the gravitational force (G) should now be taken into account.

All forces, except the gravitational force, generate a moment relative to the center of mass. The magnitude of the moment is determined by the amplitude of the force and its perpendicular distance from the center of mass. Moments that tend to rotate the segment counterclockwise are defined positive whereas moments that tend to rotate clockwise are defined negative. For the hoof of Figure 19.4 this means that positive moments tend to flex the coffin joint. Note that this association between flexion or extension and the sign of the moment is dependent on the way the free body diagram is drawn since it is reversed for mirrored images. The sum of the net coffin joint moment and the moments of all forces must equal the moment of inertia times the angular acceleration of the hoof segment (α_{hoof}):

$$\Sigma M = I_{hoof} \cdot \alpha_{hoof}$$

From this equation the net joint moment can be calculated. Now all forces and moments acting on the hoof segment are known and the analysis of this segment is complete. The calculations can be continued by analyzing the next segment, the pastern segment. The movement of the pastern joint is often neglected and the remaining part of the digit is represented by one segment.

The free body diagram of the pastern segment (Fig. 19.4, upper part) contains the moment and force acting from the hoof on the pastern. According to Newton's third law (action equals minus reaction) the force from the hoof on the pastern is the exact opposite of the force from the pastern on the hoof. Similarly, the moment from the hoof on the pastern is the opposite of the coffin joint moment. The net joint force at the fetlock joint can now be calculated in a similar way as was previously done for the coffin joint. The horizontal acceleration is used to calculate the horizontal component of the net joint force and the vertical acceleration is used to calculate the vertical component (see Fig 19.6):

$$\Sigma F_X = m_{past} \cdot a_{Xpast}$$

$$\Sigma F_Y = m_{past} \cdot a_{Ypast}$$

Finally, the angular acceleration is used to calculate the net joint moment:

$$\Sigma M = I_{past} \cdot \alpha_{past}$$

After the pastern segment, the metacarpal segment can be analyzed in the same manner, again using the principle of action and reaction. This can be continued, segment after segment, until the most proximal segment, most often the head segment. The only forces on this segment are the gravitational force and the net joint force at the distal side. The only moment is the distal net joint moment. In theory these forces and this moment should balance the linear and angular accelerations of the final segment. However, most often a residual force and moment are found. This is caused by measurement errors and non-rigidity of the segments. Although errors are present in all calculated joint forces and moments, they are largest for the final joint since they accumulate during the calculations. In order to prevent this accumulation of errors, and to remove the residual moment and force at the final segment, an alternative method has been developed (Kuo, 1998). This method solves the equations for all segments simultaneously. Because there are more equations than there are unknown forces and moments, they cannot be solved exactly. However an approximate solution can be calculated using a least squares method. In this way the errors are distributed evenly over all joints. The errors of the final joint are therefore smaller than in the segment-after-segment approach, however, the errors of the distal joints will be larger. Furthermore, the simultaneous least squares method is only useful if the whole horse is analyzed. If only part of the horse is analyzed, e.g. only one limb, both methods will give the same result.

Measurement of input variables

In order to perform inverse dynamic calculations several input variables are needed. These variables can be sub-divided into three categories: inertial properties, movement data and external force data. The inertial properties are mass, moment of inertia and location of the center of mass for all segments. These properties have been measured in cadaver segments and are represented as regression equations (van den Bogert et al., 1989; Buchner et al., 1997). This allows scaling to horses of different size by using individual body mass and/or segment lengths. The position of the center of mass is represented in a segment-based coordinate system. The origin of this coordinate system is located at the proximal joint center of rotation, the x-axis runs through the distal joint center of rotation and the y-axis is perpendicular to the x-axis and points cranially or dorsally (Fig. 19.7).

The movement data consist of the position of the joints and the angular and linear acceleration of all segments. The measurement of position data is discussed in Chapter 2. However, for inverse dynamic calculations not only the joint angles but also the position of the joints should be known. The easiest way to measure these positions is by putting the markers on the joint centers of rotation (Leach & Dyson, 1988). Joint moments are sensitive to joint center location, so it is important to know the inaccuracies introduced by this procedure. Alternatively, two markers are applied to each segment and the position of the joint center of rotation relative to these markers is determined in a separate measurement with additional markers on the joints. For some joints this procedure can limit the skin movement artifacts because the markers can be

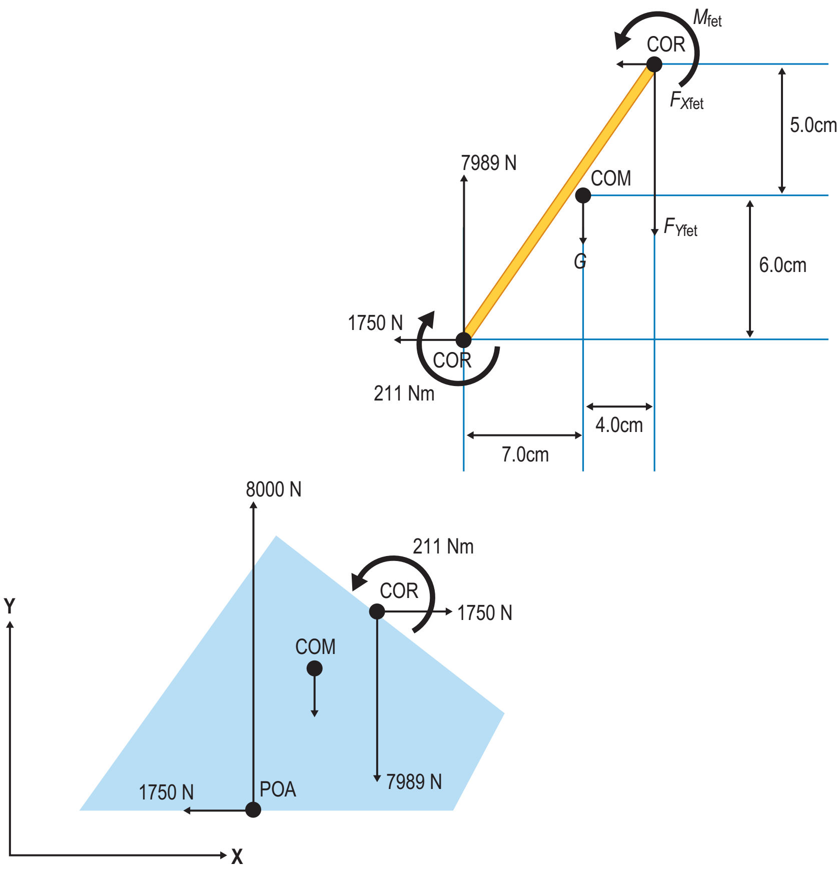

Fig 19.6 Free body diagram of the hoof and pastern segment.

applied on places with minimal skin movement (van Weeren et al., 1992a). Further discussion of the skin movement problem in equine movement analysis may be found in Chapter 2 of this volume. After the movements are measured they must be differentiated twice to obtain the accelerations. This can be done with a spline function, as described in Chapter 2, or with a finite difference method (see below). When using the finite difference method excessive noise must first be removed from the data (see Fig. 2.5). This can be done by filtering or by averaging several trials.

The external force data consist of the amplitude, direction and point of application of the external forces, most often the GRF. The GRF can be measured with a force plate, force shoe or instrumented treadmill as described in Chapter 2. For inverse dynamic calculations not only the magnitude and direction of the GRF must be measured but also the point of application. Force plates, although very accurate with respect to the force amplitude, often have systematic errors in the point of application (Bobbert & Schamhardt, 1990). These errors can be corrected with a calibration procedure in which static loads are applied at known positions. Instrumented treadmills or force shoes give the opportunity to measure consecutive strides. However, the accuracy of these systems should be evaluated carefully.

The movement and GRF data must be aligned and synchronized. Some motion analysis systems can capture the force data directly and do not need additional synchronization. For other systems synchronization pulses from the video camera can be sampled simultaneously with the force data to synchronize the force data. Alternatively, a counter operated by the force sampling equipment and visible in the camera image can be used to synchronize the motion data. The coordinate systems of the force plate and motion analysis systems can be aligned by putting markers on the edges of the force plate and measuring them with the motion analysis system. This can be performed in a separate session to prevent interference with the normal data collection.

Net joint moment and muscle force

The net joint moment is generated by the muscles. The polarity of the moment indicates whether flexors or extensors are active, whereas the amplitude is a measure of the amount of activity. Based on the net joint moments the activity of muscle groups (flexors and extensors of the different joints) can be analyzed. However, sometimes it is desirable to estimate forces of individual muscles. Depending on the number of muscles crossing the joint, the muscle forces can either be calculated or estimated from the net joint moment (Fig. 19.8).

In some joints there is only one muscle that can flex the joint. The deep digital flexor muscle (DDF), for instance, is the only muscle that can flex the coffin joint. (The navicular ligaments can generate a flexor moment but only if the joint is (hyper) extended.) In a flexed joint the moment generated by DDF will equal the net coffin joint moment:

$$M_{\mathrm{coffin}} = F_{\mathrm{DDF}} \cdot d_{\mathrm{DDF}}$$

where d_{DDF} is the moment arm of the deep digital flexor – the perpendicular distance between the joint center of rotation and the line of action of the muscle (Fig. 19.8, Fig. 19.9A). This moment arm can be measured from radiographs (Jansen et al., 1993) or from longitudinal sections of an *in vitro* limb. For some muscles the moment arm depends on the joint angle. A model containing the origin, insertion and possible curvatures of the muscle can then be used to calculate the moment arm from the joint angles (van den Bogert & Sauren, 1989). When calculating F_{DDF} from M_{coffin} using the equation above, it is assumed that there is no other active

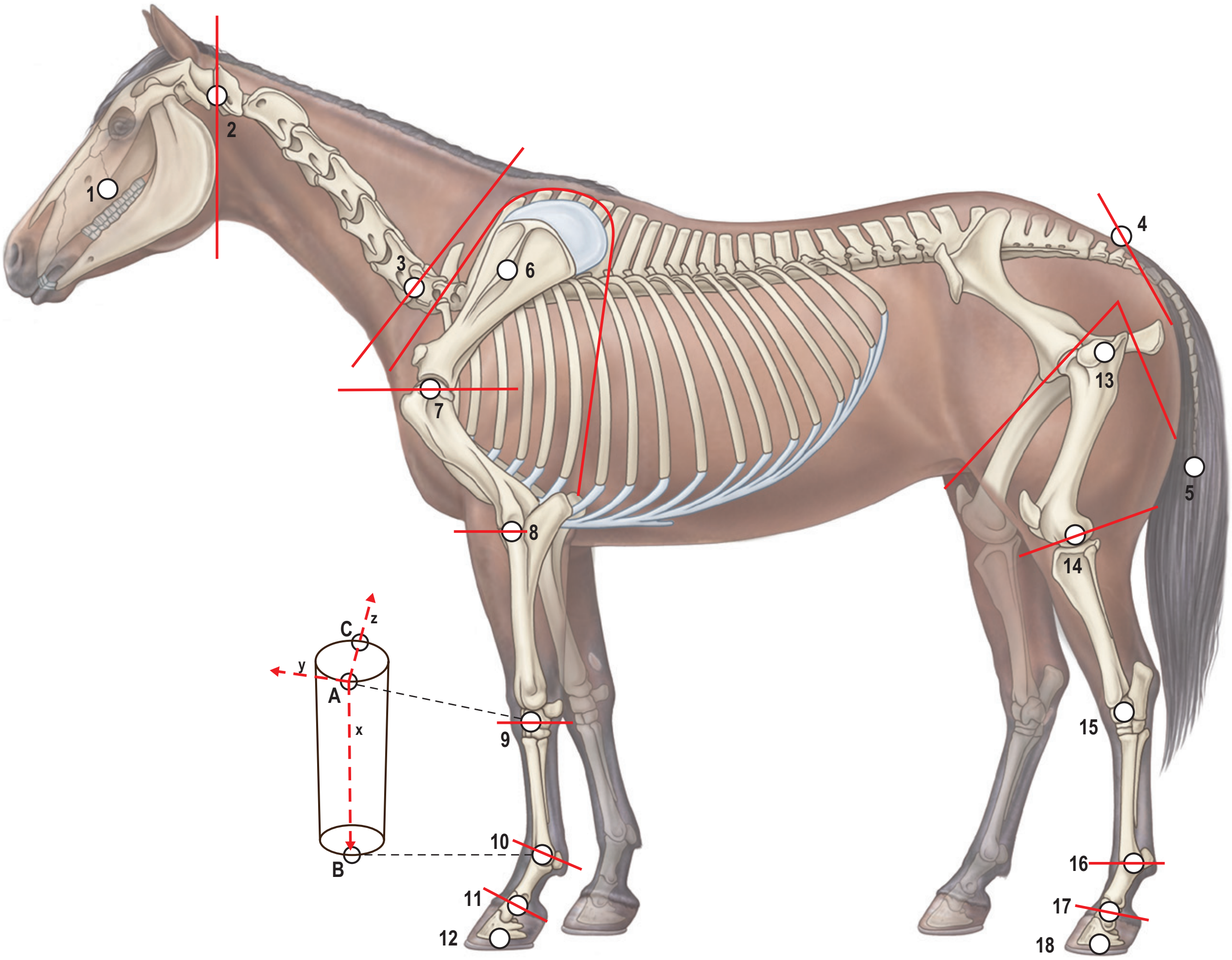

Fig 19.7 Definition of the segments and their coordinate systems. Red lines represent the segment boundaries. The schematic enlargement shows the coordinate system. The z axis is used only in three-dimensional analyses.

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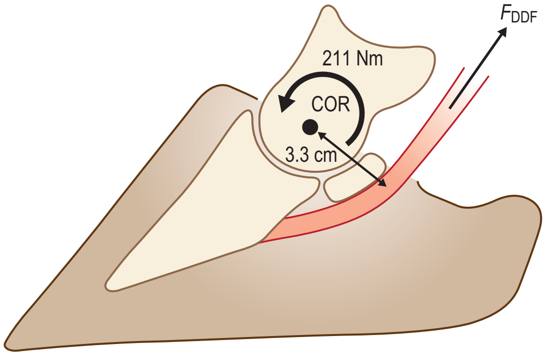
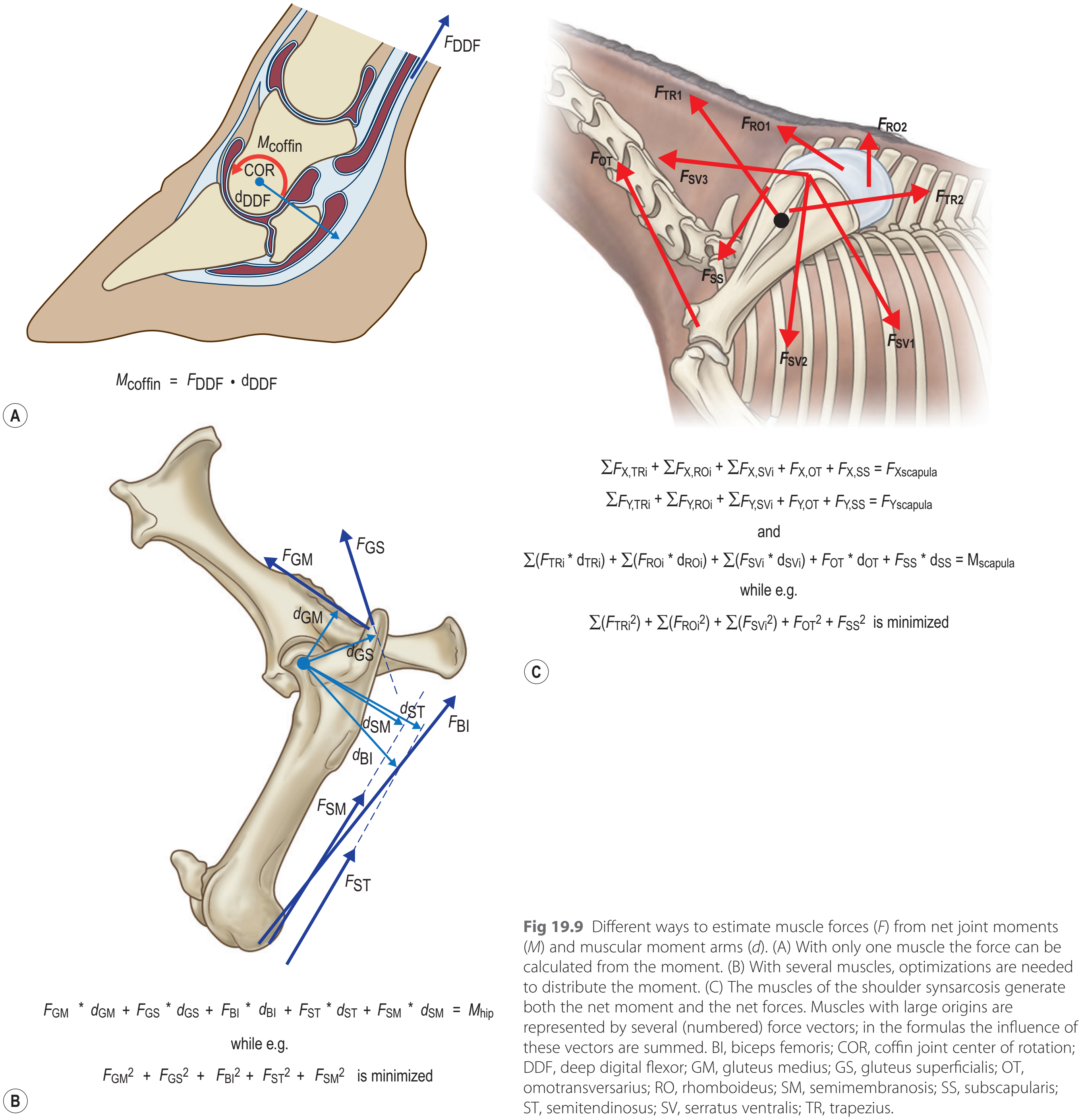


Fig 19.8 Deep digital flexor force.

muscle or force-generating ligament at the coffin joint. The antagonistic muscles (the digital extensors) are assumed to be inactive. If these muscles, contrary to the assumption, are active they will generate an extensor moment, which should be compensated by the DDF. The actual F_{DDF} will then be higher than the calculated force. The calculated force is therefore the lower limit of the actual muscle force. This type of analysis has shown that desmotomy of the distal accessory ligament causes a decrease in the DDF force that does not disappear within 6 months (Buchner et al., 1996; Becker et al., 1998).

For joints with only one muscle at each side, the calculation of muscle force is simple. However, most joints, e.g. the hip joint of Figure 19.9B, are crossed by more than one muscle. In order to calculate muscle forces from the net moments at these joints, assumptions must be made about the distribution of the moment among the available muscles. To estimate muscle forces the moments are most often distributed in such a way that a certain criterion or cost function is minimized. Computer algorithms are available to solve the distribution problem by minimizing a given cost function. This procedure is called optimization. Some commonly used cost functions are the sum of all muscle forces, the sum of the squared or cubed muscle forces and the highest muscle force. In order to correct for size differences between the muscles the force is sometimes replaced by stress: muscle force divided by physiological cross-sectional area. Other cost functions might include measures for muscle fatigue, energy costs or joint contact forces (Crowninshield & Brand, 1981; Dul et al., 1984; Glitsch & Baumann, 1997).

A major problem in optimization is that it is difficult to validate the cost function. The real muscle forces can only be found when



$$M_{coffin} = F_{DDF} \cdot d_{DDF}$$

$$F_{GM} * d_{GM} + F_{GS} * d_{GS} + F_{BI} * d_{BI} + F_{ST} * d_{ST} + F_{SM} * d_{SM} = M_{hip}$$

while e.g.

$$F_{GM}^2 + F_{GS}^2 + F_{BI}^2 + F_{ST}^2 + F_{SM}^2 \text{ is minimized}$$

$$\Sigma F_{X,TRi} + \Sigma F_{X,ROi} + \Sigma F_{X,SVi} + F_{X,OT} + F_{X,SS} = F_{Xscapula}$$

$$\Sigma F_{Y,TRi} + \Sigma F_{Y,ROi} + \Sigma F_{Y,SVi} + F_{Y,OT} + F_{Y,SS} = F_{Yscapula}$$

and

$$\Sigma(F_{TRi} * d_{TRi}) + \Sigma(F_{ROi} * d_{ROi}) + \Sigma(F_{SVi} * d_{SVi}) + F_{OT} * d_{OT} + F_{SS} * d_{SS} = M_{scapula}$$

while e.g.

$$\Sigma(F_{TRi}^2) + \Sigma(F_{ROi}^2) + \Sigma(F_{SVi}^2) + F_{OT}^2 + F_{SS}^2 \text{ is minimized}$$

Fig 19.9 Different ways to estimate muscle forces (*F*) from net joint moments (*M*) and muscular moment arms (*d*). (A) With only one muscle the force can be calculated from the moment. (B) With several muscles, optimizations are needed to distribute the moment. (C) The muscles of the shoulder synsarcosis generate both the net moment and the net forces. Muscles with large origins are represented by several (numbered) force vectors; in the formulas the influence of these vectors are summed. BI, biceps femoris; COR, coffin joint center of rotation; DDF, deep digital flexor; GM, gluteus medius; GS, gluteus superficialis; OT, omotransversarius; RO, rhomboideus; SM, semimembranosis; SS, subscapularis; ST, semitendinosus; SV, serratus ventralis; TR, trapezius.

the cost function represents the principles by which the nervous system solves the distribution problem. These principles, however, are not known. Another problem is that realistic boundary conditions must be included in the optimizations. For each muscle, the force it can generate is limited to a certain maximum. This maximum is influenced by the momentary length and the contraction velocity of the muscle fibers. Predicted forces should of course not exceed this maximum force. Furthermore, muscle force can only increase and decrease gradually, muscles cannot be either 'on' or 'off' momentarily. Dynamic models of muscle in which these properties are incorporated can be used in optimization based on inverse dynamics (Thunnissen, 1993).

These more sophisticated *dynamic optimization* models, as opposed to *static optimizations* that do not consider muscle properties (both based on inverse dynamic analysis of movement!), have not been used other than in research, presumably because more complicated calculations are required. However, they will result in more realistic estimates of muscle force. In rare cases, results from optimizations have been compared to direct measurements using invasive methods. In cats, the load sharing among synergistic muscle was not correctly predicted by *static* optimization (Herzog & Leonard, 1991) when compared to tendon force transducer data.

Most muscles can be represented by moment generators. This is possible because the bones are connected by joints that can be modeled as hinge or ball joints and can generate the bone-to-bone force at a known joint center. However in the shoulder synsarcosis there is no joint (Dyce et al., 1987). Therefore the muscles of the shoulder synsarcosis are not moment generators. Furthermore, the movement of the scapula and relative to the trunk is not limited to rotation around a fixed point. Due to the absence of a joint, substantial translations are also possible. The linked-segment model will become more realistic if the hinge joint between scapula and trunk is replaced by a free movement and the muscles are represented by force generators. The net moment and net force can still be calculated relative to a fixed point on the scapula – this can be any point, for instance the center of mass. However, the point of application of the net force on the trunk is not fixed any more. The forces of the muscles can still be calculated exactly if there are three active muscles in the model (since there are three equations of motion for a body segment), or using optimization methods if there are more than three. The only difference in the equations is that the muscles should not only generate the net moment between scapula and trunk but also the net force. Therefore the position of the muscle should not be represented by the moment arm but by its actual line of action between trunk and scapula (Fig. 19.9C).

Net joint force and joint contact force

The net joint force, calculated from the equations of motion, represents the sum of all forces between the two segments. It should not be confused with the joint contact force, which can be measured between the bones in the joint. The joint contact force is only one of the forces between the segments; other forces are the muscle and ligament forces. The real contact force therefore equals the difference between net joint force and the summed muscle (and ligament) forces (see Fig. 19.10):

$$F_{\text{contact}} = F_{\text{net}} - \Sigma F_{\text{muscle}}$$

When calculating the joint contact force, the forces of all active muscles should be taken into account. In calculating muscle forces from the net joint moment it is often assumed that there are no antagonistic co-contractions. This is implied by most of the static optimization methods. These co-contractions will cancel each other out with respect to the joint moment and are therefore ‘invisible’ to a mechanical analysis. However both muscles add a bone-to-bone force and increase the joint contact force. Ignoring antagonistic co-contractions therefore results in an underestimation of the joint contact force. Similarly, the joint contact force will be influenced by the way the net joint moment is distributed over muscles with different moment arms. Muscles with a larger moment arm need a smaller force to generate a similar moment than muscles with a smaller moment arm. The joint contact force will therefore be smaller if the contribution of muscles with a larger moment arm is higher. In humans, the contact force in the hip joint was estimated by static optimization of muscle forces and compared to measurements from an instrumented prosthesis (Brand et al., 1994). It was found that the model calculations overestimated the joint contact force, mainly due to incorrect moment arms in the model.

