Part III
Ergonomics and Human Factors Engineering

Handbook of Loss Prevention Engineering, First Edition. Edited by J. M. Haight.

15

Biomechanics and Physical Ergonomics

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15.1

Introduction

Work-related musculoskeletal disorder (WMSD) is common in industry (Chung, Lee, and Kee, 2003). WMSD causes pain, soft tissue disorder, and articular injury to the musculoskeletal system (Sommerich and Marras, 2006). WMSD can occur in most body parts; however, it is more frequent in the back and hand, such as back pain, carpal tunnel syndrome (CTS), trigger finger, and hand–arm vibration syndrome (Putz-Anderson, 1988). The risk factors of developing WMSD include excessive strength, awkward posture, repetitive use of certain body parts, vibration, and hot and cold temperatures. WMSD accounts for 30.5% of all lost-workday injuries and illnesses in 2010, according to the US Bureau of Labor Statistics (BLS, 2011). Hence many ergonomics researchers are trying to prevent WMSD by assessing physical workload with biomechanics.

Biomechanics is the discipline which describes, analyzes, and assesses human movement on a basis of the knowledge of physics, chemistry, mathematics, physiology, and anatomy (Winter, 2009). Biomechanics concerns the mechanical behavior and component tissues of the musculoskeletal system when physical work is performed. The application of biomechanics principles is important in the prevention of WMSD to improve working conditions and performance. This chapter provides a description of some of the fundamental biomechanics of the trunk, wrist, and hand and its applications in ergonomics.

15.2

Biomechanics

Biomechanical analysis of human movement can be divided into kinematics, kinetics, anthropometry, and electromyography (EMG), as shown in Figure 15.1 (Hall, 2006). Kinematics uses displacement, velocity, and acceleration to describe a body movement in a space. Kinetics is described as internal and external forces and moment that cause the movement. In order to perform kinematic and kinetic

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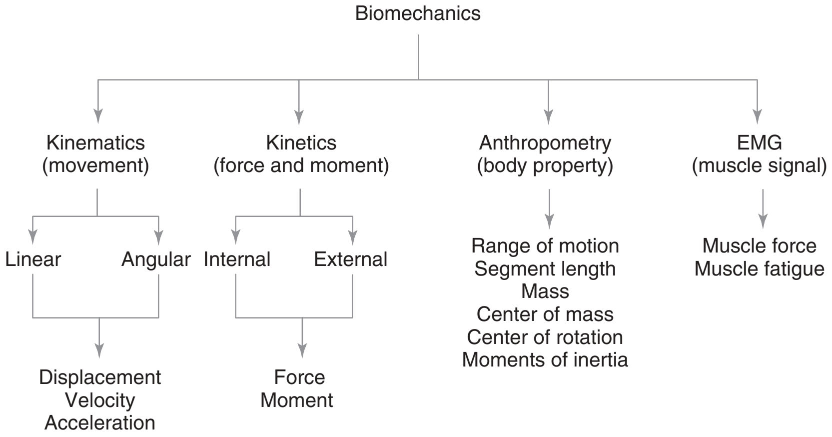

Figure 15.1 Biomechanics analysis of human movement.

analyses, anthropometric factors need to be considered including anatomy and mechanics of the human body, such as range of motion (ROM).

EMG is a signal collected from muscles to describe their activities. Information obtainable from EMG signals can estimate muscle force and fatigue. Muscle force is proportional to the amplitude of an EMG signal in a time domain. Muscle force can be quantified by processing the signal with rectification, linear envelope, integration, root mean square, and so on. Similarly, muscle fatigue is proportional to EMG signal power shift to low frequencies in a frequency domain. Muscle fatigue can be quantified by processing the signal with mean power frequency, median frequency, and zero-crossing rate.

15.2.1
Trunk Biomechanics

15.2.1.1 Trunk Anatomy

The trunk contains the spinal column, rib, sternum, and pelvis. The spinal column has 26 vertebrae that comprise seven cervical vertebrae, 12 thoracic vertebrae, five lumbar vertebrae, sacrum, and coccyx (Figure 15.2). The cervical vertebrae take part in neck motion, whereas the thoracic and lumbar vertebrae take part in trunk motion. There are many trunk muscles, but ergonomics often focuses on the major low back muscles of the erector spinae, latissimus dorsi, external oblique, internal oblique, and rectus abdominis (Figure 15.3).

