CHAPTER 40

Physical Tasks: Analysis, Design, and Operation

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1. INTRODUCTION

According to the Board of Certification in Professional Ergonomics (BCPE 21000), ergonomics is a body of knowledge about human abilities, human limitations, and other human characteristics that are relevant to design. Ergonomic design is the application of this body of knowledge to the design of tools, machines, systems, tasks, jobs, and environments for safe, comfortable, and effective human use. The underlying philosophy of ergonomics is to design work systems where job demands are within the capacities of the workforce. Ergonomic job design focuses on fitting the job to capabilities of workers by, for example, eliminating occurrence of nonnatural postures at work, reduction of excessive strength requirements, improvements in work layout, design of hand tools, or optimizing work/rest requirements (Karwowski 1992; Karwowski and Salvendy 1998; Karwowski and Marras 1999).

Ergonomics is seen today as a vital component of the value-adding activities of the company, with well-documented cost–benefit aspects of the ergonomics management programs (GAO 1997). A company must be prepared to accept a participative culture and utilize participative techniques in implementation of work design principles. The job design-related problems and consequent intervention should go beyond engineering solutions and include all aspects of business processes, including product design, engineering and manufacturing, quality management, and work organizational issues, along the side of task design or worker education and training (Karwowski and Salvendy 1999; Karwowski and Marras 1999; Genaidy et al. 1999).

This chapter deals primarily with work analysis and design, as well as related human performance on physical tasks. The information about cognitive and other human performance aspects can be found in other chapters of this Handbook.

2. ENGINEERING ANTHROPOMETRY

Anthropometry is an empirical science branching from physical anthropology that deals with physical dimensions of human body and its segments, such as body size and form, including location and distribution of center of mass; segment lengths and weights; range of joint movements; and strength characteristics. Anthropometric data are fundamental to work analysis and design. Engineering anthropometry focuses on physical measurements and applies appropriate methods to human subjects in order to develop engineering design requirements (Roebuck et al. 1975). Anthropometry is closely related to biomechanics because occupational biomechanics provides the criteria for the application of anthropometric data to the problems of workplace design (Pheasant 1989).

Anthropometry can be divided into two types: physical anthropometry, which deals with basic dimensions of the human body in standing and sitting positions (see, e.g., Tables 1 and 2), and functional anthropometry, which is task oriented. Both physical and functional anthropometry can be considered in either a static or dynamic sense. Static analysis implies that only the body segment lengths in fixed position will be considered in workplace design. Dynamic analysis requires that acceptability of design be evaluated with respect to the need to move the body from one position to another, as well as the reach and clearance considerations.

An example of the important dynamic data for workplace design is range of joint mobility (Table 3) which corresponds to postures illustrated in Figure 1. Very useful anthropometric data, both static and dynamic, are provided by the Humanscale (Henry Dreyfuss Associates 1981). When anthropometric requirements for the workplace are not met, biomechanical stresses, which may manifest themselves in postural discomfort, low back pain, and overexertion injury, are likely to occur (Grieve and Pheasant 1982). Inadequate anthropometric design can lead to machine safety hazards, loss of motion economy, and poor visibility. In other words, the consequences of anthropometric misfits may of be a biomechanical and perceptual nature, directly impacting worker safety, health, and plant productivity.

2.1. Description of Human Body Position

The anatomical body position depicts a person standing upright, with feet together, arms by the sides, and with palms forward. As a reference posture, this position is symmetrical with respect to so-called *mid-sagittal plane*. All planes parallel to it are also called *sagittal*. The vertical plane perpendicular to the sagittal is called the *coronal* plane. The horizontal (or *transverse*) plane is perpendicular to both the sagittal and coronal planes. Definition of planes of reference are especially important when the body is in other than the anatomical position.

According to Grieve and Pheasant (1982), terms of *relative* body position can be defined as follows. The *medial* and *lateral* positions refer to nearer to or farther from the mid-sagittal plane. The *superior* or *inferior* positions refer to nearer to or further from the top of the body. The *anterior* (*ventral*) and *posterior* (*dorsal*) positions refer to in front of or behind another structure. The *superficial* and *deep* positions refer to nearer to and farther from the body surface, respectively. Nearer to or farther from the trunk positions are called *proximal* and *distal*. Terms of body movements are defined in Table 4.

2.2. The Statistical Description of Anthropometric Data

The concept of normal distribution can used to describe random errors in the measurement of physical phenomena (Pheasant 1989). If the variable is normally distributed, the population may be completely described in terms of its mean ($\bar{x}$) and its standard deviation (s), and specific percentile (X_p) values can be calculated, where: $X_p = \bar{x} + sz$, where z (the standard normal deviate) is a factor for the percentile concerned. Values of z for some commonly used percentiles (X_p) are given in Table 5. Figure 2 depicts data from Humanscale calculated for different percentiles of U.S. females. A word of caution: anthropometric data are not necessarily normally distributed in any given population (Kroemer 1989).