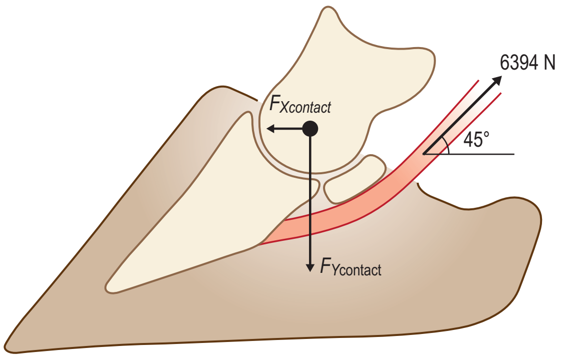


Fig 19.10 Joint contact force.

Continued calculations: power

The muscles are the motors of the body. The moments and forces generated by the muscles have been analyzed in the previous paragraphs. However, a motor does not only generate moments or forces; it also produces or converts mechanical energy. The muscles obtain their energy from the oxidation of foods and convert it to mechanical energy. The energy is distributed over the segments and is used internally, to accelerate or elevate the segments, or externally, e.g. to overcome air resistance or to pull a load. Energy production, distribution and use can be analyzed with calculations based on inverse dynamic results. If a force acts on a moving object, energy is produced or absorbed. The amount of energy equals the force times displacement of the point of application in the direction of the force. Power is the time derivative; it equals energy production divided by time, which is equal to force times velocity of the point of application:

$$P = F_X \cdot v_X + F_Y \cdot v_Y$$

For rotational movements the power equals moment times angular velocity ($P = M \cdot \omega$). Note that power will be calculated in Watts if the moment is expressed in Newton-meters and the angular velocity in radians per second. In power analyses of linked-segment models, the powers associated with all forces and moments on the segments are calculated. The sum of these powers equals the rate of change of the kinetic and potential energy of the entire system. This power balance follows from Newton’s laws of motion and may be used to determine the contributions of each joint to the movement of the entire system (van Ingen Schenau & Cavanagh, 1990).

For most forces and moments the power calculation is straightforward. However, the GRF needs special attention. The point of application of the GRF shifts forward during stance. It is tempting to multiply the velocity of this shift with the GRF to obtain the power. However this is not the powerflow associated with the GRF (van Ingen Schenau & Cavanagh, 1990). On a hard, non-deformable surface the GRF does not perform work. The GRF is a distributed force, which is summarized to one resultant force with a certain point of application. In Figure 19.11 the GRF is represented as five smaller forces acting on different positions of the hoof surface. During stance the amplitude of these five partial forces changes,

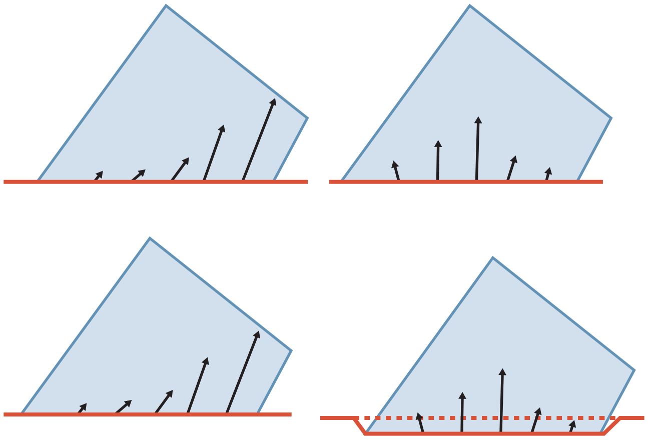


Fig 19.11 Shifts and movements of the point of application of the GRF on a hard surface (above) and on a deformable surface (below). (See text for details.)

whereas their position stays constant. This causes the point of application of the resultant GRF to shift forward. However, none of the partial forces generates power since their velocity is zero. The resultant force, which is simply the summation of all partial forces, does not generate power. In reality there are, of course, more than five partial forces, but the same reasoning applies. On a deformable surface, like sand, the situation is different. When the hoof penetrates the surface the point of application not only shifts due to amplitude changes but also moves due to hoof movements. The position of the five partial forces changes and they generate power (see Fig. 19.11). Therefore, on deformable surfaces, power can be associated with the GRF. This power is related to the movement of the surface; it equals the velocity of the hoof surface times the amplitude of the GRF. This power is used to deform the surface. This example illustrates that valid power results are only obtained if a force is multiplied by the velocity of a point on a physical body to which the force is applied. The velocity of a point that is not rigidly attached to a mass is not suitable.

When analyzing the powers of the linked-segment model, two different approaches are used: a segment oriented approach (Elftman, 1939; Winter & Robertson, 1978; Robertson & Winter, 1980) and a joint-oriented approach (van Ingen Schenau & Cavanagh, 1990). The segment-oriented approach is used to analyze *internal* use and the *distribution* of energy, or power-flow, whereas the joint-oriented approach is used to analyze power *production* and *external* use. In the segment-oriented approach two power-flows are distinguished at both the proximal and distal end of the segment: the power-flow associated with the net joint force and the power-flow associated with the net joint moment. The power-flow associated with the net joint force is a passive power-flow from the adjacent segment, or, if negative, a passive power-flow into the adjacent segment. At the joint, the passive power-flow into the proximal segment equals the passive power-flow out of the distal segment (or reversed). This is caused by the fact that the net joint forces on the distal and proximal segments are each other's opposites while the velocities at the point of application, the center of rotation, are equal. The power-flow associated with the net joint moment is an active power-flow generated by the muscles. At the joint, the angular velocities of the two segments are normally different and therefore the power-flow associated with the net joint moment is different for the two segments. This difference is generated (or absorbed) by the muscles.

All four power-flows, passive and active proximal and distal flow, can either be positive or negative. Most often some of them are positive whereas others are negative and power-flows from one segment to the other. However the sum of the four flows is not always zero. If the sum is positive, the energy of the segment increases. This energy is converted into potential or kinetic energy as the height or the velocity of the segment increases. Similarly, a negative power-flow is converted from potential and/or kinetic energy when the height and/or velocity decreases.

Using this kind of analysis the power-flow within the limb can be analyzed. This has been done for the distal front limb during walk (Colborne et al., 1997). During the major part of the stance phase the power-flow of the metacarpal and pastern segments was distal to proximal. This probably reflects the propulsion of the proximal part of the body. During final stance the power-flowed in at both ends of the segments and was probably used to accelerate and elevate the segments for the swing phase. Care must be taken with this kind of analysis because results are dependent on the velocity of the coordinate system in which the movements are represented. This will influence the results when measuring on a treadmill. We recommend that the analysis be performed only in a coordinate system attached to the ground, which implies a moving coordinate system for treadmill analysis.

In the joint-oriented approach of power analyses the power-flows of all segments are summed (van Ingen Schenau & Cavanagh, 1990). The power associated with the net joint force is opposite for two adjacent segments. When adding the powers of the different segments the powers associated with the net joint forces cancel each other out. The only power, therefore, is the power associated with the net joint moment. At each joint the powers for the two segments are summed to one joint power. This power equals the net joint moment multiplied by the difference in angular velocity between the segments:

$$P_{\text{joint}} = M_{\text{joint}} \cdot (\omega_{\text{prox}} - \omega_{\text{dist}})$$

This power is generated by the muscles crossing the joint and is therefore a measure of the activity of the muscles. The joint powers of all joints can be summed to obtain the total power production. This power is used for external power production (e.g. pulling a load, air resistance) and kinetic and potential energy changes of the segments. Power production at the joints can therefore be compared with external power losses due to air resistance, friction, etc. In human research this approach has been applied successfully in movements where most of the power is used externally and where internal loss of power is minimal. Examples can be found for bicycling, swimming and speed skating (van Ingen Schenau & Cavanagh, 1990). In walking and running the external power production is very small; most power is used to accelerate and decelerate the limbs and to provide a shock-absorbing support against gravity. Apart from the high-speed gallop, where air resistance might become substantial, the same holds for the gaits of a horse. Although it is not useful to apply this approach to the equine walk and trot, it can be used when the external power output is substantial, e.g. in pulling a load, during accelerating and in jumping.

Apart from the external power production the joint-oriented analyses might give insight into muscle function during movement (de Koning et al., 1991; Devita & Skelly, 1992). Positive joint power indicates power production that might originate from concentric activity of the muscles crossing the joint. Large positive power production peaks indicate important propulsive muscles whereas timing of the different peaks indicates the coordination of the movement. Furthermore, negative joint power indicates power absorption, which might be related to eccentric muscle contraction. These contractions are assumed to be a major cause of muscle soreness and a risk for muscle injuries (Jones & Round, 1990). Power analyses can therefore be used to find muscles that are at high risk for injuries. This type of analysis has been used for the equine forelimb during walk (Colborne et al., 1998). Moment peaks of the carpal and fetlock joints were of similar magnitude whereas the coffin joint moment was much smaller. The carpal joint power was almost zero due to the small movements of this joint. The fetlock joint had alternating periods of power absorption and production whereas the coffin joint predominantly absorbed power.

The two approaches, segment-oriented and joint-oriented power analyses, are closely related. They emphasize different aspects of the power balance. The joint-oriented approach emphasizes the external power production and the places where this power is produced whereas the segment-oriented approach emphasizes the power-flow within the body and the internal use (see Fig. 19.12). In both approaches power production and absorption have simply been related to concentric and eccentric contraction of muscles at the joint. However the biological reality is a bit more complex for two reasons: elastic structures can temporarily store energy and most muscles cross more than one joint (van Ingen Schenau & Cavanagh, 1990).

Elastic structures, like tendons and ligaments, store energy when elongated. This energy is released when they return to their normal length. The long and stiff tendons in the distal limbs of horses are able to store substantial amounts of elastic energy (Alexander & Bennet-Clark, 1977). Furthermore, the deep palmar ligament of the carpus might also absorb a substantial amount of energy during hyperextension of the carpus. Power absorption is therefore not always associated with eccentric muscle contraction but can also be caused by elastic energy storage in tendons and ligaments. The

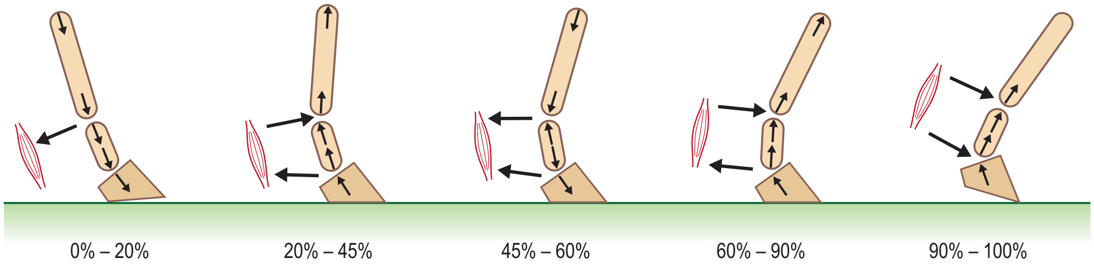


Fig 19.12 Five parts of stance phase.

subsequent power production can originate from the release of elastic energy instead of concentric muscle contraction. If elastic properties of tendons are known, and tendon force is estimated from inverse dynamic analysis, the amount of energy storage can be estimated separately.

Power production and absorption are usually analyzed at a joint level but many muscles span more than one joint. These muscles can therefore absorb power at one joint and simultaneously produce power at another joint. This has, for instance, been described for the gastrocnemius muscle in human vertical jumping: at the end of push-off, the muscle generates positive power at the ankle and negative power at the knee. This function of biarticular muscles is referred to as power transport between joints (Gregoire et al., 1984). It is assumed to be a major function of these muscles. Power transport can take place during isometric contraction without power production by the transporting muscle. Therefore, no muscle fibers are needed to transport power and tendons can also transport power. In the lower limbs of horses there are several more or less tendinous bi- or polyarticular muscles. It has been hypothesized that the proximal muscles generate the power and that this power is transported to the distal joints by the tendinous biarticular muscles (van Ingen Schenau, 1994). The major advantage of this system is that the lower limbs are very lightweight while the joints can still be actively moved and can contribute to the propulsion.

The lower limbs undergo large accelerations during gait; if they are lightweight the accelerations will cost less energy and can be performed more rapidly, enabling a faster and more economical gait.

To prevent the problems with biarticular power transport, power production can also be analyzed at the level of the muscles, using the muscle force estimation methods described previously. The estimated muscle force is multiplied by the contraction velocity of the muscle. The contraction velocity can be obtained from kinematic data (Riemersma et al., 1988; van den Bogert et al., 1988) or by multiplying the joint angular velocity by the moment arm of the muscle. For human cycling, energy expenditure predictions obtained from power analysis at the muscle level differed greatly from predictions using power analysis at the joint level (Neptune & van den Bogert, 1998). This is due to the fact that joint power does not consider power transport by biarticular muscles or antagonistic co-contraction. Estimates of energy expenditure should therefore not be obtained from analyses at the joint level but from analyses at the muscle level. Power analysis at the joint level can still be used to describe and analyze the control of movement.

Apart from the segment-oriented and joint-oriented approaches there is a third power analysis approach, which is used in gaits without substantial external power production. This approach does not use the joint moments and forces but focuses on mechanical energy changes. During a stride cycle both the potential and the kinetic energy of the segments change constantly. Based on comparison of patterns of these energy changes gaits have been classified as either inverted pendulum or bouncing gaits (Cavagna & Kaneko, 1977). In inverted pendulum gaits like walk, the limbs act as rigid struts over which the body vaults – the kinetic energy and potential energy changes are each other's opposites. In the bouncing gaits like trot, the limbs act as springs and the body center of mass moves like a bouncing ball – the kinetic and potential energy increase and decrease simultaneously. Equine gallop might have both bouncing and pendulum aspects (Minetti et al., 1999). Apart from this classification of gaits, attempts have been made to relate the changes in mechanical energy to metabolic energy consumption (Cavagna & Kaneko, 1977; Minetti et al., 1999). The major problem is that when moving at a constant speed the mechanical energy at the end of the stride equals the mechanical energy at the beginning of the stride and no net work is performed. Nevertheless, to enable analysis, negative and positive changes of energy of the segments are treated differently. Either all positive changes are added, ignoring negative powers, or different efficiencies are used to add positive and negative power production. However the efficiencies of positive and negative muscular work are speculative. Furthermore, energy can be stored temporarily in elastic structures or it can be transferred between segments and probably also between limbs. The relative importance of these processes is not known. Results of internal power analyses, therefore, are largely dependent on the assumptions of internal power transport, energy storage and efficiency. This necessitates careful validation of the mechanical energy analysis, and estimation of error bounds due to assumptions regarding power transfer, efficiency and elastic storage (Thys et al., 1996).

Accuracy of inverse dynamic calculations

All direct and indirect measurements of biological variables are influenced by certain sources of errors and, therefore, have a limited accuracy. Inverse dynamic calculations are no exception to this rule. The errors influencing the accuracy of inverse dynamic calculations can be subdivided in two categories: errors in the measurement of input variables and errors originating from model assumptions. The most important measurement errors are caused by estimation of the inertial properties from *in vitro* data, misalignment of markers with the joint rotation center, skin displacement relative to the underlying bones, the use of noisy data to calculate accelerations, inaccuracies in the measurement of the point of application of the GRF and misalignment of force and movement data. Further details on some of these inaccuracies may be found in Chapter 2. The major assumptions influencing the accuracy of the calculations are the rigidity of the segments and the fixed rotation point. If muscle forces are calculated, two major assumptions are often added: the absence of antagonistic co-contractions and the cost function used to distribute the moment among the available muscles. The influence of all these errors and assumptions on the final accuracy depends, of course, on the magnitude of the errors. This magnitude is determined by the equipment used and the conditions of the actual measurements. However, some general considerations can be made on the order of the errors and their influence on the final results.

The assumptions of a fixed rotation center can be questioned for the stifle and carpal joints, whereas the alignment of the markers with the rotation center is difficult in the coffin joint and the proximal joints. Even relatively small errors in the coffin joint marker placement can seriously influence the results for this joint because of the small moment arms in the hoof segment. Radiographs should therefore be used to validate and, if necessary, correct this marker position. Due to similar small moment arms, measurement errors in the point of application of the GRF relative to the hoof will also seriously influence the coffin joint results (Bartel et al., 1978). These errors can arise from systematic errors in the point of application or from misalignment of the coordinate systems of the force and movement data. The systematic errors in the point of application should be corrected (Bobbert & Schamhardt, 1990) and the two coordinate systems should be aligned carefully. Although the errors in the point of application, in the alignment and in the marker placement will influence the accuracy for other joints, the relative influence is much smaller due to the larger moment arms.

The accuracy of the inertial properties differs for the proximal and distal segments (Buchner et al., 1997). In general the proximal segments have a large mass, are not quite rigid and it is difficult to separate them from each other. The distal limb segments, in contrast, have a small mass, are quite rigid and the boundary between these segments is clear. Therefore, the inertial data for the distal segments is quite accurate and does not seriously influence the accuracy of the results. Furthermore, the accelerations of the distal segments are very small, at least during stance, and errors in the inertial data or the accelerations hardly influence the results for these segments. Similarly, the total ignorance of the accelerations, as is done in a quasi-static analysis, seems to be acceptable for these segments. During the swing phase, however, the results are determined completely by the accelerations. Errors in these accelerations or the inertial data seriously influence the accuracy. Skin displacements for the distal joints are small and will not influence the accuracy. However, for the proximal joints they are very large, influence the accuracy and should be corrected, using the available correction algorithms (van Weeren et al., 1992b).

The effect of random errors on the final results can be determined with Monte Carlo simulation (van den Bogert et al., 1994). In this simulation the analysis is performed multiple times, with multiple copies of the input data that are modified by adding random errors according to known probability distributions. The standard deviation of these multiple results provides an estimate of the error in the final result. Systematic errors, such as skin movement, are not random and should be modeled as a hypothetical function of time or joint angle in such an error analysis.

Three-dimensional analysis

The methodology presented above applies to a two-dimensional analysis, usually in the sagittal plane. Movement of horses seems remarkably planar, but for some applications the small mediolateral movements may also be important. In trotters, these out of plane movements were reproducible, highly individual, and presumably related to performance (van Weeren et al., 1993). It is therefore conceivable that analysis of the sources of those movements is useful. Furthermore, the magnitude of out-of-plane moments is presently unknown. In human walking, it has been shown that a two-dimensional analysis underestimates the average joint power at the hip by 23% because the hip abductor moment is ignored (Eng & Winter, 1995). Similar underestimations might be obtained in horses and a full three-dimensional analysis should be undertaken to determine for which movements and which applications the out-of-plane moments can be neglected. Finally, out-of-plane moments might provide useful information about joint loading. In humans, adductor–abductor moments reflect load distribution between the medial and lateral compartments of the knee (Lindenfeld et al., 1997).

Extension of inverse dynamic analysis to three dimensions is mathematically straightforward (Vaughan et al., 1992; van den Bogert, 1994). The equation of motion for force is the same, with the only difference that force is now a vector with three, rather than two components. The equation of motion for moments has an extra term in three dimensions, and uses a matrix I for the moment of inertia rather than a single scalar value:

$$\sum M = \mathrm{I} \cdot \alpha + \omega \times (\mathrm{I} \cdot \omega)$$

Joint moments M are vectors in three dimensions, as are angular velocities w and angular accelerations α. In the force equation, vectors are usually expressed in a global, ground-based coordinate system. In the moment equation, however, all vectors and matrices must be expressed relative to a segment-fixed coordinate system. The final term is proportional to the square of the magnitude of the angular velocity and accounts for centrifugal effects when the axis of rotation is not aligned with an axis of symmetry (principal axis) of the body segment. Note the cross product symbol '×', which makes this moment perpendicular to the axis of rotation. The inertia matrix I is a 3 × 3 matrix which is diagonal (only three elements are non-zero) when the axes of the segment coordinate system are aligned with the principal axes; otherwise I has 9 non-zero elements that reflect the non-symmetrical distribution of the mass. Three-dimensional inertial properties for equine segments have been measured with respect to anatomically defined coordinate systems (Buchner et al. 1997). When expressed in a suitable segment-fixed coordinate system, the three components of the moment vector M can be interpreted as flexion–extension, abduction–adduction and internal–external rotation moment, respectively. The angular velocity vector w must be decomposed along the same three axes in order to obtain the joint power by taking the dot product of moment and angular velocity.

Instrumentation for collecting three-dimensional movement and GRF data is now standard equipment in biomechanical laboratories. However, problems arise from modeling assumptions and the standardization of the experimental protocol. These problems may lead to inaccuracies that are, in some cases, larger than the magnitude of the results of the calculations. In those cases, a three-dimensional analysis does not provide useful additional information compared to a sagittal plane analysis.

In the experimental protocol, three markers must be attached to each segment in order to obtain all six degrees of freedom (three translations and three rotations) for each segment. It is no longer possible to have markers coincide with the joint center in three dimensions, since the joint center is inside the body. Markers must therefore be attached to standardized anatomical landmarks, relative to which the location of the joint center is known. Suitable protocols have been developed for human analysis (Bell et al., 1990; Vaughan et al., 1992), and first attempts have been made for equine analysis (Nicodemus et al., 1999).

Soft tissue movement may be more of a problem in three dimensions because of the indirect method for locating joint centers. Joint moments are known to be sensitive to errors in the joint center location (Burdett, 1982). Also, three markers may not be representative of the motion of the entire body segment when the segment undergoes complex soft tissue movements during impacts. This may lead to errors in the inertial terms of the equations of motion, the terms, which are proportional to masses and moments of inertia. On segments such as the thigh, using more than three markers should be considered. Least-squares techniques can then provide the best estimate of three-dimensional rigid segment movement that is consistent with data from all markers (Soderkvist & Wedin, 1993). Note that there are two conflicting requirements for a marker placement protocol: for location of joint centers, markers should closely follow the bone movement; for accurate estimation of inertial forces, markers should follow the 'average' of the mass distribution, of

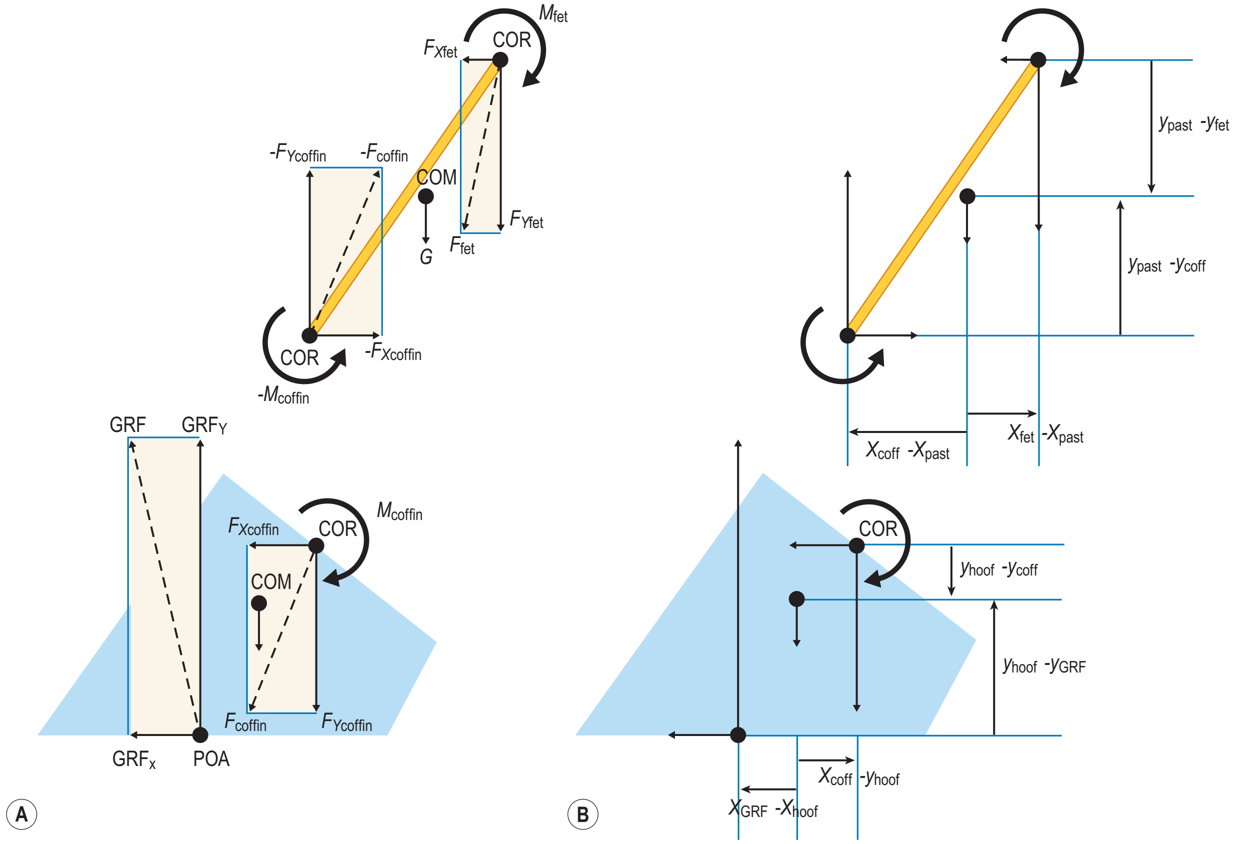


Fig 19.13 Free body diagrams of the hoof and pastern segments. (A) Free body diagrams; (B) x and y coordinates of the points of application of the forces.

which the muscles can be an important component. Different marker sets for these two calculations should be considered.