15.2.1.2 Trunk Range of Motion

The ROM is a basic anthropometric measurement for the functionality of a body segment. The measurement is generally performed by using measuring tape, goniometer, or motion capture system.

Using the trunk muscles, the trunk performs the movements of flexion/extension, left/right lateral flexion, and left/right rotation. The trunk flexes up

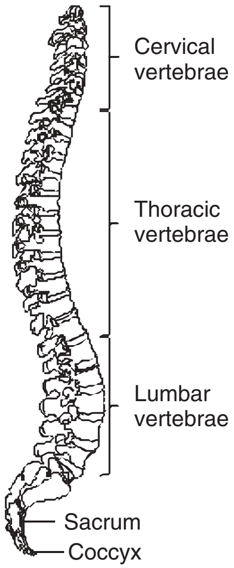

Figure 15.2 Spinal column.

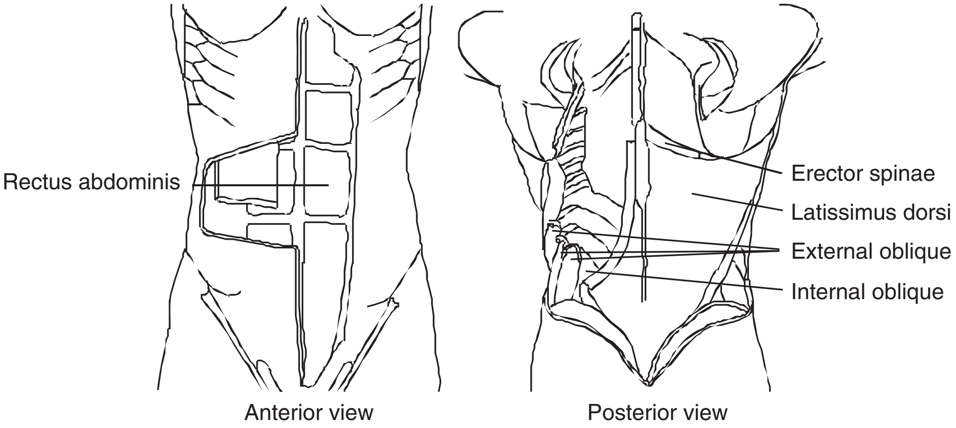

Figure 15.3 Trunk muscles.

to 58° and extends up to 15°. It can also laterally flex up to about 35° and rotate up to about 60° (Table 15.1).

15.2.1.3 **Trunk Biomechanics Model**

Chaffin (1975) developed a computerized biomechanical model to estimate force and moment at the disc between the fifth lumbar vertebra (L5) and the first sacral vertebra (S1) when a worker performed a load-lifting task (Figure 15.4). Since this model could explain the task only in the sagittal plane, more complex models have been developed for asymmetric lifting in three-dimensional planes (Chaffin, 1997).

Table 15.1 Means (with standard deviations in parentheses) of the range of motion of the trunk (°) (Doriot and Wang, 2006).

Group	Flexion	Extension	Left lateral flexion	Right lateral flexion	Left rotation	Right rotation
Young women	63 (14)	9 (17)	35 (9)	36 (7)	61 (15)	61 (11)
Young men	59 (10)	24 (14)	37 (9)	42 (7)	67 (12)	66 (10)
Old women	57 (19)	8 (18)	21 (8)	27 (9)	52 (12)	50 (12)
Old men	51 (19)	20 (18)	26 (10)	32 (7)	58 (6)	55 (13)
Mean	58 (16)	15 (18)	31 (11)	35 (9)	60 (13)	58 (12)