2.3. The Method of Design Limits

The recommendations for workplace design with respect to anthropometric criteria can be established by the principle of *design for the extreme,* also known as the *method of limits* (Pheasant 1989). The basic idea behind this concept is to establish specific boundary conditions (percentile value of the

TABLE 1 US Civilian Body Dimensions (cm) for Ages 20–60 Years

	Men				Women			
Dimension	5th Percentile	50th Percentile	95th Percentile	SD	5th Percentile	50th Percentile	95th Percentile	SD
1. Stature (height)^f	161.8	173.6	184.4	6.9	149.5	160.5	171.3	6.6
2. Eye height^f	151.1	162.4	172.7	6.6	138.3	148.9	159.3	6.4
3. Shoulder (acromion height)^f	132.3	142.8	152.4	6.1	121.1	131.1	141.9	6.1
4. Elbow height^f	100.0	109.9	119.0	5.8	93.6	101.2	108.8	4.6
5. Knuckle height	69.8	75.4	80.4	3.2	64.3	70.2	75.9	3.5
6. Height, sitting^s	84.2	90.6	96.7	3.7	78.2	85.0	90.7	3.5
7. Eye height, sitting^s	72.6	78.6	84.4	3.6	67.5	73.3	78.5	3.3
8. Shoulder height, sitting^s	52.7	59.4	65.8	4.0	49.2	55.7	61.7	3.8
9. Elbow rest height, sitting^s	19.0	24.3	29.4	3.0	18.1	23.3	28.1	2.9
10. Knee height, sitting^f	49.3	54.3	59.3	2.9	45.2	49.8	54.5	2.7
11. Popliteal height, sitting^f	39.2	44.2	48.8	2.8	35.5	39.8	44.3	2.6
12. Thigh clearance height^s	11.4	14.4	17.7	1.7	10.6	13.7	17.5	1.8
13. Chest depth	21.4	24.2	27.6	1.9	21.4	24.2	29.7	2.5
14. Elbow–fingertip distance	44.1	47.9	51.4	2.2	38.5	42.1	56.0	2.2
15. Buttock–knee distance, sitting	54.0	59.4	64.2	3.0	51.8	56.9	62.5	3.1
16. Buttock (popliteal distance, sitting)	44.2	49.5	54.8	3.0	43.0	48.1	53.5	3.1
17. Forward reach, functional	76.3	82.5	88.3	5.0	64.0	71.0	79.0	4.5
18. Breadths								
19. Elbow-to-elbow breadth	35.0	41.7	50.6	4.6	31.5	38.4	49.1	5.4
20. Hip breadth, sitting	30.8	35.4	40.6	2.8	31.2	36.4	43.7	3.7
21. Head dimensions	14.4	15.42	16.4	0.59	13.6	14.54	15.5	0.57
22. Head circumference	53.8	56.8	59.3	1.68	52.3	54.9	57.7	1.63
23. Interpupillary distance	5.5	6.20	6.8	0.39	5.1	5.83	6.5	0.44
24. Hand dimensions								
25. Hand length	17.6	19.05	20.6	0.93	16.4	17.95	19.08	1.04
26. Breadth, metacarpal	8.2	8.88	9.8	0.47	7.0	7.66	8.4	0.41
27. Circumference, metacarpal	19.9	21.55	23.5	1.09	16.9	18.36	19.9	0.89
28. Thickness, meta III	2.4	2.76	3.1	0.21	2.5	2.77	3.1	0.18
29. Weight (kg)	56.2	74.0	97.1	12.6	46.2	61.1	89.9	13.80

Adapted from Kroemer 1989, with permission from Taylor & Francis Ltd., London, http://www.tandf.co.uk.
^{f}above floor, ^{s}above seat surface.

TABLE 2 Anthropometric Estimates for Elderly People (cm)