Accelerations for certain out-of-plane movements in the horse may be small relative to the errors associated with differentiation of noisy movement data (see Chapter 2). It is therefore important to have good estimates of these errors, so that the accelerations that are smaller than the noise can simply be neglected, rather than introduce extra noise into the results.

In modeling, the body is typically represented as rigid segments linked by ball joints. For estimation of muscle forces, three moment arms must be known for each muscle, one for rotation about each axis of the segment coordinate system. Three-dimensional models of the muscle path from origin to insertion (e.g. Brand et al., 1982) are typically used to determine the instantaneous moment arms, as well as the orientation of muscle force vectors during movement. Interactive software tools are now available to develop such models of the three-dimensional musculoskeletal anatomy (Delp & Loan, 1995).

Many joints in horses and humans are hinge joints where rotations other than flexion and extension are prevented by the articular surfaces and ligaments. Such joints have an axis of rotation rather than a center of rotation. The 'joint center' used for the inverse dynamic analysis lies on this axis; typically, the midpoint of the part of the axis within the bone is used. The moment components associated with internal–external rotation and abduction–adduction components do not represent muscle function. Interpreting these moments as muscle moments may lead to severe overestimation of muscle forces and joint loading (Burdett, 1982; Glitsch & Baumann, 1997). Instead, these moments can indicate load distributions in articular contact and ligaments (Lindenfeld et al., 1997).

Formulas for inverse dynamic calculations

Hoof segment

The sum of all forces on the segment must equal its mass times acceleration. In the horizontal direction this gives the following equation:

$$\sum F_X = m_{hoof} \cdot a_{Xhoof} \Leftrightarrow GRFx + F_{Xcoffin} = m_{hoof} \cdot a_{Xhoof}$$

or:

$$F_{Xcoffin} = m_{hoof} \cdot a_{Xhoof} - GRF_X$$

For symbols see Figure 19.13 and the symbol list below.

For the vertical direction the gravitational force (G) should be taken into account:

$$\sum F_Y = m_{hoof} \cdot a_{Yhoof} \Leftrightarrow GRF_Y + F_{Ycoff} = G_{hoof} = m_{hoof} \cdot a_{Yhoof}$$

or:

$$F_{Ycoffin} = m_{hoof} \cdot a_{Yhoof} - GRF_Y - m_{hoof} \cdot g$$

The sum of the net coffin joint moment and the moments of all forces must equal the moment of inertia times the angular acceleration of the hoof segment:

$$\sum M = I_{hoof} \cdot a_{hoof}$$

or:

$$M_{coffin} + GRF_X \cdot (y_{hoof} - y_{GRF}) + GRF_Y \cdot (x_{GRF} - x_{hoof}) + F_{Xcoffin} \cdot (y_{hoof} - y_{coff}) + F_{Ycoffin} \cdot (x_{coff} - x_{hoof}) = I_{hoof} \cdot \alpha_{hoof}$$

or:

$$M_{coffin} = I_{hoof} \cdot \alpha_{hoof} - GRF_X \cdot (y_{hoof} - y_{GRF}) - GRF_Y \cdot (x_{GRF} - x_{hoof}) - F_{Xcoffin} \cdot (y_{hoof} - y_{coff}) - F_{Ycoffin} \cdot (x_{coff} - x_{hoof})$$

Note the different subtraction of the *x* and *y* coordinates: the *x* coordinate of the joint center of rotation is subtracted from the *x* coordinate of the point of application of the force whereas the *y* coordinate of the point of application is subtracted from the *y* coordinate of the center of rotation. In this way moments produced by the forces will automatically get a correct sign: positive for counterclockwise and negative for clockwise moments.

Pastern segment

Horizontal and vertical forces:

$$\sum F_X = m_{past} \cdot \alpha_{Xpast} \Leftrightarrow F_{Xfet} - F_{Xcoffin} = m_{past} \cdot \alpha_{Xpast}$$

$$\sum F_Y = m_{past} \cdot \alpha_{Ypast} \Leftrightarrow F_{Yfet} - F_{Ycoffin} + G_{past} = m_{past} \cdot \alpha_{Ypast}$$

Note that the net coffin joint force (the force from the pastern of the hoof) is inverted to obtain the force from the hoof on the pastern.

Moments:

$$\sum M = I_{past} \cdot \alpha_{past}$$

or:

$$\begin{aligned} &M_{fet} - M_{coffin} + F_{Xfet} \cdot (y_{past} - y_{fet}) + F_{Yfet} \cdot (x_{fet} - x_{past}) \\ &\quad - F_{Xcoffin} \cdot (y_{past} - y_{coff}) - F_{Ycoffin} \cdot (x_{coff} - x_{past}) = I_{past} \cdot \alpha_{past} \end{aligned}$$

Velocity and accelerations

Velocity and acceleration can be calculated using a finite difference method. The difference in position between frame number *i* and *i* + 1 is divided by the time difference to obtain an approximation of the velocity at frame *i* + 1/2 (see Fig. 19.14):

$$V_{i+1/2} = \frac{\Delta x}{\Delta \mathrm{t}} = \frac{x_{i+1} - x_i}{\mathrm{t}_{i+1} - \mathrm{t}_i}$$

Subsequently the difference in velocity between *i* + 1/2 and *i* – 1/2 is used to calculate the acceleration:

$$a_i = \frac{\Delta \mathrm{v}}{\Delta t} = \frac{\mathrm{v}_{i+1/2} - \mathrm{v}_{i-1/2}\mathrm{x}_{i+1} - \mathrm{x}_i - (\mathrm{x}_i - \mathrm{x}_{i-1})}{\Delta t} = \frac{\mathrm{x}_{i+1} - 2\mathrm{x}_i + \mathrm{x}_{i-1}}{(\Delta t)^2}$$

For power calculations the velocity at *i* instead of *i* + 1/2 must be known; this velocity can be calculated from the difference in position at frame *i* – 1 and *i* + 1:

$$v_i = \frac{\Delta \mathrm{x}}{\Delta \mathrm{t}} = \frac{\mathrm{x}_{i+1} - \mathrm{x}_{i-1}}{\mathrm{t}_{i+1} - \mathrm{t}_{i-1}} = \frac{\mathrm{x}_{i+1} - \mathrm{x}_{i-1}}{2\Delta \mathrm{t}}$$

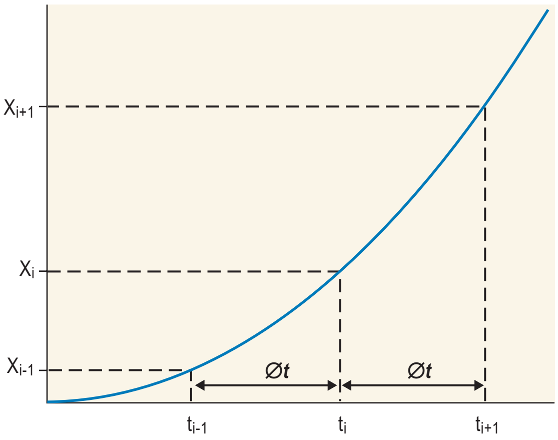


Fig 19.14 Finite differences can be used to calculate velocity and acceleration.

Symbols

α	angular acceleration of the segment
a	linear acceleration of the segment
F	force
F_{coffin}	net coffin (coff) joint force
$F_{fetlock}$	net fetlock (fet) joint force
GRF	ground reaction force
g	gravitational acceleration: 9.81 m/s^2
I	moment of inertia
m	segmental mass
M	moment
M_{coffin}	net coffin (coff) joint moment
$M_{fetlock}$	net fetlock (fet) joint moment
t	time
v	velocity
x	horizontal coordinate of point of application or center of mass
X	horizontal component of force or acceleration (subscript)
y	vertical coordinate of point of application or center of mass
Y	vertical component of force or acceleration (subscript).

Scaled energetics of locomotion

Introduction

Horses come in quite different sizes (Fig. 19.15), raising the question as to how the performance of a small and large horse should be compared. In Figure 19.15, the two breeds of horses shown are about the biggest (British Shire) and smallest (Argentinean Fallabella) that exist. Imagine a situation in which the Shire (height 1.91 m, weight 1000 kg) moves alongside the Fallabella (height 0.80 m, weight 60 kg). The Fallabella will be trotting, maybe even galloping, while the Shire is still walking. Obviously, the speeds of both horses should be scaled to their size, but how should this be achieved? Is it proportional to weight? This is not likely, since in that case the Shire would move 1000/60 = 17 times as fast as the Fallabella. Is it, then, proportional to height? This seems more plausible, but it will be shown that it is not correct either. Questions of this type will be examined in this chapter. It will be seen that the outcome depends not only on the question asked – a common situation – but also on the assumptions made. Recognizing assumptions is a trickier problem.

There is a vast amount of literature in the field of scaling. It has been produced by generations of biologists and a few engineers, who have always been fascinated by questions like why an ant can carry 20 times its own weight, and why a horse evidently cannot. There are several books on this subject (Alexander & Goldspink, 1977; McMahon & Bonner, 1983; McMahon, 1984; Schmidt-Nielsen, 1984; Pennycuick, 1992), all of which make fascinating reading, as their authors are talented writers.

Geometric scaling

PROBLEM

The first problem to be handled is the most elementary. Assume that animal B is in all aspects twice as large as animal A. A consequence is that B can take steps that are twice as a long as A. Can it also run twice as fast? And what stride frequency will it use?

In a first approximation it will be assumed that the bigger animal is just an enlarged version of the smaller one, that all linear measures (leg length, leg diameter, trunk circumference, etc.) are

Fig 19.15 The smallest and biggest breeds of horse: the Fallabella, height 0.80 m, mass 60 kg, with foal (weight at birth 8 kg); and the Shire, height 1.91 m, mass 1000 kg.

Courtesy of Dr. Agaath Kooi, Noorder Zoo at Emmen, The Netherlands.

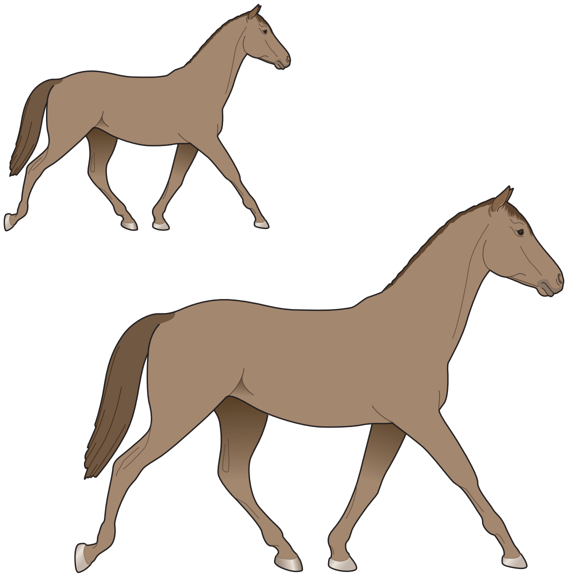


Fig 19.16 Geometric scaling. Two horses of different size, but with the same proportions.

Table 19.1 **Dimensionless numbers for length, time, speed/velocity and acceleration**

Length	Time	Velocity	Acceleration
$\hat{l} = \frac{l}{l_0}$	$\hat{t} = \frac{t}{\sqrt{l_0/g}}$	$\hat{v} = \frac{v}{\sqrt{l_0 g}}$	$\hat{a} = \frac{a}{g}$

proportional to a single length measure. An example is given in Figure 19.16. The big horse has been obtained by enlarging the small one on a photocopier. For the reference length, the height at the withers will be taken and denoted as *l*. A second assumption to be made relates to the consideration of which two categories of forces are the most important to our problem? For overground locomotion, the answer is acceleration forces (= *ma*) and gravitational forces (= *mg*) (Hof, 1996).

Having made this assumption, our scaling should now be made such that for animals of different sizes *ma* and *mg* should scale in proportion. One reason is that forces are vector quantities, they have both a magnitude and a direction, and the direction of the forces should be the same irrespective of the size. The constant of gravity *g* is practically the same (9.81 m/s^2) anywhere on earth, and as long as our horses don't walk on the moon, where g = 2 m/s^2, it may be assumed to be constant. Acceleration is calculated as distance divided by time squared (unit: m/s^2). When distance increases, the time scale should thus be made longer as well. When one animal has height l_1 and the other height l_2, all temporal variables, stance time, stride time, etc., should be scaled in the proportion t_1/l_2. The argument goes as follows:

$$\frac{ma_1}{mg} = \frac{ma_2}{mg} \Rightarrow \frac{a_1}{g} = \frac{a_2}{g} \Rightarrow \frac{l_1}{gt_2^1} = \frac{l_2}{gt_2^2}$$

This leads to:

$$\frac{t_1}{t_2} = \sqrt{\frac{l_1}{l_2}}$$

Time and temporal variables should thus be scaled as the square root of height. A consequence is that speed and velocity should be scaled inversely with the square root of height:

$$\frac{v_1}{v_2} = \frac{l_1/t_1}{l_2/t_1} = \frac{l_1}{l_2}\sqrt{\frac{l_2}{l_1}} = \sqrt{\frac{l_1}{l_2}}$$

A method to account for this scaling with size is to use so-called dimensionless numbers, the definition of which is given in Table 19.1.

It can easily be verified that these numbers are indeed dimensionless by noting that the factors in the denominator have the same units as the quantity in the numerator. The dimensionless number for speed (or sometimes the square of it, which can be confusing) is known as the 'Froude number.' Examples of the possibilities of these dimensionless numbers are given in Figures 19.17 and 19.18, both from Alexander (1977). Figure 19.18 gives dimensionless stride length (the distance traveled in a complete walking stride) as a function of dimensionless speed for a number of very diverse animals. It can be seen that by using dimensionless numbers, i.e. by accounting for geometric scaling, the differences due to size are eliminated. The data for all animals could be expressed in a single formula:

$$\hat{\lambda} = 2.3\hat{v}^{0.6}$$

Figure 19.18 shows a diagram with the gaits adopted as a function of speed. It can be seen that all animals change from walking to trotting or running at a dimensionless speed of around 0.8. They change from trot to gallop somewhere between 1.3 and 2.0.

An example might be helpful. Imagine the Shire going along with the Fallabella at a speed of 2.5 m/s (9 km/h). Dimensionless speed for Shire is $2.5/\sqrt{1.91 \times 9.81} = 0.58$, a walking speed. Dimensionless speed for Fallabella, on the other hand, is $2.5/\sqrt{0.80 \times 9.81} = 0.89$, and it will be trotting. A small dog, with a height of 30 cm, may gallop at this speed, as its dimensionless speed $2.5/\sqrt{0.3 \times 9.81} = 1.46$. The mouse (height 5 cm), which is chased by the dog, has $\hat{v} = 2.2/\sqrt{0.05 \times 9.81} = 3.1$, and is galloping at top speed. Stride length λ of the big horse can be estimated from the above equation as $\lambda = 1.91 \times \hat{\lambda} = 1.91 \times 2.3 \times (0.58)^{0.6} = 1.91 \times 1.65 = 3.16$ m. Stride frequency is thus $2.5 / 3.16 = 0.79$ strides/s. The mouse, at the other extreme, will have a stride length of only 23 cm, but a stride frequency of 11 strides/s.

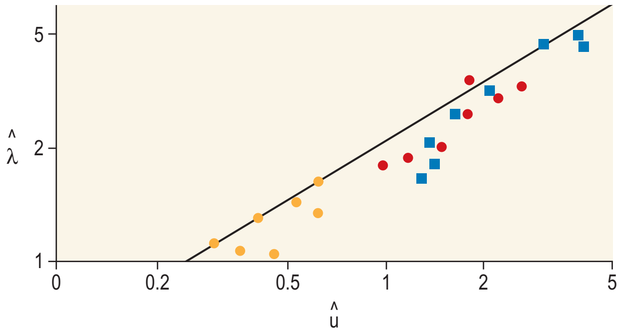


Fig 19.17 Relationship between stride length and speed. Dimensionless stride length plotted against dimensionless speed in logarithmic coordinates. Walk, orange circles; trot, red circles; canter, blue squares. The line gives the regression. Data are from Muybridge (1887) on horses, mostly with riders.

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A practical application was given by Back et al. (1995) in a study in which kinematic variables were employed in 4-month-old foals in order to predict the same variables in adult (26-month-old) horses.

ANSWER

If animal B is twice as big as animal A, it will make strides twice as long. Animal A, on the other hand, can make faster steps. Unjust as it is, it turns out that A does not make the steps with twice the frequency of B, but at a rate proportional to the square root of 2, i.e. about 1.4 times as quickly. As a consequence, a corresponding speed of B, e.g. the speed at which the horse changes from walk to trot or from trot to gallop, is 1.4 times as fast as in A. If horses of unequal size are to be compared, speeds and temporal variables should thus be corrected by a factor equal to the square root of the ratio of the respective heights at the withers.

Differences in proportion

PROBLEM

Horses of different breeds are not just bigger or smaller copies of each other, there are substantial differences in morphology. This section will explore what difference it makes whether a horse is compact or slender. Which type can carry heavier loads?

In the preceding section the scaling was purely geometric: every measure was multiplied by the same scaling factor. When looking at a picture of various horse breeds, it is obvious that this is only an approximate picture. Even a layman can see differences in the proportions of Shetland ponies and Thoroughbreds, and the expert can distinguish many dozens of breeds. In a purely geometric scaling, as used in the previous section, it will hold that mass (m) is specific mass times volume, while volume is proportional to l_0 to the third power. The overall relation can be written as $m \propto l_0^3$.

In the subsequent parts of this chapter some mathematics cannot be avoided. Many of the scaling relations that follow will be expressed in the so-called allometric form, as functions of the form $y = ax^b$. As a reminder, some properties of functions with exponents have been given in Table 19.2.

One factor that distinguishes between breeds is whether they are of slender or compact build. This might be expressed in a ratio d/l_0, in which d is a characteristic width measure, e.g. the thickness of the midshaft of a forelimb or the circumference of the trunk, and

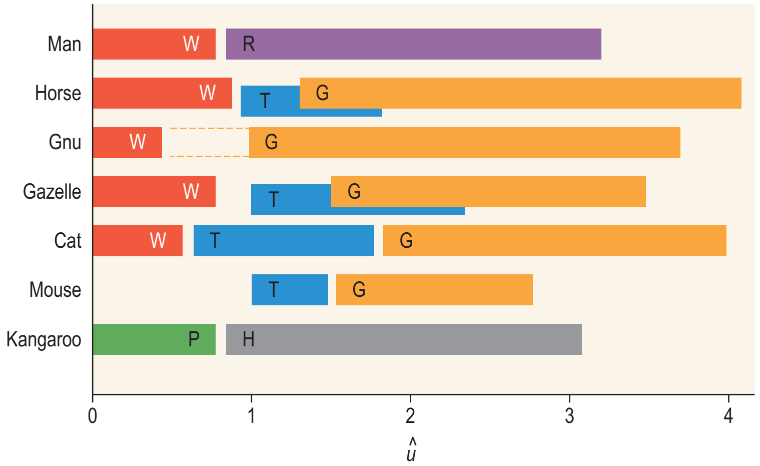

Fig 19.18 Diagram showing the ranges of speed, expressed as the dimensionless number, at which mammals commonly use their various gaits. W, walk; R, run; T, trot; G, gallop or canter; H, hop; P, pentapedal gait (slow gait, typical for kangaroos).

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Table 19.2 **Some properties of power functions, as used in this chapter**

$$ax^b \cdot cx^d = acx^{b+d}$$

$$\frac{x^a}{x^b} = x^{a-b}$$

$$\sqrt[n]{x^b} = x^{b/n}$$

$$(x^a)^b = x^{ab}$$

$$x^0 = 1$$

l_0 is a characteristic length measure, such as the height at the withers, as used in the first section. If the form of our horses may be approximated with a stack of cylinders, this leads to the following proportionalities for volume or body mass and surface area, respectively:

$$\text{Body mass: } m \propto d^2 l_0$$

$$\text{Surface area: } S \propto d l_0$$

An important item to be scaled is muscle force. It is generally known from physiology that the force of a muscle is proportional to its physiological cross-section, around 20 N/cm^2. Determining the physiological cross-sectional area of a muscle is not an easy task, as most muscles have quite a complex architecture. It is plausible, however, to assume that it is proportional to the cross-section of the limb, thus with d^2:

$$\text{Muscle force: } F_m \propto d^2$$

The moment that is exerted by the muscle is the product of force and moment arm. The moment arm can be assumed proportional to d, so that:

$$\text{Moment: } M \propto d^3$$

When a bent limb has to support a force F_s, the muscle has to supply a moment equal to $F_s x$, in which x is the perpendicular distance between the joint that is spanned by the muscle and the line between the joints proximal and distal of it. When the angle of the limb is not related to size, it can be assumed that x is proportional to l, and thus:

$$\text{Supported force: } F_s \propto d^3/l_0$$

Here we are confronted with a problem. In standing, walking or running the supported force will be equal to 1–2 times body weight, respectively. According to the equation above, body mass, and thus body weight, is proportional to $d^2 l_0$. Thus, supported weight and body weight depend in different ways on d and l_0:

$$\frac{F_s}{mg} \propto \frac{d^3/l_0}{d^2 l_0} = \frac{d}{l_0^2}$$

This means that bigger animals need higher stresses in their muscles to support their weight. At some point it becomes too much, and that may explain why whales are too big to walk. Horses are far from the largest species, fortunately, and even elephants are able to walk. There are some effects, nevertheless. Small animals walk and run with strongly angulated limbs and stand in a rather crouched position, while large animals keep their legs much straighter. A lying dog or cat can quickly jump into a standing position, but a horse (or an elephant for that matter) needs considerably more time and effort to assume a standing posture.

A possible 'solution' to this problem would be to make width d proportional to l_0^2, 'constant stress scaling' as it is called, in contrast to true geometric scaling in which all sizes scale in the same proportion: $d \propto l_0$. A third alternative is 'elastic similarity scaling' (McMahon & Bonner, 1983; McMahon, 1984) which leads to a proportionality $d^2 \propto l_0^3$. It can indeed be observed that large animals (elephants) have in general proportionally thicker legs than small ones (mice), and the general trend suggests that elastic similarity scaling is followed. Within the horse family, however, the differences in d/l_0 ratio between breeds are more interesting than a general trend over the widest possible range of animal sizes.

A second application for the above equation is to assess maximum acceleration or sprinting power. According to Newton's second law $a = F/m$, and thus maximum acceleration should scale according to the above equation.

While data on the height l_0 and the mass are commonly available, a problem is to find data on a measure related to thickness d. A way to circumvent this problem is to use the body mass equation and replace d in the subsequent equations by $m^{1/2} l_0^{-1/2}$. This results in the alternative forms:

Supported force:

$$F_s \propto m^{3/2} l_0^{-5/2} \quad \text{force factor}$$

and:

$$\frac{F_s}{mg} \propto m^{1/2} l_0^{-5/2} \quad \text{force/weight}$$

It can be seen that an ordering according to the force factor is in agreement with common sense. It increases with body mass, and thus with muscle mass, and is highest for heavy horses with relatively short limbs. The Belgian horse, with $F_s = 9400$, is the champion in force. The Shire, which has about the same weight, is second in force, due to its longer legs, $F_s = 6300$. The force/weight factor is highest in Shetland ponies, $F_s/m = 13$, with their small mass and short legs. The Quarter Horse also stands out for its high acceleration, $F_s/m = 8.6$. Thoroughbreds, on the other hand, have force/weight factors around 6; they are selected for speed at longer distances. Standardbreds have factors in between these extremes.