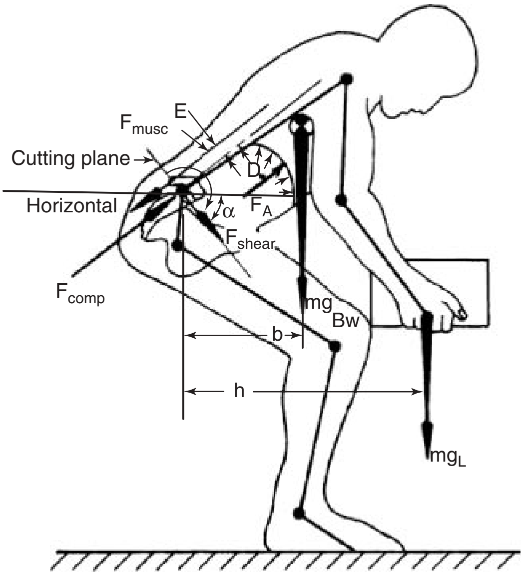

Figure 15.4 Example of trunk biomechanics model (Chaffin, 1997).

15.2.1.4 **Trunk Electromyography**

Many studies have estimated trunk muscle force and fatigue in various activities (Table 15.2). One of the continuing challenges in biomechanics has been to assess spinal loading during dynamic lifting exertions. Marras and Granata (1997) developed an EMG model to simulate multi-dimensional spinal loads and trunk moments from measured muscle coactivity and external forces.

15.2.2
Wrist Biomechanics

15.2.2.1 **Wrist Anatomy**

The wrist has eight small carpal bones, trapezium, trapezoid, capitate, hamate, scaphoid, lunate, triquetrum, and pisiform, at the ends of the forearm bones of the

Table 15.2 Study examples of the trunk by EMG.

Estimate	Study	Muscle and activity
Muscle force	Anders *et al.* (2008)	Trunk muscles at several angles of flexion and extension
	Butler, Hubley-Kozey, and Kozey (2009)	Trunk muscles during a symmetrical lift task
	Chow *et al.* (2003)	Trunk muscles for sudden release of load during lifting
	Lariviere *et al.* (2000)	Trunk muscles during flexion/extension and lateral flexion
	Shin and D'Souza (2010)	Low back extensor muscles during cyclic flexion and extension
Muscle fatigue	Coorevits *et al.* (2008)	Right low back muscles during isometric back extension
	Farina, Gazzoni, and Merletti (2003)	Trunk muscles during flexion
	Grondin and Potvin (2009)	Trunk muscles during sudden loading
	Kumar *et al.* (2001)	Trunk muscles during rotation
	Lariviere *et al.* (2002)	Low back muscles during static extension
	Shin and Kim (2007)	Trunk muscles during dynamic lifting and lowering

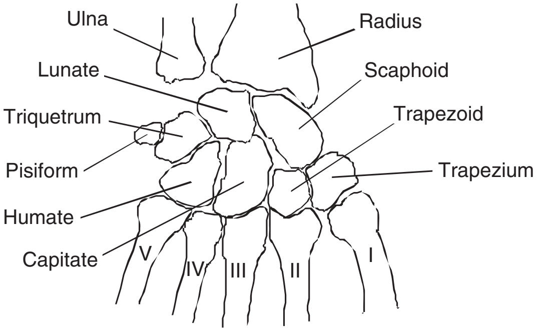

Figure 15.5 Wrist bones.

radius and ulna (Figure 15.5). The major wrist muscles are the flexor carpi radialis (FCR), palmaris longus (PL), flexor carpi ulnaris (FCU), extensor carpi radialis (ECR), and extensor carpi ulnaris (ECU) (Figure 15.6).

15.2.2.2 **Wrist Range of Motion**

The wrist has the movements of flexion/extension and radial/ulnar deviation. On average, the wrist flexes up to 67° and extends up to 66°. It can deviate up to 23° radially and 38° ulnarly (Table 15.3).