	Men				Women			
Dimension	5th Percentile	50th Percentile	95th Percentile	SD	5th Percentile	50th Percentile	95th Percentile	SD
1. Stature	151.5	164.0	176.5	7.7	140.0	151.5	163.0	7.0
2. Eye height	141.0	153.5	166.0	7.6	130.5	142.0	153.5	6.9
3. Shoulder height	122.5	134.5	146.5	7.2	113.0	123.5	134.0	6.5
4. Elbow height	93.5	102.5	112.0	5.7	86.0	94.5	103.0	5.2
5. Hip height	78.5	87.5	96.5	5.5	70.0	78.0	86.0	4.9
6. Knuckle height	64.0	71.5	78.5	4.5	61.0	68.0	74.5	4.1
7. Fingertip height	55.0	62.0	69.0	4.2	51.5	59.0	66.0	4.3
8. Sitting height	78.5	85.0	92.0	4.2	71.0	78.5	86.5	4.8
9. Sitting eye height	67.5	74.0	80.5	4.0	61.0	68.5	75.5	4.5
10. Sitting shoulder height	49.5	55.5	61.5	3.7	44.5	51.5	58.5	4.2
11. Sitting elbow height	16.0	21.5	27.0	3.4	15.0	20.5	25.5	3.2
12. Thigh thickness	12.0	14.5	17.5	1.7	10.5	14.0	17.0	1.9
13. Buttock–knee length	51.0	56.5	62.0	3.4	49.0	54.5	60.0	3.4
14. Buttock–popliteal length	41.0	47.0	53.0	3.6	40.5	46.0	51.5	3.4
15. Knee height	45.5	51.5	57.0	3.5	43.0	48.0	53.0	3.0
16. Popliteal height	36.5	41.5	47.0	3.2	33.0	38.0	43.0	3.1
17. Shoulder breadth (bideltoid)	38.0	43.0	48.0	3.1	32.5	37.0	41.5	2.7
18. Shoulder breadth (biacromial)	33.5	36.5	40.0	2.0	30.5	33.5	37.0	2.0
19. Hip breadth	29.0	34.0	39.5	3.2	28.5	35.5	42.5	4.3
20. Chest (bust) depth	21.5	25.5	29.0	2.3	20.5	25.5	30.5	3.0
21. Abdominal depth	23.0	29.0	35.5	3.9	20.5	16.0	32.0	3.5
22. Shoulder–elbow length	30.5	34.5	38.0	2.2	28.0	31.0	34.5	2.0
23. Elbow–fingertip length	41.0	45.0	48.5	2.3	37.0	40.5	44.0	2.2
24. Upper limb length	67.0	73.5	80.0	3.9	60.5	66.5	72.5	3.6
25. Shoulder-grip length	57.0	62.5	68.5	3.5	51.0	56.5	62.0	3.3
26. Head length	17.0	18.5	20.0	0.8	15.5	17.0	18.0	0.8
27. Head breadth	7.5	13.5	15.5	0.7	12.5	13.5	14.5	0.6
28. Hand length	16.0	18.0	19.5	1.1	14.5	16.5	18.0	1.0
29. Hand breadth	7.5	8.0	9.0	0.5	6.5	7.0	8.0	0.5
30. Foot length	22.5	25.0	27.5	1.5	20.0	22.5	24.5	1.4
31. Foot breadth	8.0	9.0	10.5	0.7	7.5	8.5	9.5	0.6
32. Span	154.0	169.0	184.0	9.1	138.0	151.5	164.5	8.0
33. Elbow span	80.5	89.0	97.5	5.2	72.0	80.0	88.0	4.8
34. Vertical grip reach (standing)	177.0	191.5	206.0	8.8	164.0	177.0	190.0	8.0
35. Vertical grip reach (sitting)	106.5	117.5	128.0	6.6	98.5	108.5	118.0	6.0
36. Forward grip reach	67.5	73.5	79.5	3.8	60.5	66.0	72.0	3.5

Adapted from Pheasant 1986.

TABLE 3 Range of Joint Mobility Values Corresponding to Postures in Figure 1

Movement	Mean	S.D.	5 Percentile	95 Percentile
Shoulder flexion	188	12	168	208
Shoulder extension	61	14	38	84
Shoulder abduction	134	17	106	162
Shoulder adduction	48	9	33	63
Shoulder medial rotation	97	22	61	133
Shoulder lateral rotation	34	13	13	55
Elbow flexion	142	10	126	159
Forearm supination	113	22	77	149
Forearm pronation	77	24	37	117
Wrist flexion	90	12	70	110
Wrist extension	113	13	92	134
Hip abduction	53	12	33	73
Hip adduction	31	12	11	51
Hip medial rotation (prone)	39	10	23	56
Hip lateral rotation (prone)	34	10	18	51
Hip medial rotation (sitting)	31	9	16	46
Hip lateral rotation (sitting)	30	9	15	45
Knee flexion, voluntary (prone)	125	10	109	142
Knee flexion, forearm (prone)	144	9	129	159
Knee flexion, voluntary (standing)	113	13	92	134
Knee flexion forced (kneeling)	159	9	144	174
Knee medial rotation (sitting)	35	12	15	55
Knee lateral rotation (sitting)	43	12	23	63
Ankle flexion	35	7	23	47
Ankle extension	38	12	18	58
Foot inversion	24	9	9	39
Foot eversion	23	7	11	35

Adapted from Chaffin and Andersson, *Occupational Biomechanics,* 3rd Ed. Copyright © 1999. Reprinted by permission of John Wiley & Sons, Inc., New York.

[a] Measurement technique was photography. Subjects were college-age males.

Data are in angular degrees.