The biggest land animal, the African elephant, is the strongest, but not per kg of body weight, $F_s/m = 4.1$. In this respect it is far surpassed by the ant (mass 2 mg, leg length 3 mm), which sports an F_s/m of almost 3000, and indeed is able to carry loads many times its body weight.

Table 19.3 gives F_s and F_s/m for a growing Warmblood foal. As it seems, foals are born with excessively long limbs, compared to

Table 19.3 **Size and calculated force factor for a growing Dutch Warmblood foal***

Age (months)	Mass (kg)	Height (m)	*Fs*/1000	*Fs*/m
0	57	1.013	0.42	7.31
1	101	1.109	0.78	7.76
3	178	1.239	1.39	7.81
6	262	1.352	2.00	7.62
9	331	1.428	2.47	7.47
12	395	1.492	2.89	7.31
15	452	1.532	3.31	7.32
18	494	1.565	3.58	7.25
21	510	1.584	3.65	7.15
24	519	1.606	3.62	6.97
27	534	1.624	3.67	6.88

Data on height and weight from Smolders (1989).

their weight. When the force/weight ratio is calculated, however, it appears to remain quite constant during the growth process, from 57 kg at birth to an almost full-grown 534 kg.

The proportionalities also indicate that, although large horses can draw or carry heavier loads than small ones (high force factor), small ones are stronger per kg of body weight. This may explain why donkeys and mules are favored as pack animals over larger horses. On the other hand, for drawing a heavy cart or plowing, large horses with thick legs are best. Even without the help of biomechanics, equine experts have known this for ages. The Shire horse in Figure 19.15, for example, is said to descend from the horses that carried the knights in their heavy armor in the Middle Ages. It stands out more as a riding than a pulling horse, in contrast to the Belgian.

ANSWER

In this section the consequences of the fact that animals have different proportions of thickness and length were considered. Muscle force is proportional to cross-sectional area of the muscle. When this effect is accounted for, it turns out that:

1. large animals are stronger than small ones, but that this increase is less than proportional to body weight, therefore;
2. large animals can carry less load per kg of body weight.

These two effects are expressed in, respectively, a force factor F_s and the force divided by body mass F_s/m. The latter factor explains why an ant can carry many times its body weight, while a horse cannot. Table 19.3 gives both factors for a growing Warmblood foal.

Energy cost of locomotion

A running horse consumes energy; this is obvious to the observer and to the horse. The laws of mechanics do not provide an easy answer, however, to the question how much energy is needed per meter of progression. According to Newton's first law, in an ideal frictionless world the cost of locomotion on the level should be nil. Only uphill locomotion would require energy equal to $mg\Delta h$, body weight (mg) times rise (Δh). Going upward with a speed of rise v_{rise} would thus require a power:

$$P_{\text{rise}} = mgv_{\text{rise}}$$

For level walking, theory is of no help, and we should rely on measurement. A convenient way to measure energy consumption is to measure oxygen consumption and recalculate this to the power of transport P^*_{trans} in watts. In the following an asterisk (*) will be used to denote work and energy values derived from oxygen consumption. Figure 19.19 gives data on running for animals of different sizes, in which power has already been divided by body weight (in newtons, N). Two things are apparent from this figure: first, P^*_{trans} increases linearly with speed in running, without intercept of the vertical axis. This means that P^*_{trans} divided by speed v, i.e. the energy per meter traversed, E^*_{trans}, is independent of speed. The second aspect is that E^*_{trans} depends on size; after dividing by body mass m it is smaller for big animals (see Fig. 19.20A). With m in kg and E^*_{trans} in J, the relation can be expressed as: cost of transport per unit of body weight, in running; step length, defined as the distance the body moves forward in a single foot contact; the product of both, $E^*_{\text{trans}}1_c/mg$, is constant and equal to 0.183/pm 0.045 J/N. Same animals as shown in Figure 19.19:

$$E^*_{\text{trans}}/m = 8.8m^{-025}$$

Another way to express the same relationship is:

$$\frac{P^*_{\text{trans}}}{v} = E^*_{\text{trans}} = 8.8m^{0.75}$$

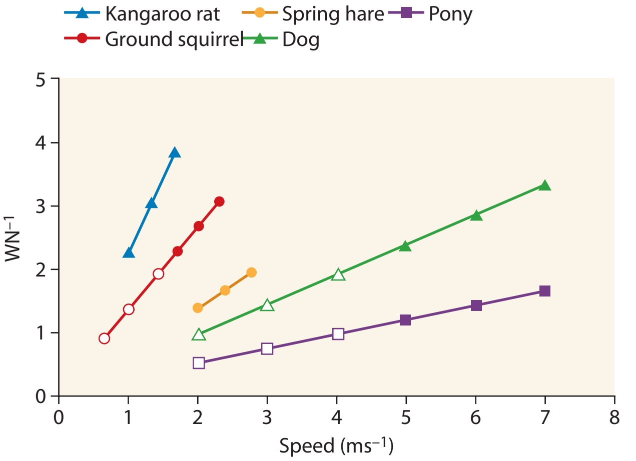

Fig 19.19 Energy consumption per newton of body weight, as a function of speed for (in order of size) a kangaroo rat, a ground squirrel, a spring hare, a dog and a pony.

Kram, R., Taylor, C.R., 1990. Energetics of running: a new perspective. Reprinted by permission from Macmillan Publishers Ltd, Nature Publishing Group, ©1990.

When Kram and Taylor (1990) first published this figure, the phenomenon had already been known for a considerable time. (Kram and Taylor used body weight mg instead of body mass m, which is more correct, but makes their formulae somewhat more difficult to compare with those of others.) It is to their merit that they provided an interpretation, by observing that while E^*_{trans}/mg decreases, step length l_c increases by about the same factor (Fig. 19.20B). The latter will not come as a great surprise to the attentive reader, as step length l_c will be proportional to leg length or height l_0, and in geometric scaling it would hold that $l_0 \propto m^{1/3}$. In fact the exponent is slightly less, 0.30. This may be because of the fact that small animals run with more angulated legs, while big animals keep their legs straighter. The overall consequence is that the product $(E^*_{\text{trans}}\, l_c)/mg$ is constant (Fig. 19.20C), and is equal to 0.183± 0.045 J/N or m. This means that for all animals the energy cost per newton of body weight is the same per step: for each step an energy is needed equal to what is required to make an upward movement of about 20 cm (0.183± 0.045 m):

$$\frac{P^*_{\text{trans}}}{v} = 0.183 \cdot \frac{mg}{l_c}$$

This is a comprehensive summary of a great amount of data. It nicely sums up why large animals need less energy to cover a certain distance; it is simply because they can make bigger steps. It further suggests that animals with long legs have an advantage, a fact that breeders of whippets and racing horses will readily admit. To give an explanation for these simple facts, on the other hand, is not so easy. In the following section some considerations will be given.

One reservation should be made at this point. Kram and Taylor (1990) found their experimental relationship from experiments on widely different animals (see Fig. 19.19). The decrease of energy consumption per unit mass and distance and the increase of step length with body size (Fig. 19.20) are undoubtedly valid for the range of animals studied. More recent work (Griffin et al., 2004) has shown that such a relation does not apply within a species. They determined cost of transport for horses of three different sizes (Table 19.4). It turns out that among horses cost of transport is practically independent of body mass over the ranges encompassing all horse breeds. The cost for trotting is least in the Arabian racing horse.

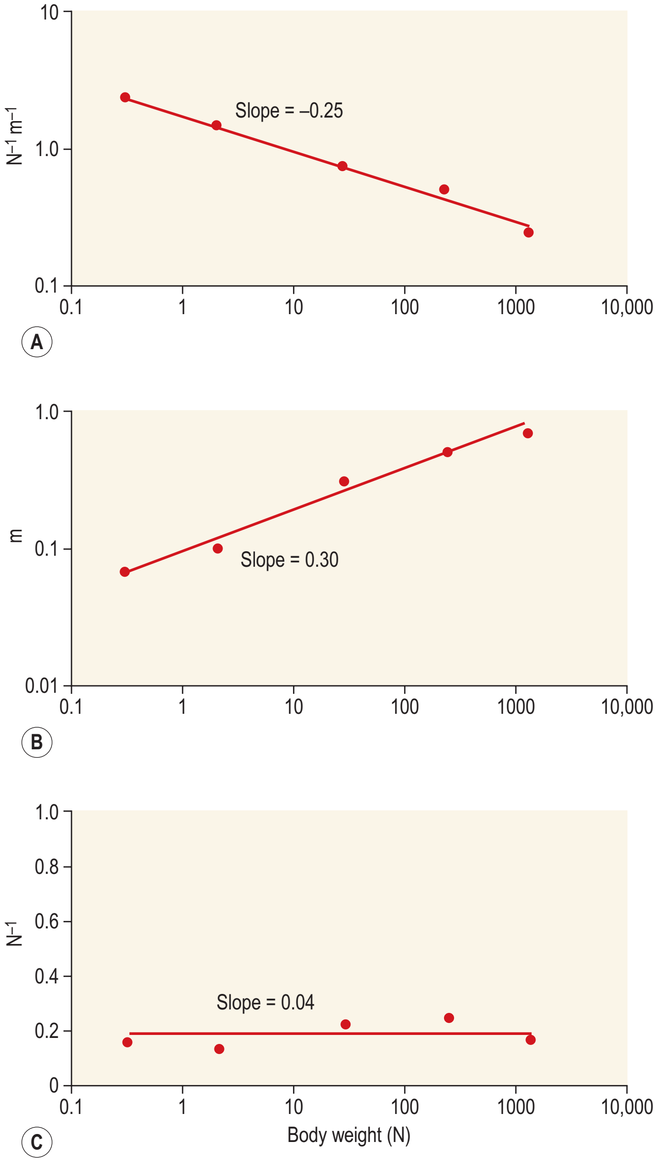

Fig 19.20 As a function of body weight mg. (A) Cost of transport per unit of body weight, E^*_{trans}/mg, in running; (B) step length l_c, defined as the distance the body moves forward in a single foot contact; (C) the product of both, $E^*_{trans}l_c/mg$, is constant and equal to 0.183 ± 0.045 J/N. Same animals as shown in Figure 19.19.

Kram, R., Taylor, C.R., 1990. Energetics of running: a new perspective. Reprinted by permission from Macmillan Publishers Ltd, Nature Publishing Group, ©1990.

Table 19.4 **Data on cost of transport (CoT)***

	Leg length (m)	Mass (kg)	CoT walk ($J.kg^{-1}m^{-1}$)	CoT trot ($J.kg^{-1}m^{-1}$)
Miniature	0.73	112	2.23 ± 0.47	2.75 ± 0.48
Arabian	1.24	448	1.98 ± 0.06	2.08 ± 0.09
Draught	1.41	715	1.91 ± 0.44	2.39 ± 0.30

*Horses of three different sizes (3 each) were trained to walk and trot on a treadmill. For walking CoT seems to decrease slightly with mass ($\alpha\ m^{-0.085}$), but this trend is not significant. For trotting the CoT is lowest for the Arabian racing horse.

From Griffin et al. (2004), mean ± SD.

There is not a simple mechanical reasoning to predict how much energy is needed for horizontal overground locomotion. It can be measured experimentally in a reasonably simple way, however, by assessment of oxygen consumption. It turns out that big animals consume less energy (or oxygen) per kilogram of body mass and per meter traveled. This can be expressed in a remarkably simple way: the (gross) energy needed to make a simple step is equal to body weight times 20 cm, irrespective of size.

Muscle work and power

This section attempts to provide some arguments for the decrease in energy consumption per meter and per kg, as presented in the previous one. This will require quite a complicated reasoning that may be omitted on first reading.

Muscles can exert force, and when they are allowed to shorten, they can do work: force times shortening. The unit of work is the joule (J). The rate at which the work is done is called power, measured in watts (W) or joule/s. The relations between force, work and velocity in muscle are depicted in Figure 19.21. When a muscle shortens at a certain speed, the force it develops decreases according to the so-called Hill relation (Hill, 1938), (Fig. 19.21A). As long as there is no lengthening or shortening, the muscle develops its 'isometric' force F_0. With increasing shortening speed muscle force becomes less, until at a speed v_0 force has decreased to zero. In lengthening (negative speed in the figure), force can increase somewhat above isometric, maybe 20–40%. This relation has often been observed in all kinds of muscle. It explains the common observation that a light load can be moved faster than a heavy one.

Mechanical power is force times shortening speed: $P = Fv$. It can be calculated for muscle from the Hill relation (Fig. 19.21B). Power is zero at two points, when speed is zero, i.e. when the muscle is isometric, and at (and above) the maximum speed, when force is zero. The maximum power is developed at an intermediate speed, around $0.3v_0$. At that point force has declined to $0.3F_0$. Power is thus (with some rounding-off) equal to about $0.1F_0v_0$, with a fairly flat maximum. An active muscle not only can do mechanical work but it can generate heat as well, a kind of unavoidable waste, not different from any other motor. Two components of heat development can be discerned: a constant part and one that increases with shortening speed (Fig. 19.21C). In Figure 19.21C the mechanical power of Figure 19.21B has also been drawn, reminding the reader that both mechanical work and heat are forms of energy. From this figure can be seen that the ratio (mechanical power)/(total energy delivered) is not constant for all speeds. It is, of course, zero for $v = 0$ and $v = v_0$ and it has again a maximum in between, but now at a speed around $0.2v_0$. At this optimum speed, mechanical work is generated at an efficiency of about 25%. In this respect a horse does better than a motorcar, which has an efficiency no greater than 15%. Note that energy and power here are net values, to be differentiated from the gross values with an asterisk in the preceding paragraph.

In the muscle force equation it has already been noted that maximum isometric muscle force F_0 is proportional to muscle physiological cross section, about 20 N/cm^2. In a single contraction, muscle can shorten to about 50% of its initial fiber length, but if this is to be done at a reasonably efficient speed, force is no higher than $0.3F_0$. As energy is force times shortening, 1 cm^3 of muscle (length 0.01 m) can thus produce 20 N × 0.3 × 0.005 m = 0.03 J. With a specific mass of muscle fibers around 1 g/cm^3, this

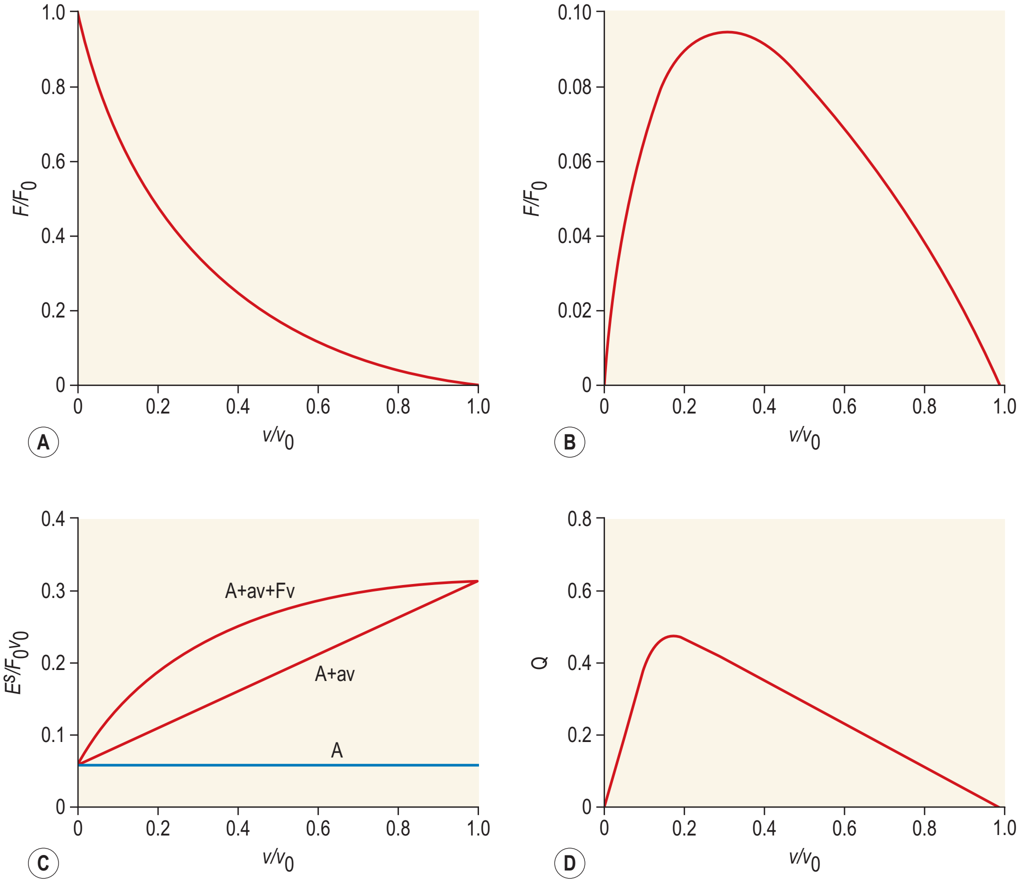

Fig 19.21 Force, velocity and power in muscle. (A) Muscle force as a function of shortening speed is shown relative to, the force in an isometric contraction. Shortening speed expressed relative to the muscle's maximum shortening speed. (B) Mechanical power (work per unit time). (C) Energy production in the form of activation heat, shortening heat and mechanical power Fv. (D) Efficiency of work production. Only the efficiency of muscle force production is shown, from ATP to, the processes leading to ATP production reduce the maximal efficiency to about 25%.

gives an energy output of 30 J/kg of muscle for a single contraction. In a real muscle, part of the mass may be due to connective and fat tissue, which may make an estimate of 20 J/kg more realistic. Maximum energy output of a muscle is thus directly proportional to its mass.

Remembering that the work needed to raise the center of gravity by an amount Δh in a jump is $mg\Delta h$, this explains why animals of any size, from fleas to horses, can jump about the same height, from 0.5–1.0 m. For an 80-kg human, the legs have mass of about 30 kg. Assuming that muscle mass is 20 kg, one would predict an energy output of $20 \times 20 = 400$ J and a jumping height of $400/(80.10) = 0.50$ m. This is exactly the height well-trained volleyball players can jump in a standing jump. Horses seem to perform better; they are reported to jump up to 2.00 m. Taking into account the height of the trunk in standing, *ca.* 1 m, a rise of 1 m is still performed. Such jumps will be made only after a run, however, and with a run and a fiberglass jumping pole humans can reach almost 6 m. (With a final running speed of 10 m/s, the human athlete has gained a kinetic energy of $\frac{1}{2}mv^2 = 4000$ J. This corresponds to a rise in center of gravity of 5.0 m.)

Maximum shortening speed v_0 is proportional to muscle length: a longer muscle contains more sarcomeres in series. In physiology it is therefore usual to give relative muscle speed in muscle lengths per second: v/l_0. In Figure 19.22 a number of data on the maximum muscle shortening speed v_0/l_0 have been given for animals of different sizes, and for a fast muscle (extensor digitorum longus) and a

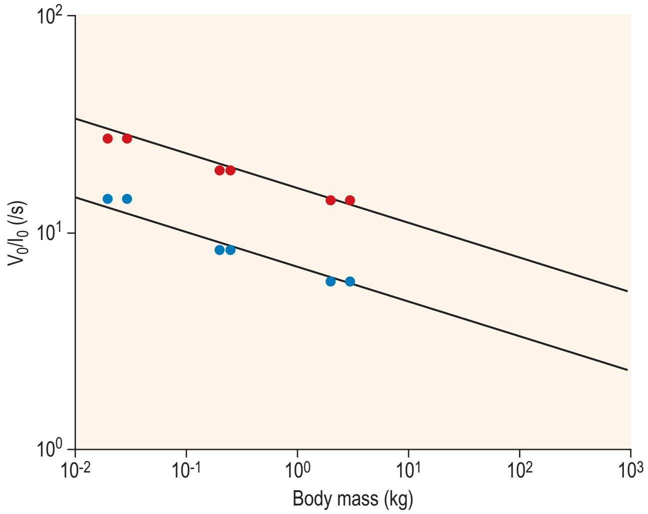

Fig 19.22 Maximal shortening speed divided by muscle fiber length, of slow (*soleus*, blue circles) and fast (*extensor digitorum longus*, red circles) muscles of mouse (data points on left), rat (data points in center) and cat (data points on right). Bigger animals have slower muscles per unit muscle Fv length *F0v0*. The lines are drawn according to the equation below. No liability is accepted for extrapolations of these data to the size of horses.

Data from Close (1972).

slow muscle (soleus). It can be seen that maximum shortening speed consistently decreases with size of the animal:

$$v_0/l_0 = c_v m^{-0.16}$$

with c_v = six muscle lengths/s for slow muscles like soleus and c_v = 14 for fast muscles and body mass in kg. For horses between 200 and 1000 kg one might thus expect v_0/l_0 to be 2–2.6/s for slow, and 4.6–6.0/s for fast muscles.

We will turn our attention at first to the exponent of m. The data of Figure 19.22 reflect activities at the cellular level: myosin ATP-ase activity. On the other hand, it is very practical. Remember, from Table 19.1 that in geometric scaling all speeds should be scaled as $l_0^{1/2}$, and next that $m \propto l^3$. Taken together, this means that v/l_0 should scale as $m^{-1/6} = m^{-0.167}$, which is in very good agreement with the measured data of Figure 19.21. It seems that muscle intrinsic speeds, related to enzyme activities, are closely adapted to the speeds that can be expected in an animal of the given size. These size-related differences are probably genetically determined, as they are already present in newborn animals and are rather insensitive to training. It is not known whether this size dependency occurs not only between species of widely different size but also within species, e.g. horses.

In a similar reasoning as for the work, the maximum mechanical power that can be generated by 1 cm³ tissue, area 1 cm² and length 1 cm can now be calculated:

$$P(1\ \text{cm}^3) = 0.1F_0/l_0 = 0.1 \cdot 20 \cdot 0.01 \cdot c_v m^{-0.16} = 0.02 \cdot c_v m^{-0.16}$$

Calculated for a muscle mass of m kg, this leads to:

$$P_{\text{muscle,peak}} = 20 c_v m^{0.84}$$

For horses between 200 and 1000 kg, this results in $P_{\text{muscle,peak}}$ = 40–50 W/kg for slow and 90–120 W/kg for fast muscle. These are peak power values. In a series of cyclic contractions, averages of one-third of the above will be the maximum.

Even when it just generates force, without shortening, muscle generates heat and consumes energy. Data on this heat production/resting energy consumption are very scarce, but there are good reasons to assume that it is proportional to the maximal work production. Thus:

$$P^*_{\text{iso}} \propto F_0 c_v m^{-0.16}$$

In Table 19.1 it was seen that time should be scaled by $\sqrt{l_0}$, and as in geometric scaling $\sqrt{l_0} \propto m^{1/3}$, by temporal factors, like step time t_c should be proportional to $m^{1/6}$. Kram and Taylor's (1990) argument was that:

$$P^*_{\text{iso}} \propto \frac{F_0 c_v}{t_c}$$

To arrive at running cost of locomotion, they assumed that (a) the average weight to be supported by muscles is equal to body weight, and (b) muscle contraction in running is nearly isometric. The latter seems rather improbable, but there are good arguments for it, related to the role of muscle elasticity in locomotion. Even if it is not completely true, if there is indeed muscle work done, it should be considered that this work would still be proportional to F_0 and to intrinsic muscle speed v_0. The simple expressions thus require a complex explanation, related to intramuscular enzyme activities.

> The simple experimental fact that energy consumption in locomotion per meter and per kg body weight decreases with increasing body size, has probably to do with the fact that the muscles of large animals are slower than those of small ones. This is an innate property and related to specific enzyme activities. It is functional, as the large limbs of big animals move more slowly.

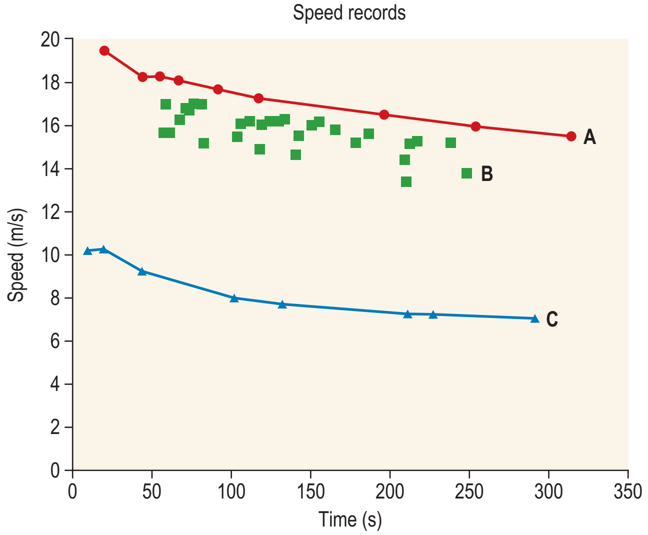

Fig 19.23 Speed records for horse and man. (A) World records of horse racing, 0.25 mile up to 3 miles; (B) course records of the trotting course Duindigt, The Netherlands, distances from 900–3600 m; (C) world records for men running in 1983, distances 100–2000 m and 30 km (shown at far right).