15.2.2.3 **Wrist Biomechanics Model**

Armstrong and Chaffin (1978) developed a pulley model to estimate tendon force for the wrist flexion and extension (Figure 15.7). The arc and radius of tendon around

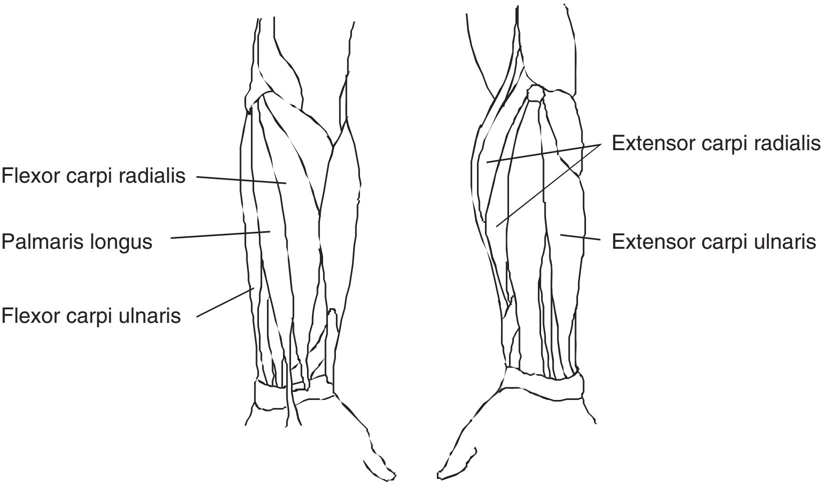

Figure 15.6 Wrist muscles.

Table 15.3 Range of motion of the wrist (°).

Study	Flexion		Extension		Radial deviation		Ulnar deviation	
	Male	Female	Male	Female	Male	Female	Male	Female
Chung and Wang (2009)	64	67	55	58	—	—	—	—
Doriot and Wang (2006)	43	45	60	61	20	20	22	25
Glanville and Kreezer (1937)	93	—	60	—	29	—	66	—
Gunal *et al.* (1996)	—	—	59	—	-	—	18	—
Marshall, Mozrall, and Shealy (1999)	67	72	73	79	21	21	47	46
Mean (SD)	67 (21)	61(14)	61 (7)	66 (11)	23 (5)	21 (1)	38 (23)	36 (15)

the wrist was represented by a pulley. Lemy and Crago (1996) also developed a dynamic model to evaluate moment at the wrist by simulating its movement. Loren *et al.* (1996) developed a more complex biomechanical model to calculate wrist flexion and extension strength within its ROM. This model included mechanical and physiological factor of muscle fiber length and muscle cross-sectional area.

15.2.2.4 **Wrist Electromyography**

One of major aims in wrist biomechanics is to assess physical stress in the wrist muscles during various wrist movements within the wrist ROM (Table 15.4). The EMG amplitude of a neutral wrist posture is about 25% of muscle force of a non-neutral posture. The flexor muscles of FCR and FCU have large EMG amplitudes for flexion motion and the extensor muscles of ECR and ECU have

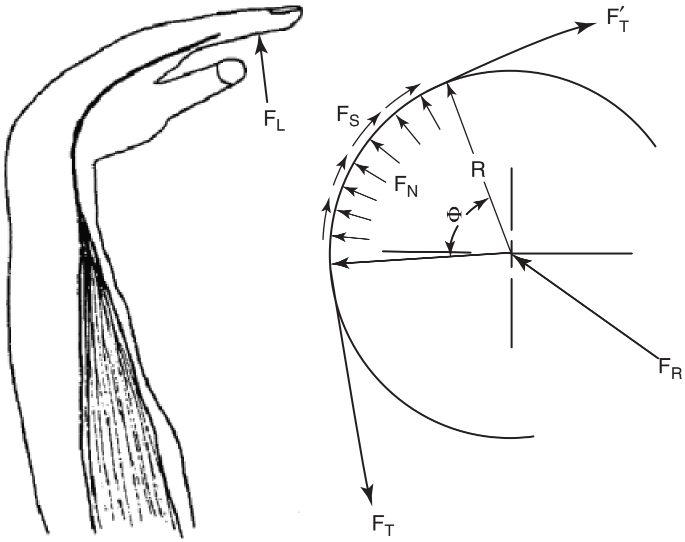

Figure 15.7 Example of wrist biomechanics model (Armstrong and Chaffin, 1978).

Table 15.4 Study examples of the wrist by EMG.