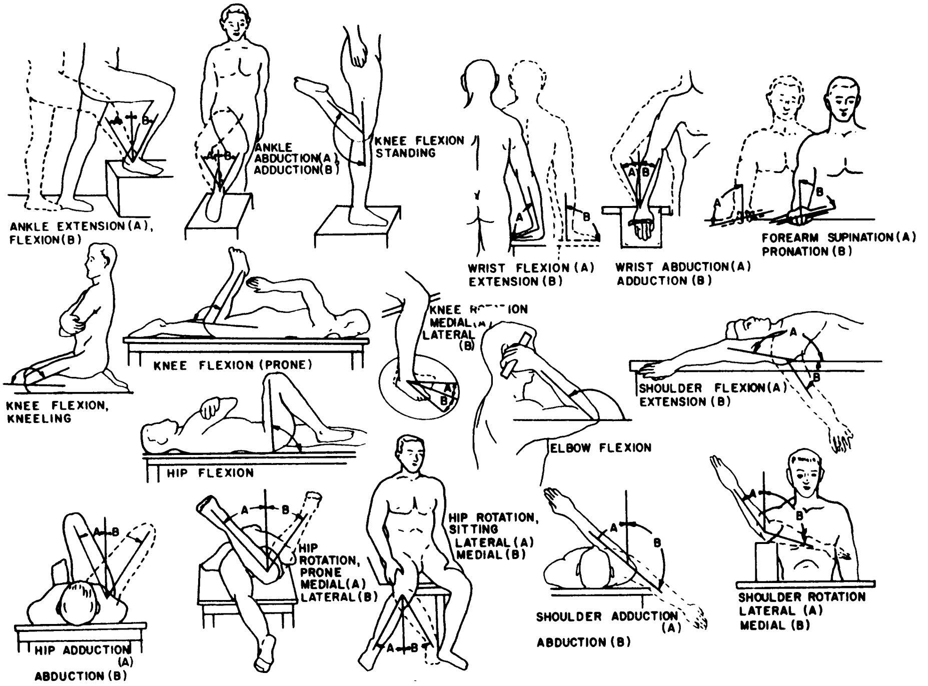


Figure 1 Illustration of Joint Mobility. (Adapted from Chaffin et al., *Occupational Biomechanics,* 3rd Ed. Copyright © 1999. Reprinted by permission of John Wiley & Sons, Inc., New York.)

TABLE 4 Terms of Movements

Body Part	Movement	Plane of Reference		
		Sagittal	Coronal	Transverse
Trunk[1]	Bend forward	Flexion		
	Bend backwards	Extension		
	Bend sideways		Lateral flexion	
	Rotate about the Long axis			Axial rotation
Shoulder[2] girdle	Raise shoulders	Elevation		
	Lower shoulders	Depression		
	Draw forward	Protraction		
	Draw backward	Retraction		
Shoulder and hip joints	Raise arm or thigh forward	Flexion (extension[a])		
	Raise arm or thigh to side		Abduction (adduction[a])	
	Rotate arm or leg along its long axis			Lateral or outward rotation (medial or inward rotation[a])
Elbow and knee joints	Bend from the fully straightened position	Flexion (extension[a])		
Wrist joint (combined with carpal joints)	Bend palm upwards	Flexion (extension[a])		
	Move hand away from trunk to the side of radius		Adduction or radial deviation (adduction or ulnar deviation[a])	
Forearm rotation	Towards:			
	palm up position	Supination		
	palm down position	Pronation		

Adapted from Grieve and Pheasant (1982).

[a] Opposite movement.

TABLE 5 Commonly Used Values of z and X_p

X_p	z	X_p	z
1	−2.33	99	2.33
2.5	−1.96	97.5	1.96
5	−1.64	95	1.64
10	−1.28	90	1.28
15	−1.04	85	1.04
20	−0.84	80	0.84
25	−0.67	75	0.67
30	−0.52	70	0.52
40	−0.25	60	0.25
50	−0.00	50	0.00

relevant human characteristic) that, if satisfied, will also accommodate the rest of the expected user population. The NIOSH's (1991) recommended weight limit concept is an example of application of the method of limits or design for the extreme principles to the design of manual lifting tasks. Such design is based on the expected human characteristics, where the limiting users are the weakest of the worker population.