Data from McWhirter (1984).

Maximum aerobic capacity

The power that can be sustained for more than a few minutes is determined by the aerobic capacity, the maximum oxygen consumption. Taylor et al. (1981) have determined a general equation for aerobic capacity as a function of body mass. Recalculated in W, and with body mass m in kg, they found:

$$P^*_{\max} = 39m^{0.79}\ \text{(all animals)}$$

Remarkably, horses (and dogs) are in an exceptional position, as their maximum aerobic capacity is substantially above the average line.

For a 500-kg racing horse one would expect, on the basis of the equation above, a maximal capacity of 11 W/kg. In fact Thoroughbred horses reach 50–60 W/kg, five times as high (150–170 mLO$_2$/kg/min). The exceptional capacities of horses can also be seen from Figure 19.23: they can run about twice as fast as humans.

> The maximal aerobic power production, the power that can be generated for longer than a few minutes, can be measured as the maximal oxygen consumption. It increases with body weight, not in proportion but as mass to the power 0.79. This means that an animal twice as heavy as a smaller one has not twice the aerobic power, but only 1.73 times as much.

To arrive at the maximum aerobic speed one might theoretically divide maximum aerobic capacity by cost of transport:

$$v_{\max} = \frac{P^*_{\max}}{E^*_{\text{trans}}}$$

For the given values for P^*_{max} = 50 W/kg and E^*_{trans} = 2.09 J/kg/m from Table 19.4 for Thoroughbreds, one would then arrive at a $v_{\max}$ of no less than 24 m/s. Unfortunately, this value is way too high (see Fig. 19.23); maximum racing velocities are around 15 m/s. Here our fine theoretical arguments seem to get stuck. Probably E^*_{trans} at maximum speed is considerably higher than the optimum values of Table 19.4, which were obtained on a treadmill that did not allow higher speeds than 5 m/s.

Expressions are given for the maximum speed of horses, unloaded and loaded with a rider, respectively. The outcome is that maximum speed decreases with mass and increases with leg length, in such a way that those animals of similar shape but different size will run equally fast, but that animals with proportionally longer legs have an advantage.

Concluding remarks

After this brief journey around the outposts of biology and engineering, it is hoped that the reader has been as much entertained by the reading as the author has with the writing. Hesitatingly, the question of practical applicability of the above might be brought forward. In our opinion such applicability is small, but not completely futile. Scaling theories give a frame of reference for the problems discussed: the order of magnitude of the effect is taken into account, based on very elementary considerations, and often rough approximations. For details one should go further into the problem. An example is the theory of geometric scaling discussed earlier in this chapter. According to this theory stride time and step time in animals of different sizes should be scaled to the square root of a characteristic length. Sound physical arguments are given for this. This theory explains some relevant findings, e.g. why your Dachshund is galloping while you are still walking. Other findings are not explained, e.g. why Standardbreds trot and Thoroughbreds gallop. Scaling theory should certainly be used when one tries to relate findings on locomotion patterns in rats to the situation in horses. Without doubt, there will remain major differences between rats and horses, but the agreements will emerge more clearly. Any predictions from it will be inferior to the insights from experts, but the charming thing is that even simple models can produce realistic predictions.

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CHAPTER **20**

Modeling, simulation and animation

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Development of a computer model

Introduction

Computer modeling is generally defined as the process of creating a representation of an object or system within the computer. The origins lie in tools developed by engineers to assist them in the industrial design process. These models allowed the engineer to create each component of a product, assemble them 'virtually' in the computer, and ensure a good fit before manufacturing. Using computer mathematical analysis tools, it is also possible to predict the forces that the component will see and make certain that it will not fail under that loading.

For biological systems, computer models are useful for many of the same reasons. Instead of having to perform *in vivo* studies, a computer representation of an anatomical structure can be created and examined in ways that would be prohibitively difficult in a live animal. The advantages are obvious; if the model is reliable, it can be used to examine many biomechanical systems including the motion of a complex joint, such as the tarsus, the loading and motion in regions that are not visible to the human eye, such as within the hoof capsule, or the loading that causes a bone to fracture. These can be studied by modeling, which does not require the use of live subjects.

History of computer modeling

The origins of computer modeling can be traced back to a program developed in 1963 at the Massachusetts Institute of Technology (Encarnacao et al., 1990). Its capabilities were limited to what would be called a simple drawing program in modern terms, but many of the fundamental drawing subroutines and standards were established by this work. Although developments were made in subsequent years, it wasn't until the late 1970s that computer-based design moved from the realm of academic theory into mainstream science. As the increasing power of computers allowed for more advanced applications, a new technique was developed in the 1980s called 'solid modeling.' In this process a three-dimensional representation of a structure is created within a computer, rather than the older method of simply having a number of two-dimensional projections.

Using this new technology, designers could view parts of a system and their interactions without the cost and time involved in creating a prototype. Assemblies of independent components, structural supports, or even entire complex mechanisms such as automotive engines could be examined for fit and accuracy before any real monetary investment was made by the company.

Computer modeling and biomechanics

Even before solid modeling became an industry standard, anatomists and biomechanists had recognized the opportunities it represented. One of the earliest uses of computers to model a musculoskeletal system represented an approximation of the human body as a series of rigid links with simple hinge or pin joints (Chaffin, 1969). Although this was useful in visualization of human motion, it was not a tool for examining specific bones or joints. It was not until medical imaging devices such as computed tomography (CT) and magnetic resonance imaging (MRI) scanners were used as the basis for the geometry that truly representative anatomy could be created in a computerized model.

After the techniques of modeling had been proven in human studies, the veterinary community began to use the same methods to explore the complexities of motion in animals. An early equine study using the fundamentals of joint motion developed for human protocols modeled the entire forelimb distal to the metacarpophalangeal joint (Cheung & Thompson, 1993), but subsequent research has typically focused on a single joint, such as the carpus (Les et al., 1997) or fetlock (Thompson & Cheung, 1993).

Applications of computer models

There are four typical applications of computer models in biomechanics: visualization, kinematics, dynamics and finite element analysis.

Visualization

The potential of computer models in visualization represents one of the great emerging applications of this technology. A well-known example is the use of CT or MRI data by a veterinarian or physician to produce a three-dimensional recreation of a bone or joint, rather than looking at it as a series of two-dimensional projections. This functionality is included in a number of commercial medical imaging products. The operator uses specific areas as 'edges' of structures and the computer rebuilds a visualization of the bone, soft tissue or any other object of interest. This type of modeling is useful for viewing different structures and the relationships between them in live subjects, but some of its most promising practical applications arise from the ability to produce physical objects by the processes of rapid prototyping and machining.

Rapid prototyping is a method by which a sample part is made from (typically) a soft plastic or other suitable material that can be held and examined, not just viewed on a computer screen. The process consists of creating a solid model in the computer, then sending the information to a rapid prototyping machine, which recreates it as a series of layers of the material. In industry, entire prototype engines have been constructed this way to demonstrate new technology and concepts that would be difficult to otherwise describe. Similarly, anatomical structures can be recreated and examined in the same way as a dissected specimen. This has been explored in humans as a method of preparing surgeons to perform operations, including neurological and orthopedic procedures (McGurk et al., 1997).

Machining is a process by which a product is manufactured from a permanent material. For orthopedic procedures, this allows preliminary evaluation of surgeries and the manufacturing of custom implants. Using CT data obtained preoperatively, the joint can be recreated precisely in the computer and a surgeon can have an exact fit for the orthopedic implant prepared prior to surgery or even constructed during the procedure (Mulier et al., 1989).

One of the most exciting areas into which visualization techniques are expanding is the field of virtual reality. The concept of virtual reality has become something of a buzzword of the media in recent years due to proliferation of home computers, increased distance interaction on the internet, and incredible advances in computer graphics. The true concept of virtual reality is that, by recreating a situation in the processor of a computer and by using highly realistic graphics, the human brain can be fooled into believing that the computer-generated images are real. Although technological limitations still prevent complete immersion in a virtual reality environment, some early demonstrations of its medical applications have been performed, such as the National Library of Medicine's Visible Human Project. This is an ambitious program to develop a complete database of human anatomy based on cryosections and CT scans of male and female cadaver specimens. The results of this research have already been used to develop educational and research tools for audiences ranging from school-age children to medical professionals.

Another focus for the development for visualization tools in medicine is in preoperative planning. An entire surgery can be simulated and performed any number of times to rehearse the mechanics of the procedure prior to a single incision being made on a live patient. However, the use of a purely anatomical model cannot completely prepare the student for all situations and complications that may arise during a procedure and that necessitate a rapid and accurate response by the surgeon. However, in the same way that pilots can practice emergency maneuvers and landings in jet simulators, critical conditions could be simulated to prepare a student for surgical emergencies.

The application of virtual reality in the field of equine biomechanics is quite advanced. An early example is 'Persival,' a mechanical horse simulator (Fig. 20.1) developed by Patrick Galloux of the Ecole Nationale d'Equitation in Saumur, France (Galloux et al., 1994). His group has constructed a mechanical simulator that recreates the movements of a horse at a walk, trot and canter, as well as during jumping. Virtual reality is used to allow the rider to follow a show jumping course by watching a screen in front of the simulator or by wearing virtual reality glasses. The rider sees the obstacles, and sensors are used to detect and react to the rider's aids. It has been found that by using this simulator, the time required to train a rider was shorter than when using a real horse, and the novice rider was able to learn safely and without the need for 'lesson' horses. A horse simulator is also available that allows the ride to experience and replay a virtual dressage test (http://www.racewood.com/dressage.php).

Fig 20.1 Persival, the Ecole Nationale d'Equitation's mechanical horse simulator.

Kinematics (movement)

Kinematics is defined as the observation of motion in a mechanical system. It encompasses a spectrum that ranges from the rotation of a horse's limbs as it gallops across a polo field, to the movements of a player's arm and mallet as a shot is made, to the way the polo ball arcs through the air after it has been hit. Kinematic studies have described the horse's movement at various gaits and during jumping. This information can be used to create an accurate simulation of the motion of a particular joint that shows how the various components interact and allows the user to visualize the effects of disease, lameness or surgeries. Other types of computer simulations might show deformation of the structures within the hoof during weight bearing, or the actions of the rider in giving a horse the aids for different movements.

It is important to recognize that kinematics is limited to the process of observation; it does not have the ability to make inferences. For example, kinematics can be used to study how a bone, joint, limb or animal moves based on a set of data describing that movement, but it cannot predict the results of a perturbation of the system, such as an injury or lameness. Using computer models as kinematic simulations is, to a great extent, a specific application of the previously discussed visualization tools. However, it goes beyond simple visualization because the kinematic information represents a bridge between visualization, a purely external observation, and dynamics, an understanding of the forces that are responsible for creating the movement and the forces that arise as a consequence of the movement. Halvorsen et al. (2008) used filtering for optimally tracking kinematics. Bobbert & Santamaría (2005) and Bobbert et al. (2007) used body kinematics to calculate limb dynamics (Bobbert et al., 2007) and energetics (Bobbert & Santamaria, 2005).

Kinetics (dynamics)

As stated above, kinematics is a passive observation of how a system moves. Dynamics uses kinematic data, combined with additional information, to evaluate the forces within the system. Having calculated the dynamics, much more complex simulations can be performed. Two methods are primarily used for the development of dynamic results: inverse dynamics, and forward or direct dynamics. In general, inverse dynamics is a technique by which internal forces are estimated using data from external observations, while forward dynamics predicts external forces and motions by prescribing internal forces. An application of computer modeling using inverse dynamics involves the calculation of net joint moments and joint powers from knowledge of the kinematics, ground reaction forces (GRFs) and morphological data using a link-segment model. In this type of model, the complex structure of the limbs is simplified by representing the limb segments as rigid bodies linked by hinge joints (Schryver et al., 1978; Hjertén & Drevemo, 1987; Clayton et al., 1998; Colborne et al., 1998; Lanovaz et al., 1999) (Fig. 20.2). The musculature that drives the limb has a complex geometry and many mechanical and material properties that are difficult to quantify. In order to study the effect of muscle action without defining all of the specific parameters of the system, the net muscular action within the limb is represented in the model as net torques or net joint moments acting at each of the joints. Zarucco et al. (2003) developed and tested an experimental model for in-vivo short-term recording of peak isometric forces of the digital flexor muscles in the forelimb of adult horses and thus provided further insight to functional implications of the complex architecture of these muscles. Realistic inertial parameters such as mass and moment of inertia are assigned to each segment of the computer model. Kinematic data and GRFs are measured and used as inputs to the model. An inverse dynamics solution is used to calculate the torques required to cause the observed motion and forces. This 'net effect' of muscle action derived from the model can be applied in both clinical and research settings to study the function and dysfunction of the limb at the different joints (Buchner et al., 1996; Clayton et al., 1998). Brown et al. (2003) developed a detailed musculoskeletal model of the distal equine forelimb to study the influence of musculoskeletal geometry (i.e. muscle paths) and muscle physiology (i.e. force–length properties) on the force- and moment-generating capacities of muscles crossing the carpal and metacarpophalangeal joints. They predicted that the suspensory and check ligaments contributed more than half of the total support moment developed about the MCP joint in the model. Additional information can be added to the model to increase the level of sophistication. For example, knowledge of the orientation of anatomic structures such as the line of action of tendons can allow for a more detailed estimation of internal muscle and tendon forces (Riemersma et al., 1988; Jansen et al., 1993). Merritt et al. (2008) developed a two-dimensional model of the musculoskeletal system of the distal limb region and applied it to kinematic and kinetic data from walking and trotting horses. The forces in major tendons and joint reaction forces were calculated. The components of the joint reaction forces caused by wrapping of tendons around sesamoid bones were found to be of similar magnitude to the reaction forces between the long bones at each joint. This finding highlighted the importance of taking into account muscle-tendon wrapping when evaluating joint loading in the equine distal forelimb (Figs 20.3–20.6).

Swanstrom et al. (2005) developed a musculoskeletal model of the Thoroughbred forelimb and a dynamic simulation of the motion of the distal segments during the stance phase of high-speed (18 m/s) gallop. The musculoskeletal model was comprised of segment, joint, muscle-tendon, and ligament information. The dynamic simulation incorporated a proximal forward-driving force, a distal ground reaction force model, muscle activations, and initial positions and velocities. A simulation of the gallop after transection of an accessory ligament demonstrated increased soft tissue strains

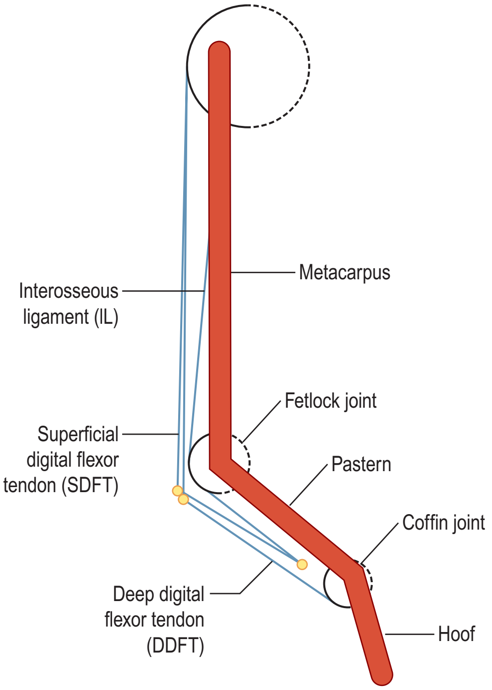

Fig 20.3 Two-dimensional, sagittal plane model of the equine forelimb. The model contained three rigid body segments and three major tendinous structures.

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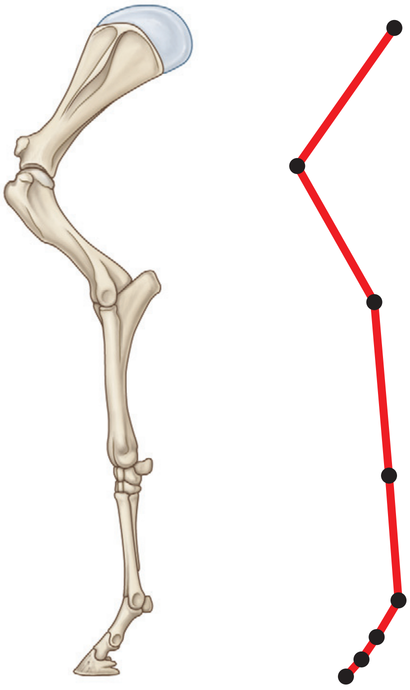

Fig 20.2 Link-segment model of the equine forelimb.

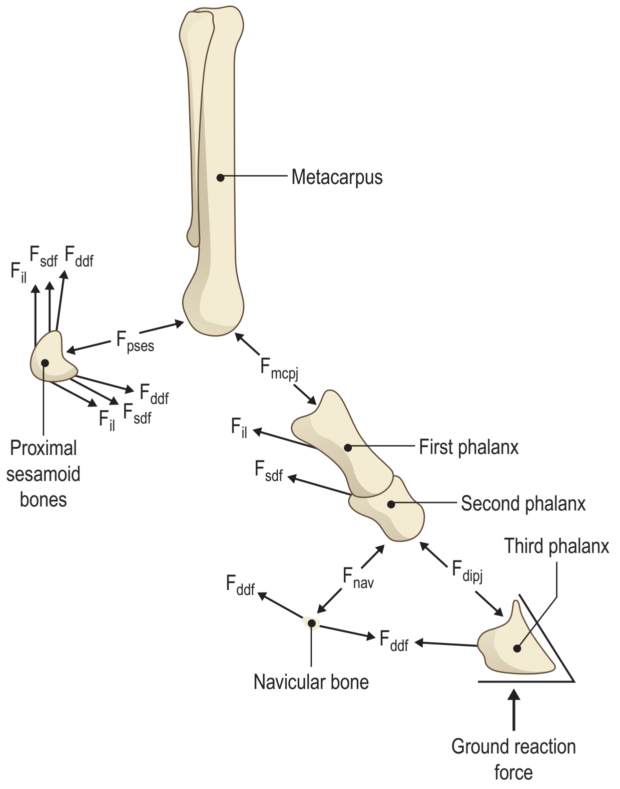

Fig 20.4 Forces considered when calculating the joint reaction forces at the fetlock and coffin joints. The forces were the ground reaction force, the force exerted by the distal phalanx on the middle phalanx (Fdipj), the force exerted by the navicular bone on the middle phalanx (Fnav), the DDFT force (Fddf), the SDFT force (Fsdf), the IL force (Fil), the force exerted by the proximal phalanx on the distal metacarpus (Fmcpj), and the force exerted by the proximal sesamoid bones on the distal metacarpus (Fpses).

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in the remaining support structures of the distal forelimb, consistent with those previously reported from *in vitro* studies. Forward or direct dynamics utilizes data describing muscle activation patterns and the force of muscular contraction to determine the position of each segment of the limb. Although this method is theoretically ideal, as it is the most accurate representation of what is actually occurring in the system, it is practically difficult to measure these inputs with the accuracy needed to produce a model that represents the internal forces and interactions. A variation on this type of dynamic analysis was performed for an entire horse in 1987 using a mechanical mechanism analysis package (Van den Bogert, 1989). The horse was represented by a series of rigid bodies connected by springs, dampers and torque producers representing tendons and ligaments. The innovative aspect of this simulation was that, instead of simply prescribing the motion of a segment by kinematic data, an intelligent model was created that prescribed the limitations of joints, the reaction forces created by the tension in ligaments and muscle activations. The model was analyzed and validated through both kinematic and ground reaction force data. However, in order to simulate the entire horse, a number of assumptions had to be made due to the complexity of the project and the limitations in computer power at the time. The entire system was assumed to be purely two dimensional with the segments of the horse moving in the sagittal plane. Complex joints, such as the carpus and tarsus, were approximated as simple hinges, and it was necessary to completely ignore certain joints, such as the coffin joint and the articulation of the spine. In spite of these assumptions, the simulation was found to accurately recreate the ground reaction force patterns measured in research studies.

Musculoskeletal models have been used to investigate underlying concepts of equine locomotion that are often broadly accepted, but not understood in detail. Merritt et al. (2010) investigated the function of the fetlock joint and found that the metacarpus was loaded in compression by the combined actions of the proximal sesamoid bones and the first phalanx. Although this kind of compressive loading was already understood to exist in the metacarpus, the study illustrated the extent to which this loading depended upon the concerted function of the entire forelimb, rather than being a feature of the fetlock alone. Harrison et al. (2010) utilized an extensive forelimb model to investigate elastic energy storage and release in the distal forelimb. Elastic energy storage had long been considered an important feature of locomotion in large animals, but these authors were able to quantify its role in detail for the first time. Even in the muscular structures of the distal forelimb, such as the superficial and deep digital flexor muscles, these authors reported that between 69–90% of the total work was done by elastic energy release, rather than by active muscle contraction, with the amount of elastic energy storage increasing at faster speeds. Studies of this kind help to close critically important gaps in overall understanding, by providing the detailed mechanisms of action for features of locomotion, which were previously understood in only the broadest terms.

The availability of a complete and accurate model of even a single joint opens up incredible opportunities. Should a specific treatment be recommended, such as a tenectomy, the outcome can be predicted by incorporating into the model the loss of the forces transmitted by that tendon. The model could then be used to predict the effectiveness of the treatment, allowing for a more educated and confident recommendation of the likely benefits. This application was validated by a study in which the human lower leg was recreated in a computer to evaluate orthopedic surgical procedures. It was found that the model accurately predicted the effects of tendon transfers and lengthening procedures (Delp et al., 1990). It is within the realm of possibility that a sufficiently complex model of the equine limb could be created that it would be capable of assessing the effects of orthopedic shoeing, changes in the physical properties of the footing, muscular atrophy, or surgical procedures such as tenectomy or arthrodesis.

Finite element analysis

The stress on a structure can be measured through a dynamic analysis as described above or it can be computed through application of mechanical measurement techniques such as strain gauges. Having determined the stress on a structure, it is of great interest to know what effect this might have on the structure in terms of causing deformation (strain) or stimulating biological adaptation. For example, hoof deformation at impact could be used to evaluate how energy is dampened or dissipated. Observation of the habitual patterns of stress in a bone can be related to the way in which that bone adapts to its environment and reconstructs itself. The complexity of these types of calculations makes it almost impossible to accurately determine or calculate by hand the way in which forces will be distributed across a particular structure.

In the field of engineering, this problem has been solved by the development of the process called finite element analysis (FEA) or finite element modeling (FEM). To understand the process of FEA, consider a very simple piece of geometry, a cube. It is relatively easy to predict the way a cube deforms based on the forces applied and the properties of the material from which the cube is made. A steel cube deforms in a specific way, which is different from an aluminum or wood cube.