Estimate	**Study**	**Muscle and activity**
Muscle force	Buchanan *et al.* (1993)	Wrist muscles during isometric tasks
	Claudon (2003)	Wrist flexor muscles in neutral, flexion, and extension positions
Muscle fatigue	Chabran, Maton, and Fourment (2002)	Wrist muscles during flexion and extension tasks
	Park and Martin (1993)	Wrist muscles at 10% sub-maximal contraction

large EMG amplitudes for extension motion. Similarly, high EMG amplitudes are observed in FCR and ECR for radial deviation but in FCU and ECU for ulnar deviation (Fagarasanu, Kumar, and Narayan, 2004). Buchanan *et al.* (1993) also proposed a mathematical model to estimate five individual wrist muscles by using an EMG coefficient method.

15.2.3
Hand Biomechanics

15.2.3.1 Hand Anatomy

The hand has five digits called *thumb* (digit 1), *index finger* (digit 2), *middle finger* (digit 3), *ring finger* (digit 4), and *little finger* (digit 5). All fingers have metacarpal bones in the palm and the fingers except the thumb have proximal, middle, and distal phalanges. The thumb has only proximal and distal phalanges (Figure 15.8).

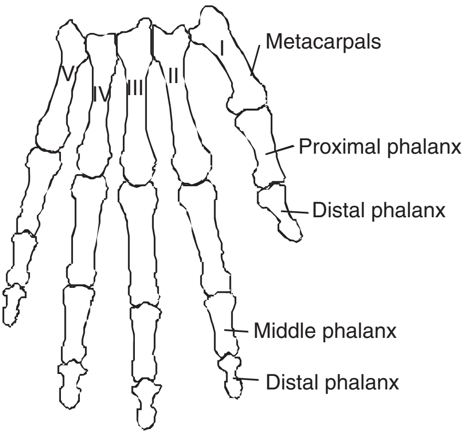

Figure 15.8 Hand bones.

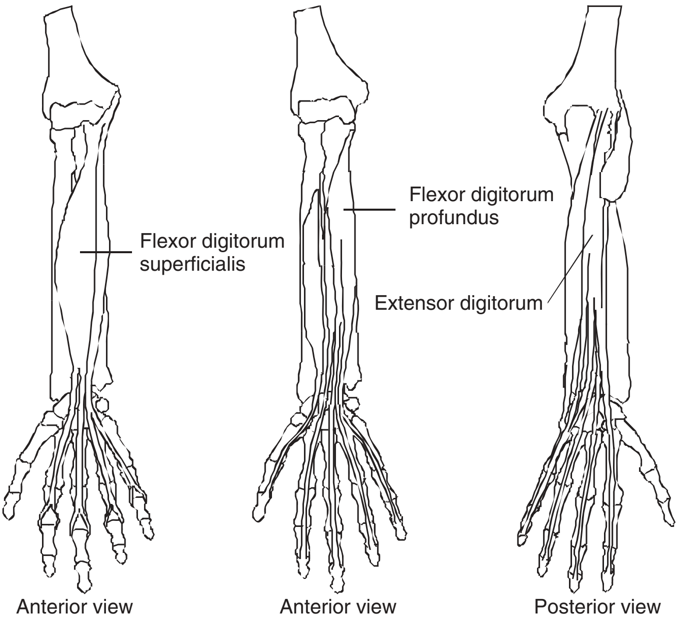

Figure 15.9 Hand muscles.

The fingers except the thumb have a metacarpophalangeal joint (MCP), a proximal interphalangeal joint (PIP) and a distal interphalangeal joint (DIP); however, the thumb has a carpometacarpal joint (CMC), MCP, and interphalangeal joint (IP) (Taylor and Schwarz, 1955). There are many finger muscles in the palm and forearm. Ergonomics generally emphasizes the relatively large muscles of flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), and extensor digitorum (ED) in the forearm (Figure 15.9).

Table 15.5 Range of motion of the finger flexion (°).