2.4. Anthropometric Design Criteria

The basic anthropometric criteria for workplace design are clearance, reach, and posture (Pheasant 1986). Typically, clearance problems refer to design of space needed for the knees, availability of space for wrist support, or safe passageways around and between equipment. If the clearance problems are disregarded, they may lead to poor working postures and hazardous work layouts. Consideration of clearance requires designing for the largest user, typically by adapting the 95th percentile values of the relevant characteristics for male workers. Typical reach problems in industry include consid-

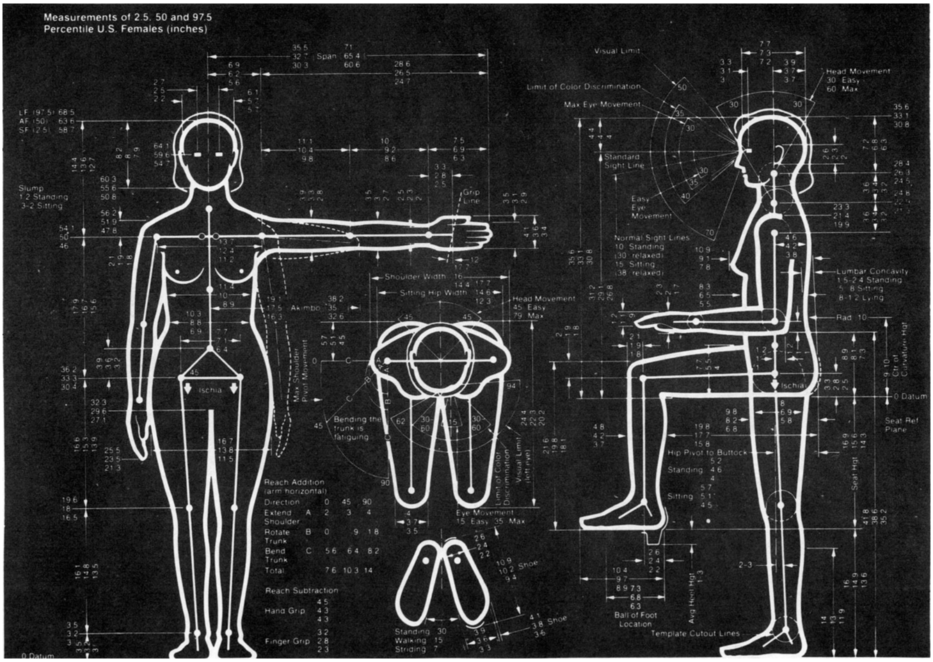


Figure 2 Illustration of Design Data Presented in Humanscale. (Reproduced with permission from Henry Dreyfuss Associates 1984)

eration of the location of controls and accessibility of control panels in the workplace. The procedure for solving the reach problems is similar to the one used for solving the clearance problems. This time, however, the limiting user will be a smaller member of the population and the design will be usually based upon the 5th percentile value of the relevant characteristic for female workers.

Both the clearance and the reach criteria are *one-tailed constraints,* that is, they impose the limits in one direction only (Pheasant 1989). The clearance criterion points out when an object is too small. It does not, however, indicate when an object is too large. In some design problems, such as safeguarding of industrial machinery, the conventional criteria of clearance and reach are often reversed.

2.5. Alternative Design Procedures

An alternative to single-percentile anthropometric design models has been presented by Robinette and McConville (1981). They point out that single-percentile models are inappropriate for both theoretical and practical reasons. As discussed by Kroemer (1989), there are two other methods that can be used to develop the analogues of the human body for the design purposes. One method is to create models that represent the extreme ends of the body size range called the subgroup method. The other method is the regression-based procedure. which generates design values that are additive. The estimated U.S. civilian body dimensions published by Kroemer (1981) are given in Table 1. A useful and correct general procedure for anthropometric design was recently proposed by Kroemer et al. (1986). This procedure consists of the following steps:

- *Step 1:* Select those anthropometric measures that directly relate to defined design dimensions. Example: hand length related to handle size.
- *Step 2:* For each of these pairings, determine independently whether the design must fit either only one given percentile of the body dimension, or if a range along that body dimension must be fitted. The height of a seat should be adjustable to fit persons with short and with long lower legs.
- *Step 3:* Combine all selected dimensions in a careful drawing, mock-up, or computer model to ascertain that all selected design values are compatible with each other. For example: the required leg room clearance height needed for sitting persons with long lower legs may be very close to the height of the working surface, determined from elbow height.
- *Step 4:* Determine whether one design will fit all users. If not, several sizes or adjustment must be provided to fit all users.

2.6. Computer-Aided Models of Man

In order to facilitate the application of anthropometric data and biomechanical analysis in workplace design, several computer-based models of man have been developed. These computer-aided tools