Most objects are more complicated than simple cubes. They are made up of very complex surfaces and curves, which make it difficult, if not impossible, to predict how the structure will deform under stress. The process of FEA consists of breaking up a piece of complex geometry into a series of simple shapes, such as cubes or

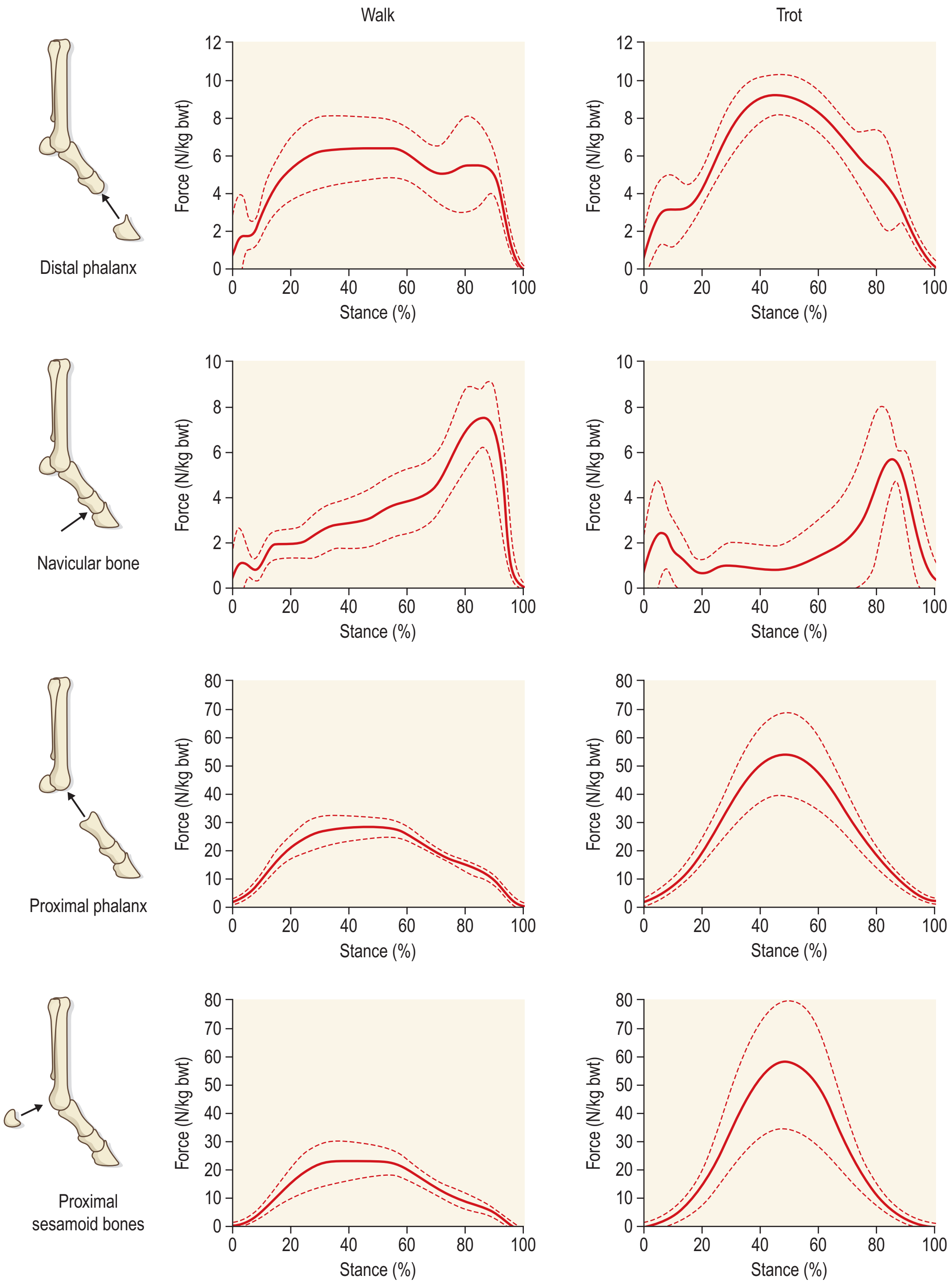

Fig 20.5 Magnitudes of calculated joint reaction force components from long bones and sesamoid bones in the coffin and fetlock joints for walking and trotting during the stance phase of the stride. The magnitudes are shown as solid lines with dashed lines to represent ±1SD. The stance phase of the stride was the time during which the vertical component of the ground reaction force was greater than 50N. 0% of stride was the time of first hoof–ground contact, 100% of stride was the time of last hoof–ground contact.

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pyramids. These subdivisions, called elements, react to stress in a mathematically predictable way. The entire structure is represented by numerous elements, which are each described in terms of the motion of their corners, or in more complex models, the motions of the midpoints between the corners as well. When the model is analyzed, the deformation of one element defines the force on the next element, and subsequently its force on the next, and so on. The minimal requirement is to analyze each corner of each element in three directions (up/down, left/right and forward/backward). When we take into account the fact that a finite element model can consist of thousands of these elements, it becomes evident that a powerful computer is an essential tool in performing this type of analysis.

Biological structures are even more complex than most products manufactured in industry, making finite element analysis invaluable for predicting their behavior under various loading conditions.

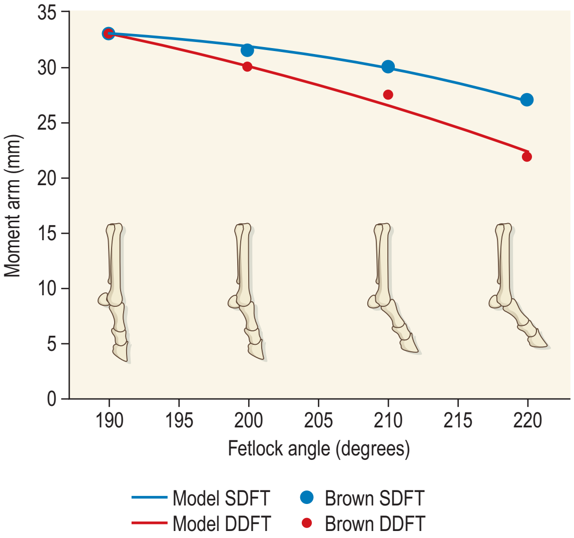

Fig 20.6 Moment arms from the forelimb model compared with those published by Brown et al. 2003. Moment arms for the forelimb model were calculated using a simulated tendon excursion method.

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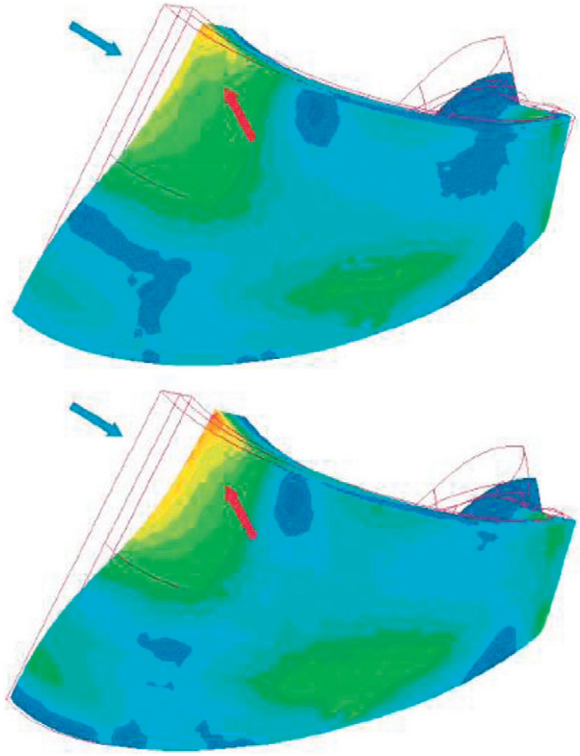

Fig 20.7 FE models, presentation of results. The 5° raised heels (upper diagram), and 5° lowered heels (lower diagram) shown in lateral view: displacement is shown as deformed geometry, colours represent von Mises stresses with red representing maximum stress and blue representing minimum stress. Red arrows indicate the maximum stress zone in the proximal dorsal wall; blue arrows indicate the maximum displacement of the dorsal wall. Comparing the 5° raised heels model with the 5° lowered heels model, less stress and smaller deformations are found in the 5° raised heels model.

Reprinted with permission from Hinterhofer, C.H., Stanek, C.H., Haider, H. The effect of flat horseshoes, raised heels and lowered heels on the biomechanics of the equine hoof assessed by finite element analysis (FEA) in Transboundary and Emerging Diseases 2001 (2), 73–82. Copyright © 2001, John Wiley and Sons.

For example, by creating a computer model of a particular bone, and applying forces to the bone from data known *a priori*, the type and location of fractures in that bone may be predicted.

A number of equine studies have been performed using finite element analysis. One of the earliest was an analysis of the structure of the hoof. The intent of the project was to examine the role of mechanical factors in lameness and degenerative diseases within the hoof capsule (Hogan et al., 1991). A two-dimensional finite element analysis was performed, and the deformation results were examined to determine motions that were not visible through direct observation. The results indicated that during weight-bearing the coffin bone moved downward toward the sole, and rotated away from the dorsal hoof wall (Fig. 20.7). Additionally, approximations of the stresses induced in the laminar tissue during loading were determined. The stress values within the hoof derived from this and similar studies have given a much more comprehensive understanding of the behavior of the hoof. The results were of particular interest because, at that time, there was little direct information describing the motion of the coffin bone with respect to the hoof wall during loading.

Due to improvements in computing capabilities and finite element programs, Les et al. (1997) were able to develop a more comprehensive three-dimensional model (Fig. 20.8) than that of Hogan et al. (1991). Using CT data, an accurate model of the metacarpus was created in the computer, and it was then subdivided into a series of hexahedral elements. This model was compared to *ex vivo* loading results, and the accuracy of the FEA was validated. This study was an excellent example of the opportunities opened up by FEM. Once a particular model has been validated, many different loading conditions can be simulated and analyzed within the computer and an accurate representation of the stress response can be determined without the need to use additional live subjects. Hinterhofer et al. (2000, 2001) studied the use of finite element analysis in evaluating the effect of trimming and shoeing on hoof mechanics in the horse. Stresses are high in the material surrounding the quarter nails, in the heels and in the proximal dorsal wall. Raising the heels by 5° resulted in significantly ($p < 0.05$) lower stress and displacement values. The model with heels lowered by 5° yielded the highest stress and displacement values, and the FE model with the regular horseshoe lay between the two extremes (Hinterhofer et al., 2000) (Fig. 20.7). Maximal displacement was calculated in the hoof capsule shod with a regular horseshoe without a clip. Minimal displacement was found in the capsule with a toe clip and 2 side clips placed behind the 3rd nail. All models showed higher displacements when calculated with a loose nail fixation (Hinterhofer et al., 2001).

A more complex, thirty-two component finite element model of horse and donkey digits with over 10^6 elements was used to compare von Mises stress levels in the deep and superficial digital flexor tendons in the horse (respectively, 1.34 MPa and 0.56 MPa) and the donkeys (respectively, 0.78 MPa and 0.27 MPa). The same model was used to evaluate the effects of weight-bearing on capsular deformation patterns (Collins et al., 2009).

Pollock et al. (2008a,b) defined a mathematical model to predict strains in the humerus at stance within ± 2 standard deviations of experimental strains at four of these locations and predicted negligible strains at the remaining two locations, which is consistent with experimental findings.

Development of a computer model: a horse history

Although the end result of computer models can vary greatly between applications, the steps involved in the process are quite similar. Visualization requires the greatest accuracy in the overall

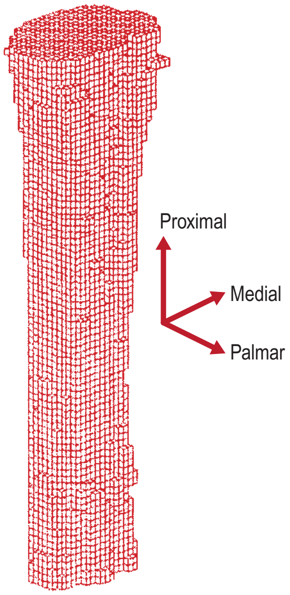

Fig 20.8 Finite element model of the equine metacarpus.

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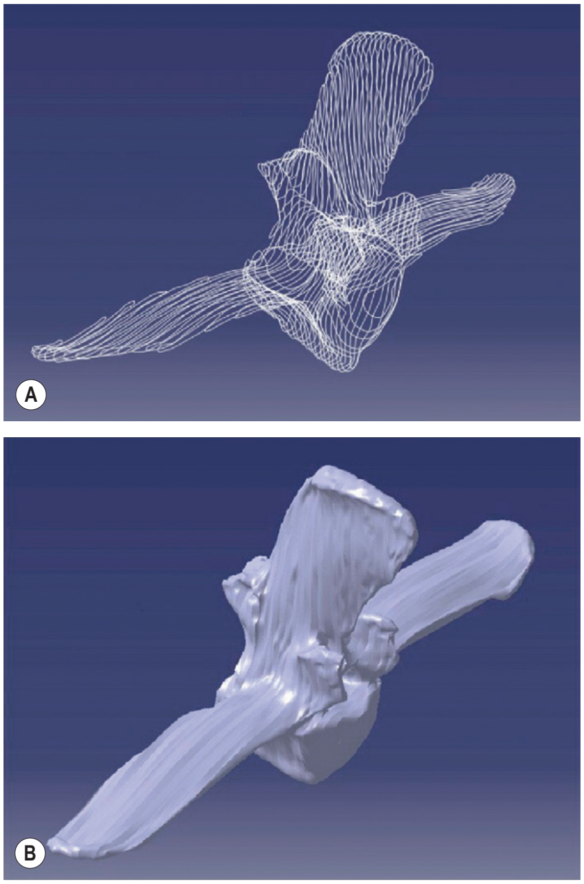


Fig 20.9 A three-dimensional reconstruction of the first lumbar vertebra from CT images. (A) Spline curves of successive CT slices were lined up to generate the surface contour of the bone. (B) The bone surface was then generated from the spline curves and filled with bone.

Reprinted from Groesel, M., Gfoehler, M., Peham, C., 2009. Alternative solution of virtual biomodeling based on CT-scans. Journal of Biomechanics 12 (4), 2006–2009, with permission from Elsevier.

form and appearance of structures. When attempting to simulate a surgical procedure, it is critical that the anatomy appear as realistic as possible. The model must accurately predict what the surgeon sees during the procedure if it is to have any practical value. In order to reproduce anatomical structures accurately, it is necessary to use very advanced medical imaging techniques. When studying skeletal structures, CT scans can be used to build a representation of structures with high X-ray absorbance (Fig. 20.9). Soft tissue structures are typically visualized more clearly using MRI images. Regardless of the source of data, the process of recreating the region in question is the same. The resulting images are stored as a series of pictures that are then analyzed to locate the edge of the structure of interest. These interface locations are stored in the computer and are used to define the edges. Graphics tools are subsequently used to rebuild the edges into a solid structure. By this method, almost any complex anatomical structure can be recreated for a visual examination. Zarucco et al. (2006) developed a three-dimensional generic musculoskeletal model of the equine forelimb comprised of bony segment, muscle-tendon, and ligament information, and based on high-resolution computed tomographic (CT) and T1-weighted magnetic resonance (MR) images from an isolated forelimb of a Thoroughbred racehorse. Image fusion was achieved through coregistration of CT and MR images with an image analysis program (analyze) by adjustment of the relative position and orientation of fiducial markers visible in both modalities until the mutual information between the images was maximized. Three-dimensional surfaces of the bones and origin/insertion sites, centroid paths and volumes of the muscle-tendon and ligamentous structures were obtained from the multimodal (CT/MR) images using semiautomated and manual segmentation combined with sagittal and transverse color-cryosection anatomic images obtained from three other cadaveric equine forelimbs. Once bony and soft-tissue structures were reconstructed in the same coordinate system, data were imported to a software package for interactive musculoskeletal modeling (SIMM).

Lawson et al. (2007) created a subject-specific distal forelimb model using bones extracted from CT scans to examine movement from in-vivo invasive-marker motion capture. The movements of the sesamoid bones were simulated using the constraints of maintaining an isometric virtual ligament and maintaining contact between the appropriate articular surfaces, creating a variable moment arm for the tendons. The simulation of the proximal sesamoid bones was compared to movement recorded *in vitro*. The paths and origins used for the deep digital flexor tendon (DDFT), superficial digital flexor tendon (SDFT) and suspensory ligament (SL) were altered and the effects on their calculated strains during trot stance were examined. It was shown that within the anatomically realistic spectrum, changes to tendon paths can have an appreciable effect on calculated strains; however the origin sites chosen are not as influential as changes to paths at the metacarpo-phalangeal joint.

These techniques are also useful in kinematic and dynamic modeling. Regardless of how it may appear, joint motion is never as simple as a two-dimensional rotation. Using the techniques specified above, a more comprehensive representation can be constructed which will allow for a much more accurate study of the dynamics of joint motion, and hence a better understanding of pathologies.

Finite element models perhaps require the most comprehensive and accurate descriptions of skeletal and accessory structures and their properties. The accuracy of the analysis is directly dependent upon how closely the model approximates the original geometry. Although this analysis technique is inherently an approximation due to its very nature of subdividing curved surfaces into linear segments, without an accurate framework on which to build the structure of the finite element model, the analysis will be inherently flawed. The model itself is only as good as the information from which it was created, and without a great deal of precision in the original model, the results will be useless.

If a kinematic or dynamic model is being developed, another major step is necessary to the completion of the simulation. External data, such as kinematic information describing the motion of the horse and GRFs, are necessary for a comprehensive model. There are, however, two ways in which these data can be used. The first is to apply the information as the perturbation input to the model. By specifying the kinematic and force input, data such as joint torques, moments and temporal responses may be analyzed. The second method is to use the external data to verify a solution arrived at by other means. In the full body equine simulation of Van den Bogert (1989), an intelligent system was used to describe the motion of the segments of the horse. A standard muscular model controlled some joints with activation timing based on the percent of stride, while others were controlled by constraints based on approximate joint angles. Since the force data were independent of the solution, they could be used to confirm the veracity of the solution. With a model of the equine hind limb, the function of the 'passive stay apparatus' could be explained. A model of the forelimb was used to determine force distributions in the digital flexor tendons, and to experiment with various methods to change the force distribution. Simulations of this type are valuable tools in basic research on functional anatomy and etiology of injuries. An application with much potential is the optimization of sports performances using simulation methods (Van den Bogert & Schamhardt, 1993).

Development of a computer simulation: a human perspective

Introduction

Research on equine movement does not always use horses and the same accounts for humans. In most areas of biomedical research, animal models are used when rigorous control of experimental conditions is required, measurements require invasive techniques, or when the use of human or equine subjects is not ethically acceptable (Van den Bogert et al., 1989; Van den Bogert & Schamhardt, 1993).

In the context of biomechanics of human movement, animal models are typically used to study basic biological mechanisms. A good example is research on muscle mechanics, where full experimental control over muscle length and activation is required, and direct measurements of variables such as muscle force, muscle fiber length, and even heat production can be done (Fig. 20.10). This approach would be possible in animal models and not in human subjects. There is, however, a strong pressure on researchers and their institutes to make use of simulation techniques instead from an animal welfare perspective and thus reduce the use and number of testing animals.

For more applied questions, related to specific human injuries or specific human movement tasks, animal models are not appropriate because the dynamics and anatomy are not comparable. For instance, the study of knee injuries in distance runners has a basic biological component and a mechanical component. Basic biology, or in this case the reaction of cartilage to mechanical loads, can be studied in animal models, e.g. in the horse. It is, however, obviously impossible to use animal models to learn how to reduce forces in the knee joint with appropriate orthotics or other mechanical interventions. Furthermore, in human subjects, the force in the joint cannot be measured; other factors contributing to injury cannot be controlled, and ethical problems arise in the study of more acute, serious injuries. Analogous to the use of animal models, it is desirable to study such movement-related questions with methods that allow full experimental control and access to all mechanical variables for measurement. In the case of human or equine movement, one possible option currently available is to build a model of the system under investigation, and then perform experiments on the model. Although physical and mechanical models have been used, computer models (also numerical models) are almost exclusively used for this purpose.

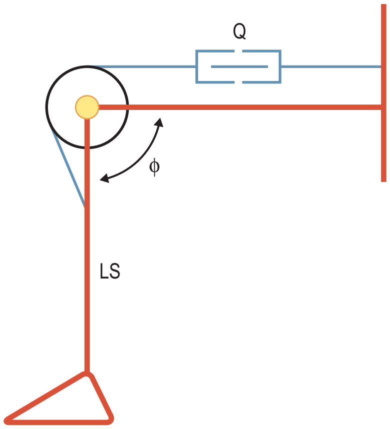


Fig 20.10 Typical example of a human knee joint flexion simulation. ϕ, the joint angle; LS, the leg segment length; Q, the quadriceps muscle force.

Van den Bogert & Nigg (2007) defined simulation as follows: simulation is the process of performing experiments on a numerical model. The term *experiment* implies that it is crucially important that the model reflects the causality of the system that is investigated. The input of the model should precede the output in a causative sense. Once such a numerical model is developed, variations on the original experiments can be performed quickly and at low cost. It should, however, be kept in mind that the experiment is always performed on the model only, and conclusions may not apply to the human system when the model is not valid, and the model is only valid within the scope of its original design and validation. This is a central problem in modeling and simulation. It is important that a model replicates those features of the system that are essential for the question that is studied. This requires careful design of the model and appropriate validation tests once the model is finished. In biomechanics, simulation is applied in four different areas: dynamics of movement, tissue mechanics, fluid flow, and measuring techniques. In dynamics of movement, simulations allow the experimenter to apply controlled perturbations to the anatomy, muscle coordination, and control system, and observe the resulting changes in movement and forces.

Tissue mechanics can be studied using finite element models (FEM), which are the numerical equivalent of partial differential equations (PDE), which describe the local relationships between stress and strain in tissue. These methods have been applied to bone, cartilage, tendon, ligament, muscle, and even (animal) brain tissue during impact.

Biomechanical measuring techniques often suffer from errors, and simulation may be used to determine how errors in the raw data are propagated to the final result of the calculation.

Designing musculoskeletal models

Movement simulations can be driven using a variety of methods, summarized below from Van den Bogert & Nigg (2007). In simulations of human movement during free fall or space flight, movement of the body can be produced by well-coordinated limb movements (Passerello & Huston, 1971). Since the required muscle forces are extremely small, it is appropriate to consider joint rotations as the cause of the movement (Yeadon, 1993). The required

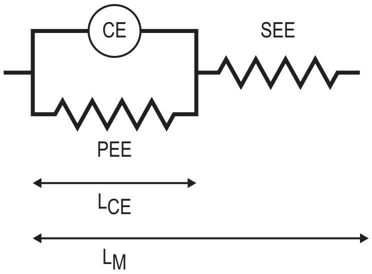


Fig 20.11 The three-component Hill muscle model. CE, contractile element; PEE, parallel elastic element; SEE, series elastic element.

muscle forces may be computed, but are not relevant to the problem as long as they do not exceed the force-generating capacity of the muscles.

When muscle forces are included in a simulation of movement, it is usually desirable to include several well-known mechanical properties of muscle (Hill, 1938): the force–length relationship, the force–velocity relationship, and the activation dynamics. A muscle model, which includes these properties, will allow the muscle forces to respond realistically to changes in length and neural stimulation. Muscle models exist in various levels of complexity, but for movement simulation, the three-component Hill model (Fig. 20.11) has been used almost exclusively (Winters, 1990; Zajac, 1989). The model consists of a contractile element (CE) and two non-linear elastic elements, the parallel elastic element (PEE) and the series elastic element (SEE). The CE represents the muscle fibers, the SEE represents tendon and other elastic tissue in series with the fibers, and the PEE represents the passive properties of the fibers and elastic tissue surrounding the muscle fibers. The elastic elements are described by a mathematical force–length relationship, which has the property that no force is generated below a certain length (the slack length), and stiffness increases as force increases. The stiffness parameter can be scaled such that the tendon strain at maximal muscle force is about 3–5% or about half the level where damage occurs (Winters, 1990). It should be kept in mind that the three-component Hill model is based on a limited set of experimental observations, such as isometric, isotonic, and isokinetic contractions, usually performed at maximal activation. Interactions between the effects of length change and activation may, therefore, be poorly predicted.

The Hill model, in spite of its limitations, is presently considered the most practical muscle model for simulation of human movement. When muscles are connected to a skeleton with many degrees of freedom, the muscle model needs to be coupled to the equations of motion, resulting in a combined system of equations representing the musculo-skeletal system (Van den Bogert et al., 1998).

The output of a muscle model is the magnitude of muscle force, a scalar. The equations of motion require a force vector (magnitude and direction) and also a point of application, so that the moment can be computed. Also, the muscle model requires the instantaneous length of the muscle as input. All of these require a model of the musculoskeletal anatomy. One method for doing this is to model the muscle as a straight line of action between origin and insertion. If the kinematic state variables are known, the position vectors of origin, and insertion, can be calculated from the position and orientation of the two body segments. The same vector, but in opposite direction, is applied to the origin point. Straight line muscle models have limitations, and usually require additional wrapping points to model muscles and tendons that follow a curved path over underlying tissue (Delp & Loan, 1995). Failure to properly model the path of the muscle may result in underestimation of moment arms and hence, overestimation of muscle forces required for movement. This was a problem in early estimates of articular contact forces in the human hip. Model calculations were as much as 100% higher than direct measurements using an instrumented prosthesis (Brand et al., 1994).

The contribution of a muscle force to a generalized force can be determined using the principle of virtual work. When the system undergoes a hypothetical small change in the generalized coordinates, the muscle will undergo a virtual length change. The principle of virtual work states that the work done by the muscle should be equal to the work done by the generalized forces, i.e. the dot product of the generalized force vector and the generalized displacement.

If a generalized coordinate is a joint angle, the corresponding generalized force will be the moment of the muscles at that joint. If the generalized coordinates are segment orientations, the muscle moment will contribute to the generalized forces for both segments. The partial derivatives, which are the moment arms, may be derived from an anatomical model, for instance, using straight lines, or measured directly in cadaver specimens or *in vivo* using three-dimensional imaging techniques. Moment arms can be simply measured as the distance from the muscle's line of action to the joint center, requiring assuming a fixed joint center. A more elegant method is to collect data of muscle length at various joint angles (or other generalized coordinates), and use regression analysis to find a mathematical relationship describing it as a function of the generalized coordinates. Partial derivatives may then be computed analytically. This method was first used by Grieve et al. (1978) to determine moment arms of the ankle plantarflexors, and applied later to determine moment arms for hip and ankle muscles (Spoor et al., 1990; Visser et al., 1990).