Finger	Joint	Becker and Thakor (1988)	Chao *et al.* (1989)	Degeorges and Oberlin (2003)	Swanson (1972)	Yoshida *et al.* (2003)	Zheng and Li (2010)	Mean (SD)
Thumb	CMC	—	53	—	—	—	45	49 (6)
	MCP	—	—	—	—	77	50	64 (19)
	IP	—	—	—	—	81	80	81 (1)
Index	MCP	71	83	97	62	—	85	80 (13)
	PIP	104	101	110	—	—	100	104 (5)
	DIP	61	73	57	—	—	80	68 (11)
Middle	MCP	85	90	100	64	—	—	85 (15)
	PIP	104	103	114	—	—	—	107 (6)
	DIP	74	80	57	—	—	—	70 (12)
Ring	MCP	85	88	107	67	—	—	87 (16)
	PIP	107	105	110	—	—	—	107 (3)
	DIP	67	75	57	—	—	—	66 (9)
Little	MCP	86	90	105	64	—	—	86 (17)
	PIP	99	103	111	—	—	—	104 (6)
	DIP	71	78	58	—	—	—	69 (10)

15.2.3.2 Hand Range of Motion

The IP, PIP, and DIP joints can perform only one movement of flexion/extension. The MCP joint performs two movements of flexion/extension and abduction/adduction. The CMC has three movements of flexion/extension, abduction/adduction, and opposition. However, flexion would be of common interest in ergonomics, as shown in Table 15.5 (Swanson, 1972; Becker and Thakor, 1988; Chao *et al.*, 1989; Degeorges and Oberlin, 2003; Yoshida *et al.*, 2003; Zheng and Li, 2010).

15.2.3.3 Hand Biomechanics Model

The Euler angles are a common method to explain the orientations of body segments including the hand in kinematics (Figure 15.10) (Chao *et al.*, 1989; Chiu *et al.*, 1998; Bennis and Roby-Brami, 2002). Most biomechanics models of the finger have been based on the tendon pulley model of Landsmeer (1949, 1962) in ergonomics to identify finger movements in various hand postures and to predict finger muscle and tendon forces in two-dimensional static conditions.

15.2.3.4 Hand Electromyography

Since the fundamental functions of the hand are gripping and pinching, many studies have examined muscle force and fatigue for these movements (Table 15.6). Keir and Mogk (2005) developed an EMG model to predict gripping force by considering six hand and wrist muscles.

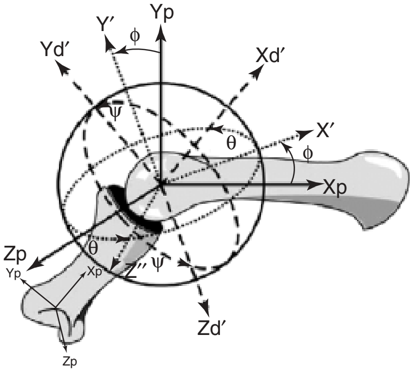

Figure 15.10 Example of finger joint orientations by Euler angles (Su *et al.*, 2005).

Table 15.6 Study examples of the hand by EMG.

Estimate	Study	Muscle and activity
Muscle force	Alves and Chau (2008)	Flexor muscles during pinching
	DiDomenico and Nussbaum (2008)	Hand muscles during gripping
	Hoozemans and Dieen (2005)	Hand muscles during precision and power gripping
Muscle fatigue	Blackwell, Kornatz, and Heath (1999)	FDS during 60–65% sub-maximal contractions
	Hagg and Milerad (1997)	Hand muscles during intermittent gripping
	Soo *et al.* (2012)	Hand muscles during cyclic gripping

15.3
Applications of Biomechanics in Ergonomics

15.3.1
Application of Trunk Biomechanics

Manual material handling (MMH) is a common task in industry. It generally involves lifting, lowering, pushing, pulling, carrying, and holding heavy materials. The low back in the trunk is the most commonly injured body part during MMH. The risk factors causing WMSD during MMH would be associated with load characteristics, physical effort, environmental factor, and individual factors (Hsiang, Brogmus, and Courtney, 1997). Load characteristics include heavy or large objects, improperly designed handles, and manipulation of loads resulting in bending or twisting of the trunk. Physical efforts are a sudden or unstable movement of a load, repetitiveness, and insufficient rest. Environmental factors are related to uneven floors, floor levels, confined spaces, unsuitable ventilations, and hot or cold temperatures. Individual factors contain inappropriate clothing,

Table 15.7 Frequency multiplier (Waters *et al.*, 1993).