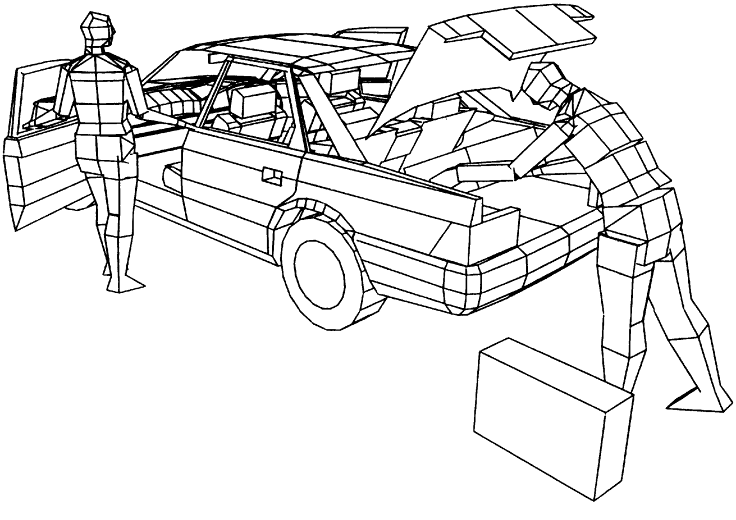


Figure 3 Illustration of Workplace Design Using SAMMIE System. (Reproduced with permission from SAMMIE CAD, Ltd.)

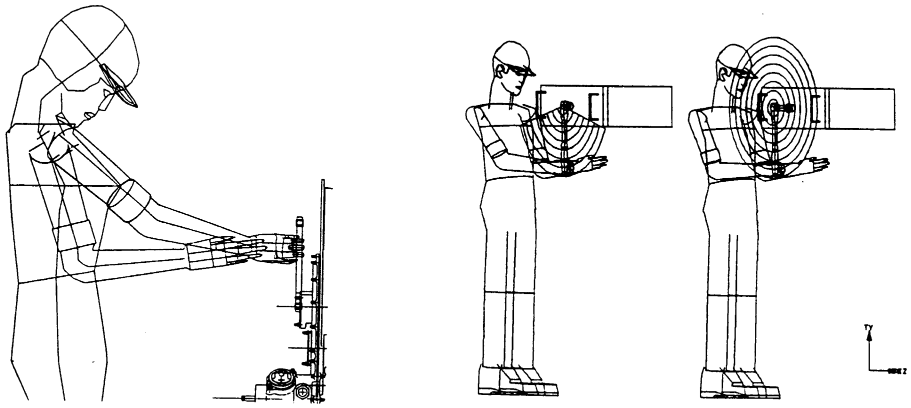


Figure 4 Illustration of the CREW CHIEF Design Capabilities: Left—removing a recessed bolt from a jet engine; right—modification of ratchet wrench interaction with handles on a box. (Reproduced with permission from McDaniel, copyright by Taylor & Francis, 1990)

should make the analysis and application of biomechanical principles at work less complicated and more useful. For a review of the state of the art in ergonomic models of anthropometry, human biomechanics and operator–equipment interfaces, see Kroemer et al. (1988). Other developments in computer-aided ergonomics, specifically computer models of man and computer-assisted workplace design, are discussed by Karwowski et al. (1990). According to Schaub and Rohmert (1990), man model development originated with SAMMIE (System for Aiding Man–Machine Interaction Evaluation) in England (see Figure 3) (Porter et al. 1995). Examples of computer models developed in the United States include BOEMAN (Ryan 1971) for aircraft design, COMBIMAN and CREW CHIEF (McDaniel 1990) (see Figure 4), Deneb/ERGO (Nayar 1995) and JACK (Badler et al. 1995)

Other computer-aided man models developed in Europe include ERGOMAN (France), OSCAR (Hungary), ADAPTS (Netherlands), APOLINEX (Poland), and WERNER, FRANKY, and ANYBODY (Germany). A comprehensive 3D man model for workplace design, HEINER, was developed by Schaub and Rohmert (1990). Advances in applied artificial intelligence made it possible to develop knowledge-based expert systems for ergonomic design and analysis (Karwowski et al. 1987; Jung and Freivalds 1990). Examples of such models include SAFEWORK (Fortin et al. 1990), ERGONEXPERT (Rombach and Laurig1990), and ERGOSPEC (Brennan et al. 1990). Other models, such as CAD-video somotograph (Bullinger and Lorenz 1990) and AutoCAD-based anthropometric design systems (Grobelny 1990), or ergonomic databases (Landau et al. 1990), were also developed.

The computer-aided systems discussed above serve the purpose of biomechanical analysis in workplace design. For example, COMBIMAN, developed in the Human Engineering Division of Armstrong Laboratory since 1975, is both illustrative and analytic software. It allows the analysis of physical accessibility (reach and fit capabilities), strength for operating controls, and visibility accessibility. CREW CHIEF, a derivative of COMBIMAN, also allows the user with similar analyses. Another important development is Deneb's ERGO, a system capable of rapid prototyping of human motion, analyzing human joint range of motion, reach, and visual accessibility. In a recent study by Schaub et al. (1997), the authors revised the models and methods of ERGOMAN and reported added capabilities to predict maximum forces/moments of relevant posture, evaluate stress of human body joints, and carry out a general risk assessment. Probably the most advanced and comprehensive computer-aided digital human model and design/evaluation system today is JACK, from Transform Technologies (2000).