The coupling between skeleton and muscles requires computation of muscle lengths from the bone positions in the skeleton, computation of muscle force from the state equations of the muscles and the application of the muscle forces to the skeleton. For a complete musculo-skeletal model, passive forces should also be considered. Ligaments, when their function is to guide joint kinematics, need not be included, since their function has been incorporated in the joint model. For instance, the cruciate ligaments in the knee can be assumed to be inextensible during normal movements, resulting in a moving center of rotation at the intersection of the cruciates. These guiding ligaments do not perform mechanical work, and can be omitted from the equations of motion. They will, however, have an effect on the articular contact force. To model this, joints can no longer be considered to be kinematic mechanisms and deformation needs to be modeled (Blankevoort & Huiskes, 1996). Internal passive force also occurs at the end of the range of motion of a joint. This may result from stretching ligaments, compressing muscles, or a combination of both.

The net effect on the movement can be modeled as an extra joint moment, which is a function of one or more joint angles (Riener & Edrich, 1999). Passive tension in ligaments spanning several joints, which occurs in some animals (Van Ingen Schenau & Bobbert, 1993), can also be modeled as a simple passive muscle model with only a SEE and coupled to the skeleton in the same way as muscles. Interactions between skeletal dynamics and muscle dynamics can only be observed in a model in which both are represented and coupled.

External forces are forces acting between the system of interest and the environment. Common external forces are: gravity, contact forces, and aerodynamic forces. Gravity is simply modeled as a constant force vector of magnitude (mg) and downward direction, applied to the center of mass of each rigid body segment in the model, where m is the mass of the body segment and g is the acceleration of gravity (9.81 m/s^2). Modeling the contact as a kinematic connection like a joint can often include contact forces. This was, for example, appropriate for the foot-ground contact forces in a simulation of vertical jumping (Pandy & Zajac, 1991), provided that the simulation is terminated when tensile forces in the connection begin to occur.

When simulation is used as a scientific tool, experiments are performed on a numerical model. Direct validation of a numerical model is usually difficult because the same experiments cannot be done on human subjects. This could be because the experiments are related to severe injury, because human subjects are not sufficiently reproducible, because humans are too fatigable or because the outcome is a variable, which cannot be measured. Most invasive research in horses is also precluded by modern ethical standards.

How then do we ensure the validity of scientific studies using computer models? Only indirect methods are available. For this reason, the term validation may be too strong and evaluation should be used instead. First of all, a model should be consistent with observations that can be made on humans. When optimization of performance is carried out, and a realistic movement is obtained, the model is generally considered to be valid because no movement data were used to develop the simulation. When solving the tracking problem, it is expected that, after optimization, all variables are within two standard deviations of the mean. If this is not the case, the model is unable to perform the movement in a sufficiently realistic manner. This should be reason to closely examine the model and make improvements where necessary. Passing this test, however, does not guarantee a valid model. Due to the redundancy of the locomotor system, the model could have found a different solution than the human to achieve the same external movement and force variables. In that case, additional predictions must be elicited from the model, which can then be compared to measurements that were not used for development of the model. This is especially important when the tracking problem is solved. We recommend testing the response of the model to controlled interventions and compare that response to results of the same experiments on humans. Even when the final application is a study on severe injuries, it is often still possible to evaluate the model dynamics using non-destructive perturbation tests. Care must be taken that these experiments test those aspects of the model that are important for the final application. For development of a model for knee ligament injuries, perturbations of initial conditions were used to evaluate the validity of the model (McLean et al., 2003). Finally, a model should not be overly sensitive to errors in model parameters. Critical model parameters can be identified by sensitivity analysis: each parameter is adjusted by a small amount and the change in the results of the simulation is examined. In some cases, this will show that certain model parameters are too critical and the results of a simulation study would depend entirely on a random error in such a parameter. In certain cases, optimization methods are helpful. In a quasi-static model of the knee joint, it was found that the behavior was sensitive to the lengths of the ligaments (Blankevoort & Huiskes, 1996). Solving the tracking problem then eliminated these unknown parameters. Ligament lengths, which minimized the difference between simulated and measured movements, were found and these values were used for subsequent applications of the model.

Another powerful safeguard against overly sensitive models is statistical analysis. Experiments on humans or animals are never performed on a single individual because one individual may not be representative of the population. Statistical analysis is performed to ensure valid generalizations. When using complex musculoskeletal models, the same principle should apply. These models have many degrees of freedom, many natural frequencies, and are often unstable and chaotic. Results from a single model could well be completely irrelevant.

In a simulation study on the effect of shoe hardness on impact forces in running, both positive and negative responses were found in a group of models (Wright et al., 1998). By examining the model, this could be attributed to two mechanisms, which worked in opposite directions. Impact forces tend to increase initially with harder material. This then increases the rate of knee flexion, resulting in a better shock absorption by the body. In subjects with a certain movement style, the latter mechanism resulted in overcompensation.

Statistical analysis showed no significant effect for the population as a whole, confirming earlier results on human subjects. Thus, statistical analysis prevented incorrect generalizations, which could have been made when just one model had been used. In this case, the model was sensitive to movement style. Sensitivities to other variations within the human population, such as anatomical variations, may be detected or eliminated similarly, by creating a population of models with the appropriate range of parameter values. Note, however, that modeling and simulation are sometimes used specifically to determine the influence of inter-subject variations, and in such case the statistical approach is not appropriate. In summary, simulation experiments only tell the truth about the model that was used. Generalization to the human population is always hazardous and requires extensive validation and careful examination of the results.

Practical applications

The field of biomechanical movement simulation has matured sufficiently to allow its use in answering certain basic and applied questions on human movement, but for the equine species this development is still in its infancy, despite the work of Van den Bogert et al. (1989) and Van den Bogert & Schamhardt (1993). The best-developed areas of application are gait and sports injuries. In gait, the functional role of muscles has been identified by solving the tracking problem in a forward dynamic model, followed by an induced acceleration analysis (Neptune et al., 2001). Minimum energy optimizations have produced realistic movements, suggesting that minimal energy is the governing principle of human gait (Anderson & Pandy, 2001). In sports medicine, simulation has shown how the effect of foot orthoses on knee joint mechanics can differ between subjects (Neptune et al., 2000). Simulation has perhaps its greatest impact in the area of acute injuries, where no human experimentation is possible, although this would open perspectives for the use of the equine species being a model for these human injuries. Nonetheless, there is a long history of increasingly realistic passive human movement simulations in vehicle collisions. With active muscle models and optimization in realistic musculoskeletal models, these techniques are now becoming feasible for studies on knee and ankle ligament injuries during sports (Wright et al., 2000; McLean et al., 2004). Although the basic methodologies are quite straightforward, the complexity of modeling required for these applications is still beyond the capabilities of most laboratories. Van den Bogert & Nigg (2007) expect, however, that commercial and user-friendly software will become available to make the technology more accessible in the near future for human applications and eventually on the long run for use in the horse; in the equine species animation seems a more likely application in the short term.

Development of computer animation: an equine perspective

Introduction

The movement of horses has always been an object of intense interest, not only in modeling and simulation (Van den Bogert et al., 1989; Van den Bogert & Schamhardt, 1993), but also in animation. In the Scientific American of 1861 was a report on a horse race on stage, in which horses were galloping on a treadmill and a synchronously rolling curtain behind the horses was depicting the scenery from a local racetrack (Fig. 20.12). The early Muybridge experiments in trying to capture the movement of horses (and other animals) on film, started over a debate about the question whether trotting horses have an airborne moment where all four hooves are off the ground or not (Muybridge, 1899). To prove this point

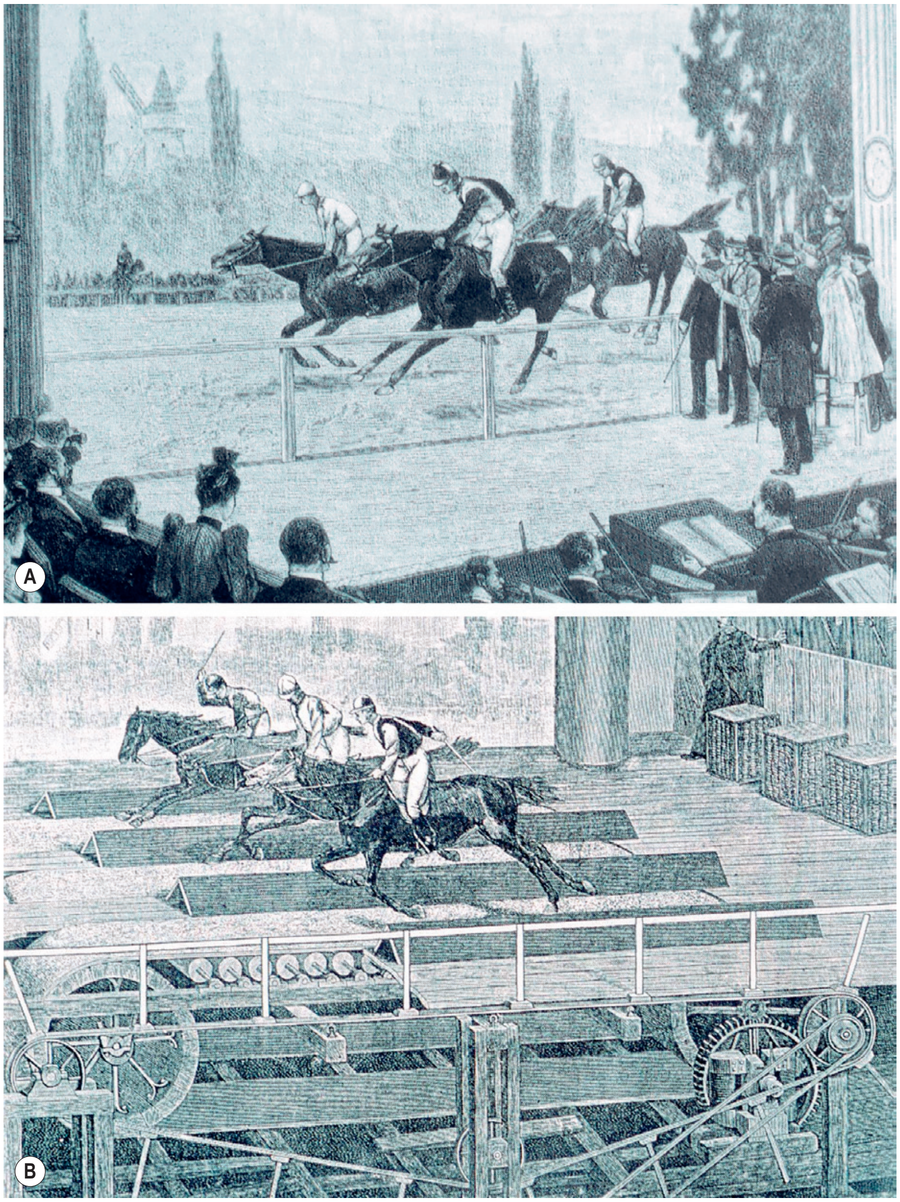


Fig 20.12 Treadmill for animation: a horse race on stage showing (A) the foreground display and (B) the mechanical background. *Scientific American* (1861).

Muybridge began his experiments with line triggered cameras. His photographs were the first that definitely showed all phases in the horse's gaits. But the interest in understanding the movement of quadrupeds has not become any less intense over the later years (Van de Panne, 2000). Many films and other forms of media entertainment include the movement of all kinds of (virtual) creatures, either in live-motion or in other forms of special effects. These include animated animals, either drawn by hand or by computer, and other CGI (computer generated imagery) effects (Hahn, 2008). Many older and more modern films have featured animated and life-like movements of horses and horse-like creatures, such as *Spirit: Stallion of the Cimarron* (Dreamworks Animation SKG, Glendale CA, USA) and *Avatar* (20th Century Fox, Los Angeles, USA). On the other hand, veterinary medicine is also becoming more and more interested in understanding, capturing and simulating equine movements. Many different devices have been developed to capture equine motion and visualize it in a way that makes in-depth analysis of equine gaits possible. Thus, subtle lameness and asymmetrical use of limbs can be detected and treated earlier or more severe injury may even be prevented. This is an area where many disciplines interact and should work together as there are many cross links between animation for film and animation in the interest of equine medicine.

History

As stated above, there has been a large background in the study of locomotion among scientists. It has only been in the last 120 years or so that certain advanced film tools became available to interested scientists to capture the motion of live animals. As mentioned before, one of the earliest scientists was Eadweard Muybridge (Kingston upon Thames, UK: 1830–1904). He is considered one of the pioneers in the study of animal movement. Muybridge wanted to analyze the specific footfall sequences of horses in different gaits. For this endeavor he used a series of twelve mounted photographic cameras. These cameras were then triggered one at a time as the horse passed them at a walk, trot or canter, thus taking 24 photographs within the short period of time it took for the horse to pass. Muybridge gained fame with his recording of equine movement on photographic film, thus proving horses do have moments in the trot and canter strides when all 4 feet are off the ground. He is often credited as being a pioneer in the science of biomechanics. Although he started his experiments with an extensive focus on equine motion, his studies have included almost all animals and any movement imaginable. Muybridge was also among the early inventors of precursors of film movement, with his zoöpraxiscope. His photographs of animal movement and analysis of animal gaits are used even today as a reference for animators who try to draw correct and life-like animal motions.

Animation is also based on the photographic principle of film. To the human eye, projected images that follow each other very fast (24 per second), seem to become connected and are perceived as a single, moving image. Almost everyone will have had some experience with this in their youth through flipping books where images drawn on successive pages of a book are flipped through at a certain speed at which the images seem to come alive and 'move'. The same principle applies to an animated film: different images are drawn and captured on a film frame, with slightly different poses on each drawing. This means that for every second of animated film, 24 drawings will have to be made. This traditional way of animation is called 'classical or key frame animation' (Thornton, 2004). For every frame a pencil or ink drawing is made and then inked and captured on one frame of film. When all these separate frames/drawings are projected at a speed of 24 frames per second, they become a moving animated film. In these early animation films, there was already much interest in trying to capture the movement of animals as realistically as possible and different techniques were developed for recreating life-like animal movements. In the old days this implied first filming a desired motion, such as walking or trotting, and then projecting it and capturing this motion in drawings by slowing down the film. One of the first developed techniques for helping this process along was called 'rotoscoping'. This process consists of first filming the action played out by real life actors or animals, projecting the filmed images onto a frosted glass pane and tracing over them onto paper, frame by frame. The projector used for the projection of the still images was a rotoscope (Gleicher, 1999).

The rotoscope was invented in 1915 by animator Max Fleischer (Fig. 20.13), who developed it for his animation series *Out of the Inkwell*. It has been used extensively and in many animation films and features such as *Betty Boop* and *Snow White* (Walt E. Disney: 1901 (Chicago)–1966 (Los Angeles)). More recently a computer replaced the rotoscope, but the principle remained unchanged and was a great help for animators in being able to capture difficult and life-like movements, such as dancing. In a way, rotoscoping can be seen as a component of a larger technique: 'motion capture'. Already in classical animation there was a demand for perfecting the movement of both animals and humans in drawings, and also a great need for a proper understanding of the placement of limbs, the correct footfall and angles of the joints. Muybridge's photo series were helpful, but not sufficient reference material. Animators need a lot of data for reference of locomotion and other actions. This is where the motion capture technique appeared on the animation scene. It is basically a matter of recording movement in live-action on film, then translating these movements into a model. This is often done by attaching certain markers (such as reflecting dots or strips) to certain moving points on the subject's body and then translating the motions of these markers into a model that can be used for quantitative gait analysis or used to create an animated version of the subject. These recorded movements can be animated characters (Gleicher, 1999).

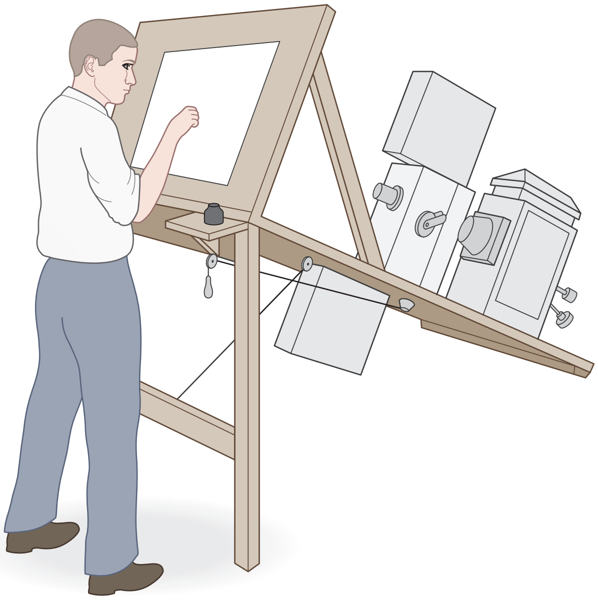


Fig 20.13 The rotoscope was invented in 1915 by animator Max Fleischer.
From Cabarga L (1988). The Fleischer Story. Revised Edition. DaCapo Press: New York.

Modern animation

Besides 'key frame animation' there is also the possibility of 'computer animation'. This form is based upon the same principle as classical animation, but instead of hand-drawing the image on cells, the images are now created in the computer. The advantage of this is that the computer, being programmed with certain algorithms, can 'fill in' missing frames that are between certain key-frames. Key frames are also used in classical animation. They show images of certain key positions of the animated object but movement based only on key frames is jerky so the moments between keyframes need to be filled with images showing intermediate positions between the key frame moments. These images are aptly called 'in-betweens'. One of the advantages of computer animation is that it cuts down the time needed to draw the in-betweens. Computers can also be used for motion capture techniques.

Motion capture

Nowadays the basis for motion capture is still the same as in the early days of classical animation, but a variety of technologies are available for tracking and recording the real-time motion (Menasche, 1999) using multiple markers placed onto animal models or using markerless techniques. The resulting data can be used to generate the movement of a computer-animated model. As Gleicher (1999) puts it aptly 'Motion capture creates a representation that distills the motion from the appearance. It encodes the motion in a form that is suitable for the kinds of processing or analysis that we need to perform'. The technique has developed further and further, to a point where it is now even possible to capture and recreate very subtle and life-like facial expressions with motion capture techniques. This is what was used in films like *Avatar, King Kong* and *Lord of the Rings*.

There are many advantages to motion capture as compared to classical animation: the whole process of capturing movement is more rapid, sometimes even using real-time results. This greatly reduces the cost of animating complex and long movements and allows a large amount of data to be collected in a single session. It facilitates understanding and analyzing complex actions and realistic physical interactions such as secondary motions, weight and exchange of forces.

Many systems are available for motion capture. There is a distinction between real-time, on-line systems where the animation is produced instantly, sometimes also referred to as performance animation, and systems that are not real time (Gleicher, 1999). Real-time motion capture may have applications in veterinary diagnostics, but it needs to be further developed to become more user-friendly and less expensive. For animation purposes, the non-real time motion capture method is more often used as it allows more possibilities for animating production purposes. Many different types of markers (acoustic, inertial, LED, magnetic or reflective) or combinations of any of these can be used to track movements of the points of interest. The same techniques are used in equine motion analysis.

There is also a dichotomy between optical and non-optical systems. Optical systems use data captured from image sensors to triangulate the three-dimensional position of a marker between one or more cameras with over-lapping fields of view. Non-optical systems do not use external cameras or markers that are 'seen' and then translated into data, instead the data are captured directly without an optical data receiver in between. They are based upon several different techniques (Menasche, 1999) and have recently become more popular. Optical and non-optical systems can be further divided into passive and active systems (Mundermann et al., 2006).

Optical systems

Passive markers systems: passive optical systems use highly reflective markers that reflect light back toward the camera's lens. The camera can be adjusted so only the bright reflective markers will be recorded, ignoring other materials such as fabric. Passive systems do not require the subject to wear wires or electronic equipment. The markers are usually attached directly to the skin.

Active optical systems do not use reflective markers but instead emit light information in the form of laser light, light patterns or light pulses, often using small LED illuminators. The system can illuminate one LED at a time in quick succession or multiple LEDs. These illuminated LEDs can then be used to triangulate movements.

Markerless systems. When using markerless systems, the subject does not need to wear markers or a special suit or skeletal system. Special computer algorithms are created to analyze multiple streams of optical input and identify specific forms, making it possible to track them. The data can then be processed using different techniques, for example the motion of an animal can be extracted from a video and then be controlled by using a system called active contouring (Skrba et al., 2008). The model is scaled to match the form of the animal in the video and it is aligned with the video. The contour of this video model is then anchored to the horse model. This means that the model changes the position of its limbs when the horse in the video does this too. Another method that uses markerless, optical techniques is statistical analysis of video images (Skrba et al., 2008). In this method, live video footage of a moving animal is segmented into binary images in order to isolate the foreground subject from the background. It can be applied to the recognition of animal movement within wildlife (Skrba et al., 2008). This technique and other similar ones still have their limitations in creating a life-like motion capture model since the data are not always suitable for use in the simulation of three-dimensional animal characters. Nonetheless Wilhelms & van Gelder (2003) already indicated that automatic tracking with active contours could be used successfully for moderately slow movements and where the background is relatively simple. This is relatively easily arranged in the controlled circumstances of a clinical setting.

Non-optical systems

Mechanical motion capture systems are often referred to as *exo-skeleton motion capture* systems, due to the way the sensors are attached to the body. Instead of small markers, a skeletal-like structure is attached to the subject's body. When the subject moves their body and joints, the exo-skeleton moves simultaneously, mirroring the placements of limbs and angles of joints. There are obviously some restrictions to this technique when applied to animal movement (Fig. 20.14).

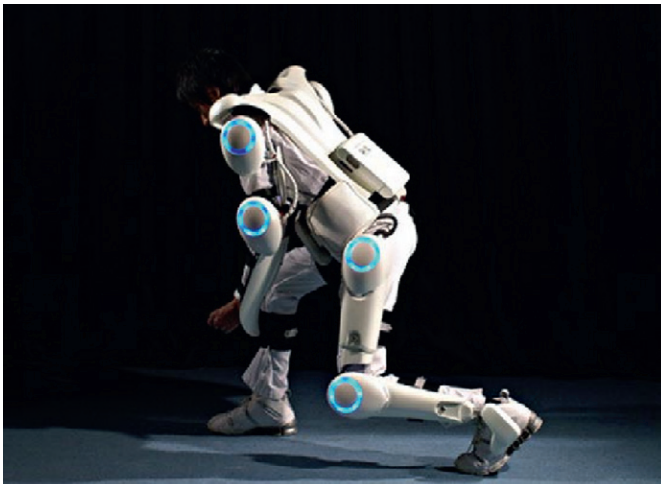


Fig 20.14 A typical example of a so-called 'exo skeleton' motion capture technique.
From www.solomonia.com.

Magnetic systems use transmitters that establish magnetic fields within a space, and then use sensors that can determine their position and orientation within the space based on these fields (Gleicher, 1999).

For entertainment purposes there are some downsides to the use of motion capture. There is the problem of attaching markers to a hairy, moving and sometimes even wild animal. These markers have to be small enough to not influence the movement of the joints that they are attached to, but sturdy and noticeable enough to be 'seen' by cameras and other capturing systems. As with the use of motion capture and analysis for other purposes, artifacts due to skin displacement (Van Weeren et al., 1990) or neurosensory stimulation (Mundermann et al., 2006; Clayton et al., 2008) can yield motion patterns that do not reflect natural patterns of movement. Another challenge is to persuade the animal to perform the desired movement in a restricted space that the cameras or other capturing systems are able to cover. Dogs and horses can be trained to perform specific required movements and can also be taught to walk and run on treadmills. Another limitation is that real animals can only perform movements that follow the laws of physics, which may not be sufficient for entertainment purposes. However, motion capture techniques can be used as a basis and supplemented by computer animation and CGI to achieve what is physically impossible for a live animal. There is also the disadvantage of cost: although the actual time needed to animate a movement can be greatly reduced, it is necessary to buy or develop specific hardware and software that are required to obtain and process the data. This obviously requires financial investment. Finally, traditional animation techniques, such as secondary motion or manipulating the shape of the character, as with squash and stretch animation techniques, must be added later.

New techniques are constantly being developed that can be applied to film, animation, and games. It is anticipated that these advances will facilitate the application of motion capture techniques for veterinary uses by eliminating the need for a treadmill, the attachment of multiple markers and very controlled locomotion circumstances for useful analysis of gaits (Fig. 20.15).