Frequency lifts per minute	**Work duration**					
	[≤1]h		**[≤2]h**		**[≤8]h**	
	***V*<75**	***V*≥75**	***V*<75**	***V*≥75**	***V*<75**	***V* ≥ 75**
0.2	1.00	1.00	0.95	0.95	0.85	0.85
0.5	0.97	0.97	0.92	0.92	0.81	0.81
1	0.94	0.94	0.88	0.88	0.75	0.75
2	0.91	0.91	0.84	0.84	0.65	0.65
3	0.88	0.88	0.79	0.79	0.55	0.55
4	0.84	0.84	0.72	0.72	0.45	0.45
5	0.80	0.80	0.60	0.60	0.35	0.35
6	0.75	0.75	0.50	0.50	0.27	0.27
7	0.70	0.70	0.42	0.42	0.22	0.22
8	0.60	0.60	0.35	0.35	0.18	0.18
9	0.52	0.52	0.30	0.30	0.00	0.15
10	0.45	0.45	0.26	0.26	0.00	0.13
11	0.41	0.41	0.00	0.23	0.00	0.00
12	0.37	0.37	0.00	0.21	0.00	0.00
13	0.00	0.34	0.00	0.00	0.00	0.00
14	0.00	0.31	0.00	0.00	0.00	0.00
15	0.00	0.28	0.00	0.00	0.00	0.00
>15	0.00	0.00	0.00	0.00	0.00	0.00

footwear, training, and knowledge (Mital, Nicholson, and Ayoub, 1997). Thus, many ergonomists have concentrated on work-related low back disorders to predict low back stress and to suggest safety guidelines by using trunk biomechanics.

One of widely used guidelines for the prevention of low-back pain is the National Institute of Occupational Safety and Health (NIOSH) lifting equation. The NIOSH first developed the lifting equation in 1981 for sagittal plane lifting and revised it in 1993 to consider asymmetric lifting (Waters *et al.*, 1993). The revised NIOSH lifting equation uses a recommended weight limit (RWL) as follows:

$$\begin{aligned}\mathrm{RWL} = {} & 23\ \mathrm{kg} \times (25/H) \times (1 - 0.003|V - 75|) \times (0.82 + 4.5/D) \times (1 - 0.0032A) \\ & \times FM \times CM\end{aligned}$$

where H is the horizontal distance in centimeters from the ankle to the hand grasp of the load, V is the vertical height in centimeters from the floor to the hand grasp of the load, D is the total distance moved in centimeters between the origin and the destination of the lift, A is the angle in degrees between the sagittal plane and the plane of asymmetry, FM is a frequency multiplier for lifting frequency in Table 15.7, and CM is a coupling multiplier between the hand and the load in Table 15.8.

Table 15.8 Coupling multiplier (Waters *et al*., 1993).

Couplings	$V < 75$ cm	$V \geq 75$ cm
Good	1.00	1.00
Fair	0.95	1.00
Poor	0.90	0.90

NIOSH (2007) also recommended guidelines for safe MMH, some of which are as follows:

- Design workplaces to eliminate unnecessary lifts.
- Use pallets and devices to avoid lifting loads manually.
- Reduce load weight with light containers and fewer materials in the containers.
- Provide workers with enough space to access to loads without awkward postures.
- Reduce lifting frequencies and durations by job rotation with other workers and non-lifting tasks.
- Be alert to unstable and heavy loads before lifting.
- Wear proper shoes and gloves to avoid slips, trips, falls, and excessive grip force.
- Hold loads as close to the body as possible in a neutral posture with a secure grip.

15.3.2
Application of Hand and Wrist Biomechanics

CTS is a common WMSD in the wrist (Putz-Anderson, 1988). Repetitive use of poorly designed hand tools can cause CTS because it results in excessive grip and wrist force and awkward hand and wrist postures. Hand and wrist biomechanics are used to develop ergonomic hand tools in terms of various design factors, such as handle size, handle shape, grip span, and handle material (Pheasant and O'Neill, 1975; Scheller, 1983; Lewis, 1987; Fellows and Freivalds, 1991; Jung and Hallback, 2005).