3. DESIGN FOR HUMAN STRENGTH

Knowledge of human strength capabilities and limitations can be used for ergonomic design of jobs, workplaces, equipment, tools, and controls. Strength measurements can also be used for worker preemployment screening procedures (Chaffin et al. 1978; Ayoub 1983). Human strengths can be assessed under static (isometric) or dynamic conditions (Kroemer 1970; Chaffin et al. 1977). Dynamic strengths can be measured isotonically, isokinetically, and isoinertially. Isometric muscle strengths are the capacity of muscles to produce force or moment force by a single maximal voluntary exertion; the body segment involved remains stationary and the length of the muscle does not change. In

TABLE 6 Static Strengths Demonstrated by Workers when Lifting, Pushing, and Pulling with Both Hands on a Handle Placed at Different Locations Relative to the Midpoint between the Ankles on Floor

	Location of Handle (cm)[a]		Male Strengths (N)			Female Strengths (N)		
Test Description	Vertical	Horizontal	Sample Size	Mean	SD	Sample Size	Mean	SD
Lift—leg partial squat	38	0	673	903	325	165	427	187
Lift—torso stooped over	38	38	1141	480	205	246	271	125
Lift—arms flexed	114	38	1276	383	125	234	214	93
Lift—shoulder high and arms out	152	51	309	227	71	35	129	36
Lift—shoulder high and arms flexed	152	38	119	529	222	20	240	84
Lift—shoulder high and arms close	152	25	309	538	156	35	285	102
Lift—floor level, close (squat)	15	25	309	890	245	35	547	182
Lift—floor level, out (stoop)	15	38	170	320	125	20	200	71
Push down—waist level	118	38	309	432	93	35	325	71
Pull down—above shoulders	178	33	309	605	102	35	449	107
Pull in—shoulder level, arms out	157	33	309	311	80	35	244	53
Pull in—shoulder level, arms in	140	0	205	253	62	52	209	62
Push—out waist level, stand erect	101	35	54	311	195	27	226	76
Push—out chest level, stand erect	124	25	309	303	76	35	214	49
Push-out—shoulder level, lean forward	140	64	205	418	178	52	276	120

Adapted from Chaffin et al., *Occupational Biomechanics,* 3rd Ed. Copyright © 1999. Reprinted by permission of John Wiley & Sons, Inc., New York.

[a] The location of the handle is measured in midsagittal plane, vertical from the floor and horizontal from the midpoint between the ankles.

dynamic muscular exertions, body segments move and the muscle length changes (Ayoub and Mital 1989). The static strengths demonstrated by industrial workers on selected manual handling tasks are shown in Table 6. Maximum voluntary joint strengths are depicted in Table 7.

3.1. Occupational Strength Testing

The main goal of worker selection is to screen the potential employee on the basis of his or her physical capability and match it with job demands. In order to evaluate an employee's capability, the following criteria should be applied when selecting between alternative screening methods (NIOSH 1981):

1. Safety in administering
2. Capability of giving reliable, quantitative values
3. Relation to specific job requirements
4. Practicality
5. Ability to predict the risk of future injury or illness

Isometric strength testing has been advocated as a means to predict the risk of future injuries resulting from jobs that require a high amount of force. Chaffin et al. (1977) reported that both frequency and severity rates of musculoskeletal problems were about three times greater for workers placed in jobs requiring physical exertion above that demonstrated by them in isometric strength tests when compared with workers placed in jobs having exertion requirements well below their demonstrated capabilities. The literature on worker selection has been reviewed by NIOSH (1981), Ayoub (1983), Chaffin et al. (1999), and Ayoub and Mital (1989). Typical values for the static strengths are shown in Figure 5.

3.2. Static vs. Dynamic Strengths

The application of static strength exertion data has limited value in assessing workers' capability to perform dynamic tasks that require application of force through a range of motions (Ayoub and Mital 1989). Mital et al. (1986) found that the correlation coefficients between simulated job dynamic strengths and maximum acceptable weight of lift in horizontal and vertical planes were substantially higher than those between isometric strengths and weights lifted. Two new studies offer design data based on dynamic strengths (Mital and Genaidy 1989; Mital and Faard 1990).

TABLE 7 Maximum Voluntary Joint Strengths (Nm)

	Range of Moments (Nm) of Subjects from Several Studies			
Joint strength	Joint Angle (degrees)	Men	Women	Variation with Joint Angle +
Elbow flexor	90	50–120	15–85	Peak at about 90°
Elbow extensor	90	25–100	15–60	Peak between 50° and 100°
Shoulder flexor	90	60–100	25–65	Weaker at flexed angles
Shoulder extensor	90	40–150	10–60	Decreases rapidly at angles less than 30°
Shoulder adductor	60	104	47	As angle decreases, strength increases then levels at 30° to −30°
Trunk flexor	0	145–515	85–320	Pattern differ among authors
Trunk extensor	0	143	78	Increases with trunk flexion
Trunk lateral flexor	0	150–290	80–170	Decreases with joint flexion
Hip extensor	0	110–505	60–130	Increases with joint flexion
Hip abductor	0	65–230	40–170	Increases as angle decreases
Knee flexor	90	50–130	35–115	In general, decreases some disagreement with this, depending on hip angle
Knee extensor	90	100–260	70–150	Minima at full flexion and extension
Ankle plantarflexor	0	75–230	35–130	Increases with dorsiflexion
Ankle dorsiflexor	0	35–70	25–45	Decreases from maximum plantar flexion to maximum dorsiflexion

Adapted from Tracy 1990.