There are many great ways in which the animation and motion capture techniques that are being developed for the entertainment industry can be applied for veterinary diagnostic purposes and vice versa. A great example of this interdisciplinary approach to equine movement is the use of a live-action horse for the creation of a mix of CGI adapted live-action movement and a digitally animated horse model in a feature film. The way the entertainment industry and the veterinary world can work together in a mutually beneficial way is shown in the example of the film *SINT*, a Dutch horror film made in 2010 (http://www.sintdefilm.com) that uses footage of a live-action galloping horse to create a spectacular chase sequence over the roofs of Amsterdam. It is interesting to briefly discuss how this process was created as it vividly demonstrates the intersection of science and entertainment and the way these two disciplines can learn and benefit from each other. Seeing how an animated horse is created from the movements of a real one, and how this animated model can be used to perform actions that the original horse never did, may help us to see new approaches to clinical gait analysis and lameness examination.

Fig 20.15 Dr. Hilary Clayton rides her horse MSU Magic J, who is wearing a blanket covered with predefined, anatomical markers, in front of an infrared motion capture system to develop an animation of the gaits of dressage horses.

The scenes were storyboarded well ahead of shooting and were used as a basis to guide the horse selection and training. A suitable horse was selected on the basis of being easy going and willing to keep up a steady rhythm in each gait while being ridden on the treadmill. For the recording session, the horse was positioned on the treadmill and the rider was attached to a safety harness. After some trial runs, the horse and rider were filmed at different gaits (walk, trot and canter) and from many different angles (Fig. 20.16). The treadmill area was shielded in green covers to provide an even green background to facilitate replacing the background with the rooftops of Amsterdam later on. Additional horses were filmed in a large film studio, running past a 50 × 10 m green screen, or on set pieces made to look like rooftops.

The horse and rider and their movements were then cut out of the (green) environment around them. This was done frame by frame and created a cut-out figure of horse and rider without any background. The next step involved matching the camera angle of the horse footage to footage of the rooftops of Amsterdam. This involved re-calibrating all the frames using three-dimensional camera tracking software, resulting in a new virtual camera. The next stage involved creating a whole new, CGI background involving rooftops and snow. This CGI background was then filmed with the virtual camera created earlier. The moving, cut-out horse and rider were inserted into this newly created background, then moving elements were added like hoof prints, snow reacting to the horse and falling snow. Finally, color correction was applied to the whole sequence. The final result shows a spectacular ride of the horse and rider galloping over snowy rooftops in Amsterdam, while being chased by police cars on the streets below (Fig. 20.17).

In addition to footage of the live-action horse and rider in this chase sequence, a small part of the scene consists of a computer animated horse model, instead of the live action horse. This is the part where the horse loses its footing and slides down a diagonal rooftop, hitting a chimney, regains its footing and continues on at full speed. This was an action that could not safely be performed by a real horse, so the sequence had to be animated completely. This

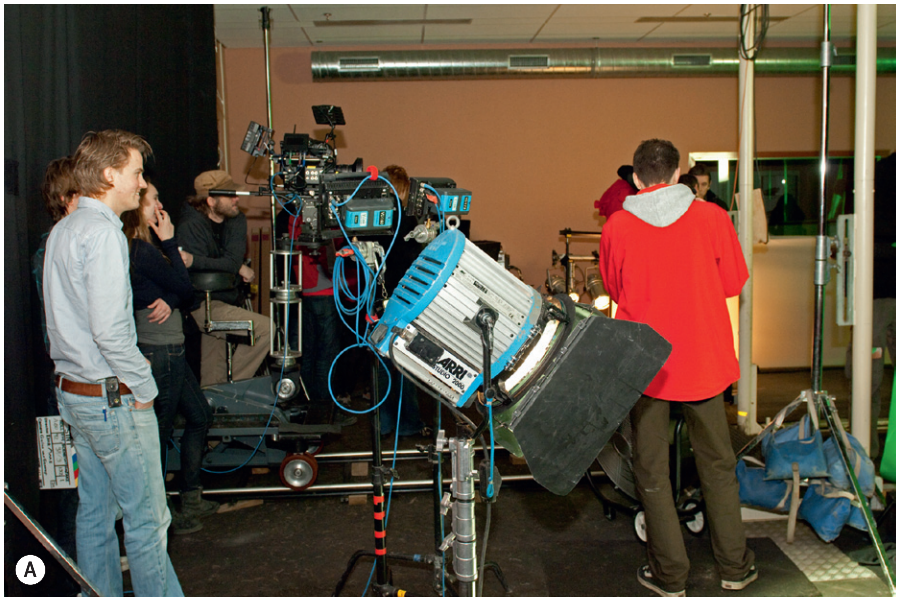


Fig 20.16 Recording on treadmill in small green room: (A) camera stationary setup, (B) treadmill, (C) camera swing setup, (D) light setup and (E) video result.

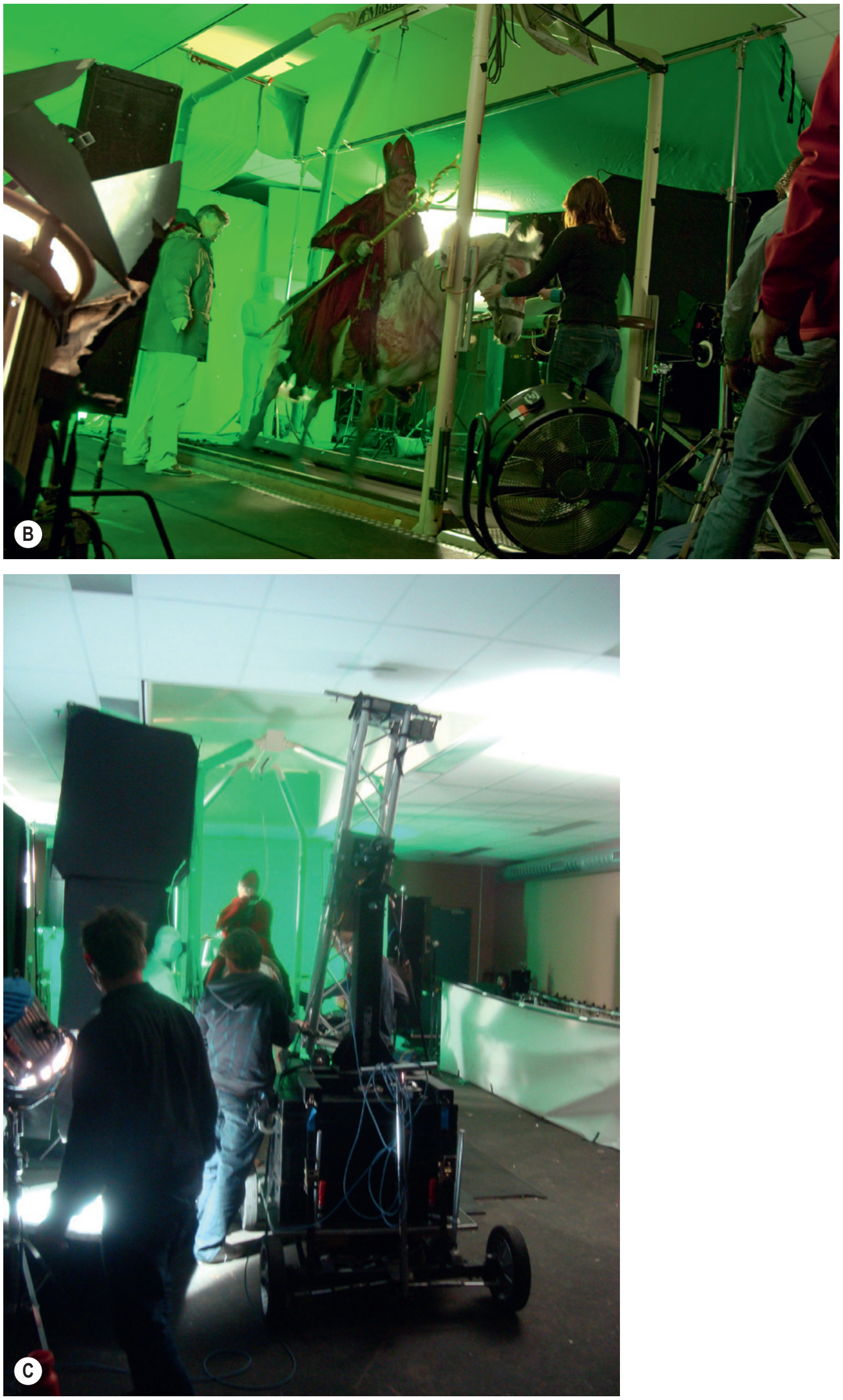


Fig 20.16 *Continued*

Fig 20.16 *Continued*

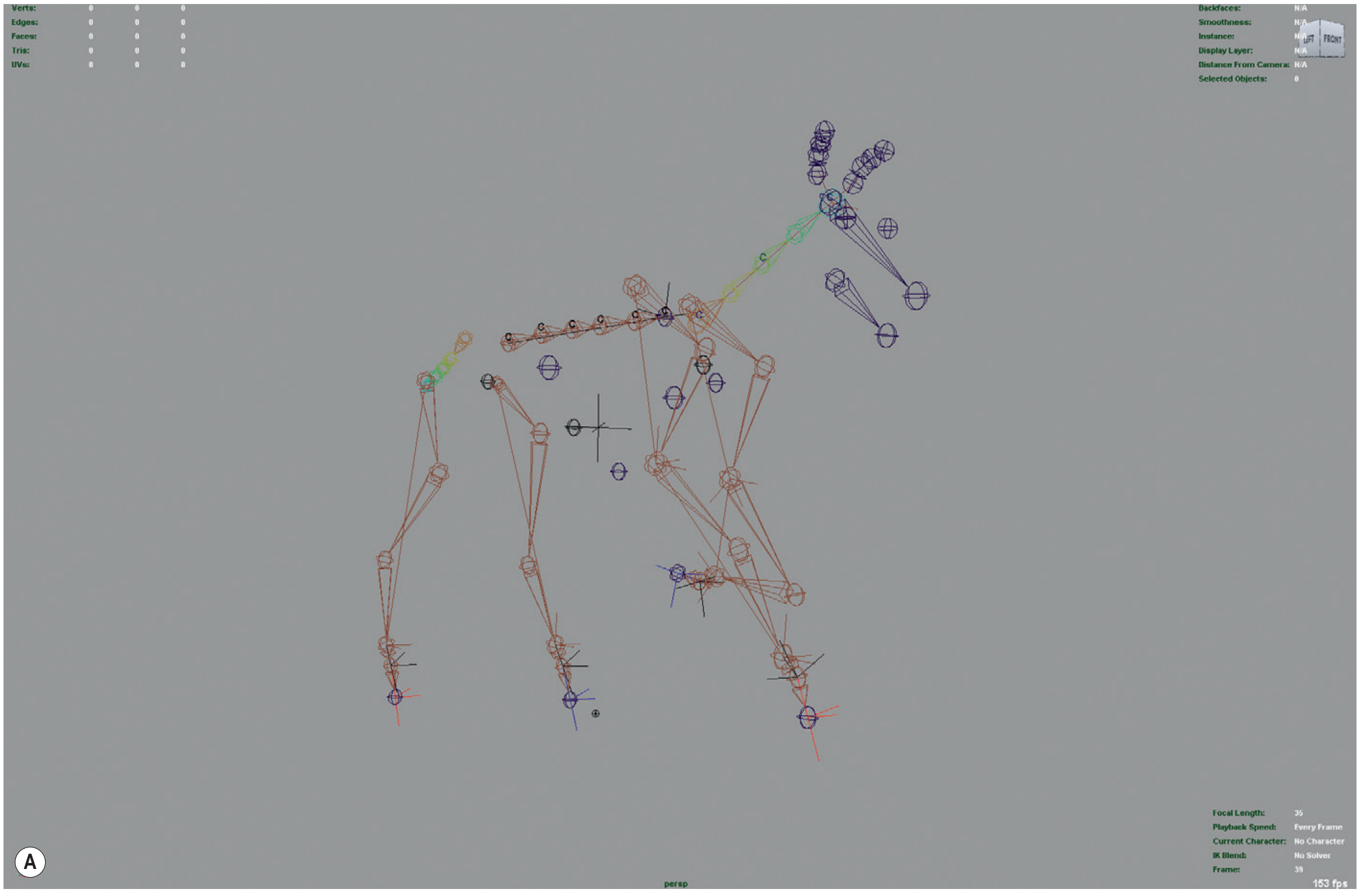
process is a lot more time-consuming to create and thus more expensive than the live-action movements. A completely animated horse model can be used to create almost life-like movements, including ones that have not been seen before. The creativity and correct anatomical knowledge of the animators is the essential ingredient in making these animated movements, as there often is no example that makes the desired movement exactly the way it has to be made.

The way to create an animated horse model starts with the basics, often going back to anatomical books. Skrba et al. (2008) provides an overview of animation methods that are used for quadruped animation. The first step involves creating an animation skeleton, often called IK (inverse kinematics) skeletons (Fig. 20.18). These IK skeletons are not as precise and detailed as a real skeletal structure, but they are a way to control the animated model and making it move according to physical laws. They are a simplified version of the anatomical skeleton; not every joint has to be included, only the primary moving joints. Skrba et al. (2008) defines it as a hierarchy of local reference frames, each frame corresponding to a joint. Relations and hierarchies between the joints are programmed, often based on real anatomical 'laws'. Examples are the directions and ranges of motion and whether the movement of one joint, influences movement of other joints. For example, the effect of the reciprocal apparatus in the equine hind limb that synchronizes flexion of the stifle, hock and fetlock joints. After the IK skeleton is finished, the model can be viewed from any direction as it moves. Just having the IK skeleton of a moving horse is not sufficient, so the next step involves adding 'body' to the model and adding 'skin' to the body in a process called modeling, or creating a mesh model. Horse meshes can be created by an artist or bought online. The IK skeleton is bound to a mesh and rules are created determining how much of the mesh is influenced by each IK bone. Finally, controls are created in a process called 'rigging' that enables the animator to control the horse's 'acting' intuitively.

After these rules or laws have been programmed, the creative work begins. For each frame it has to be decided which parts of the model need to be moved, in which direction and how much. This is a

Fig 20.17 Story board (A) of the rear view and screen shot (B) of the front view of a spectacular scene in which horse and rider gallop over snowy rooftops in Amsterdam while being chased by police cars on the streets below.

From www.sintdefilm.com.



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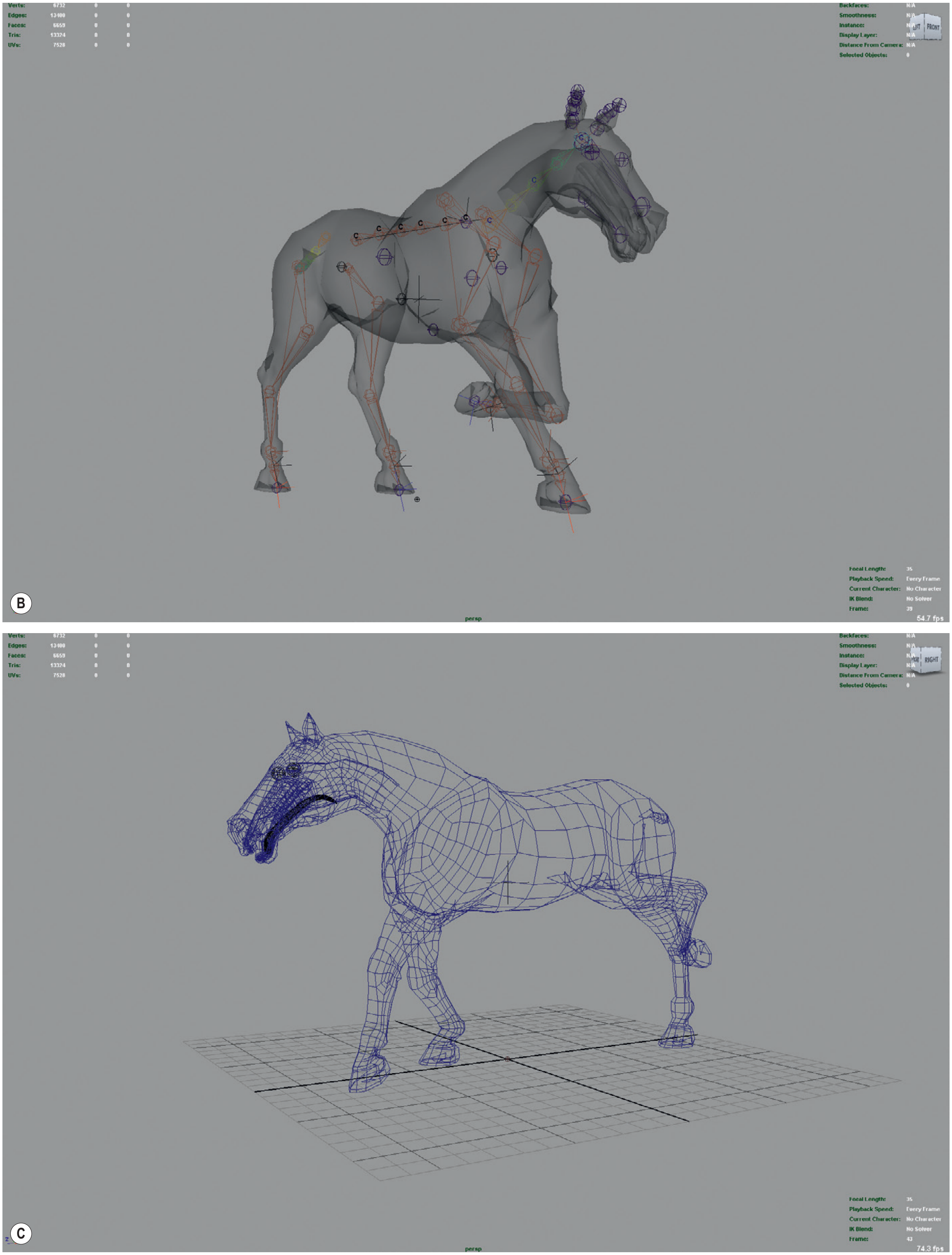
Selected Objects: 0

Focal Length: 35
Playback Speed: Every Frame
Current Character: No Character
IK Blend: No Solver
Frame: 39

Fig 20.18 The 'Rhett' model by Tim Mayo and Chris Carson. (A) Defining the IK skeleton, (B) adding a mesh body to the skeleton, (C) setting bone influence rules and (D) tuning rigging controls.

From www.noxlabs.com.



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UVs:         7528   0   0
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```
Backfaces:              N/A
Smoothness:             N/A
Instance:               N/A
Display Layer:          N/A
Distance From Camera:   N/A
Selected Objects:       0
```

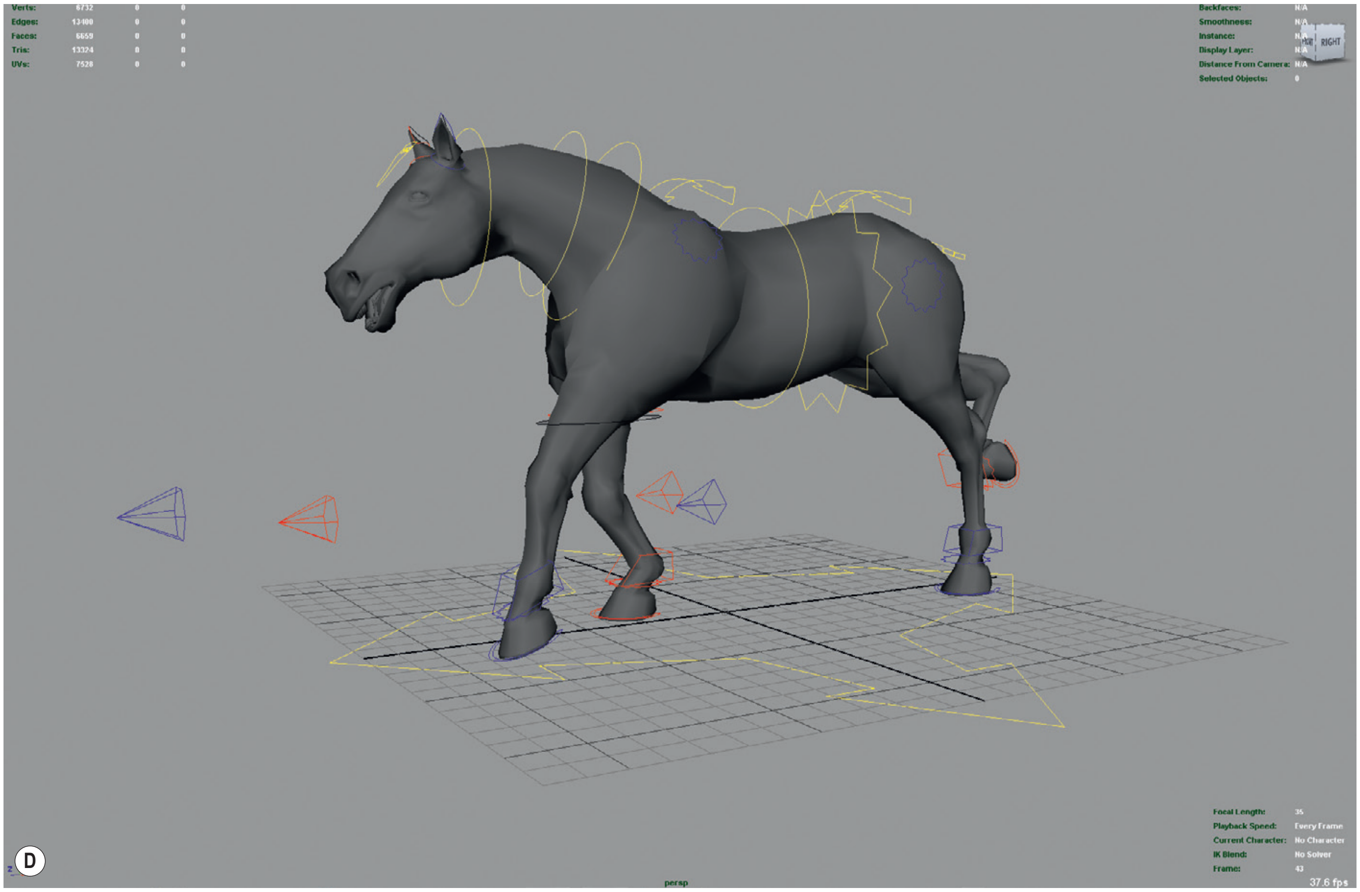
```
Focal Length:         35
Playback Speed:       Every Frame
Current Character:    No Character
IK Blend:             No Solver
Frame:                39
                        54.7 fps
```

```
Verts:       6732   0   0
Edges:      13400   0   0
Faces:       6659   0   0
Tris:       13324   0   0
UVs:         7528   0   0
```

```
Backfaces:              N/A
Smoothness:             N/A
Instance:               N/A
Display Layer:          N/A
Distance From Camera:   N/A
Selected Objects:       0
```

```
Focal Length:         35
Playback Speed:       Every Frame
Current Character:    No Character
IK Blend:             No Solver
Frame:                43
                        74.3 fps
```

Fig 20.18 *Continued*



Verts: 6732 0 0
Edges: 13400 0 0
Faces: 6659 0 0
Tris: 13324 0 0
UVs: 7528 0 0

Backfaces: N/A
Smoothness: N/A
Instance: N/A
Display Layer: N/A
Distance From Camera: N/A
Selected Objects: 0

Focal Length: 35
Playback Speed: Every Frame
Current Character: No Character
IK Blend: No Solver
Frame: 43
37.6 fps

Fig 20.18 *Continued*

combination of intense anatomical knowledge, lots of data and reference materials (often Muybridge's photographs are consulted for specific gaits and body posturing) and talent of the animator. After the main movements have been programmed, the computer can fill in the in-betweens. After this the animation process still involves a lot of cleaning-up and addition of small details, such as rippling of the skin, light fall, movement of hair, mane and tail, that give the animation a feeling of reality.

All this work combined results in a 2-min chase scene with footage that was partly shot of a real horse galloping on the treadmill, in the studio and partly made up of an animated horse model.

If we consider the potentials for veterinary use, then the possibilities are exciting. Imagine shooting video of a patient with a suspected lameness, loading it into a computer program and seeing a model of the movement of that horse and being able to view it from every angle or monitoring progression of lameness by comparing or overlapping images taken at different points in time or quantify the reduction of lameness after treatment. As long as we are able to see the potential in the developments of the entertainments industry (Moeslund et al., 2006) and have the ability and willingness to look over the boundaries of veterinary medicine, then the possibilities for future collaborations are endless.

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