Jung and Hallback (2002) examined the relationship between grip force and wrist posture. As shown in Figure 15.11, maximal grip force is the highest around a neutral posture (0°) of the wrist and gradually decreases as the wrist either flexes or extends from the neutral posture.

Dong *et al*. (2007) evaluated custom-designed dental scaling instruments by measuring pinch force and EMG amplitudes from hand and wrist muscles (Figure 15.10). Among the instruments, that with a tapered round handle and a 10 mm diameter (TR-10 in Figure 15.12) required less pinch force and muscle load than the instruments with a hexagonal handle and a 7 mm diameter.

Some ergonomics guidelines for the design and use of hand tools to reduce CTS are as follows (Cacha, 1999):

- Keep the wrist straight during the use of hand tools to reduce pressure on the tendons and nerves passing through the carpal tunnel.

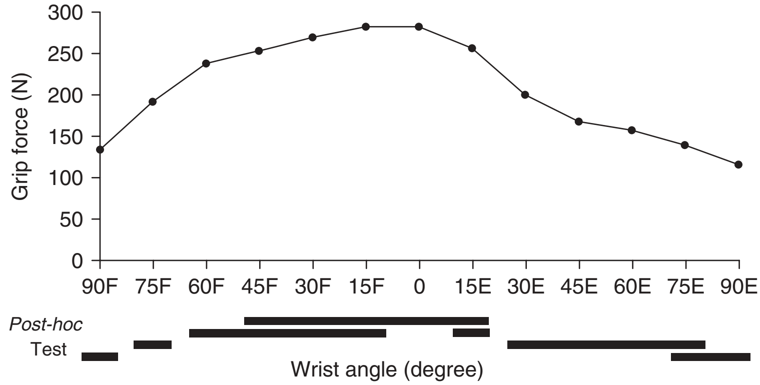

Figure 15.11 Grip force by wrist postures (Jung and Hallback, 2002).

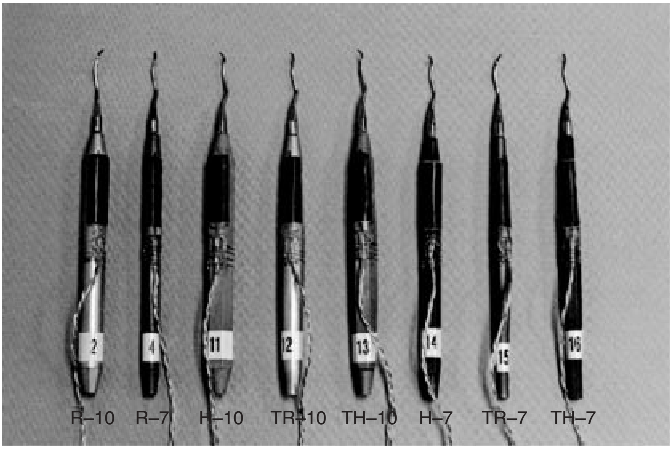

Figure 15.12 Custom-designed dental scaling instruments (Dong *et al.*, 2007).

- Avoid tissue compression on the palm by using the proper handle size and shape covered with compressible materials.
- Provide an optimal grip span to prevent excessive grip force exertion with too small or too large handles.
- Wear proper gloves during the use of hand tools to protect against heat, cold, and vibration.

15.4
Conclusion

Biomechanics is the interdisciplinary study of the mechanical movement and force of the musculoskeletal system, including kinematics, kinetics, anthropometry, and EMG. Physical ergonomics aims at providing a safe working environment for workers. This chapter explains how biomechanics is used in physical ergonomics to assess physical workload and to reduce WMSDs.

Physical ergonomics mainly concerns low-back pain and hand and wrist disorders commonly occurring in industrial workers. This chapter provides a fundamental knowledge of biomechanics for the trunk, wrist, and hand in terms of anatomy, ROM, biomechanical model, and EMG. It also gives exemplary applications of biomechanics to suggest ergonomics guidelines for safe MMH and hand tool design.

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