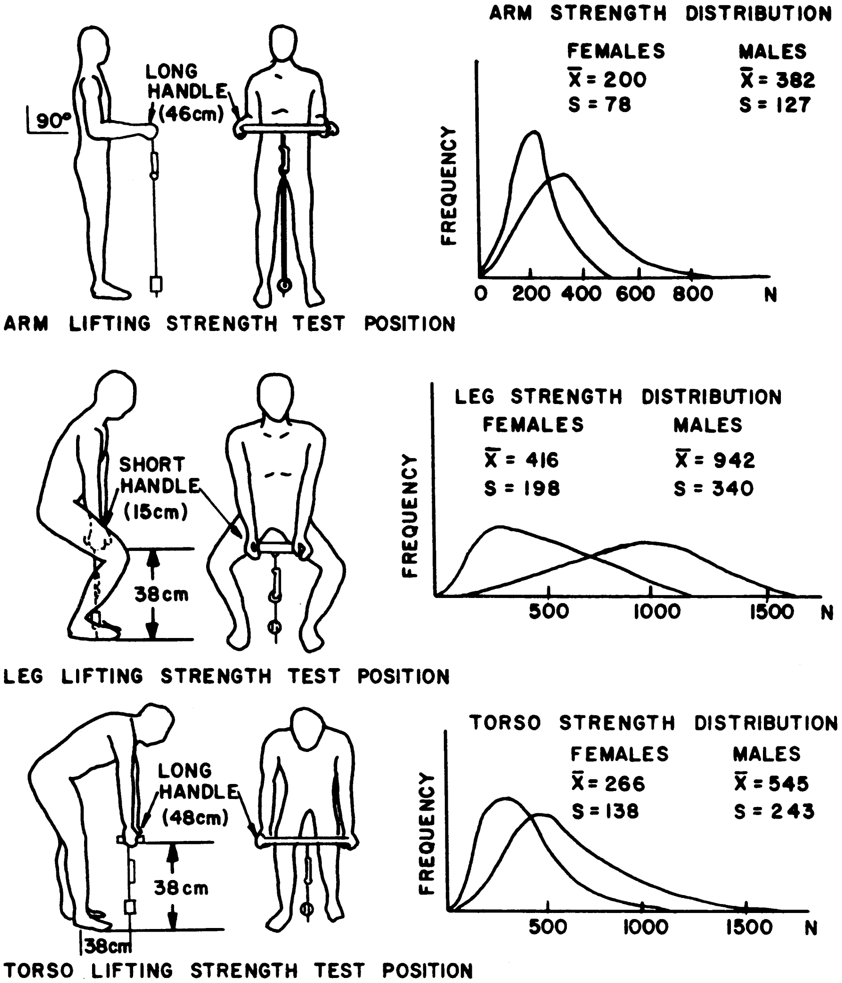


Figure 5 Results of Static Strength Measurement. (Adapted from Chaffin et al., *Occupational Biomechanics,* 3rd Ed. Copyright © 1999. Reprinted by permission of John Wiley & Sons, Inc., New York.)

The study by Mital and Genaidy (1989) provides isokinetic strengths of males and females for infrequent vertical exertions in 15 different working postures. This study showed that dynamic strength exertions of females are approximately half those of the male exertions, not about 67%, as in the case of isometric strength exertions. Mital and Faard (1990) investigated the effects of reach distance, preferred arm orientation, and sitting and standing posture on isokinetic force exertion capability of males in the horizontal plane. The results indicated that peak isokinetic strengths increased with the reach distance and were strongly influenced by the arm orientation. Also, peak isokinetic exertions were substantially greater than static strength when subjects were allowed to exert at freely chosen speed.

Karwowski and Mital (1986) and Karwowski and Pongpatanasuegsa (1988) tested the additivity assumption of isokinetic lifting and back extension strengths (the additivity assumption states that strength of a team is equal to the sum of individual members' strengths). They found that, on average, the strength of two-person teams is about 68% of the sum of the strengths of its members. For three-member teams, male and female teams generate only 58% and 68.4% of the sum of the strengths of its members, respectively. For both genders, the isokinetic team strengths were much lower than static team strengths.

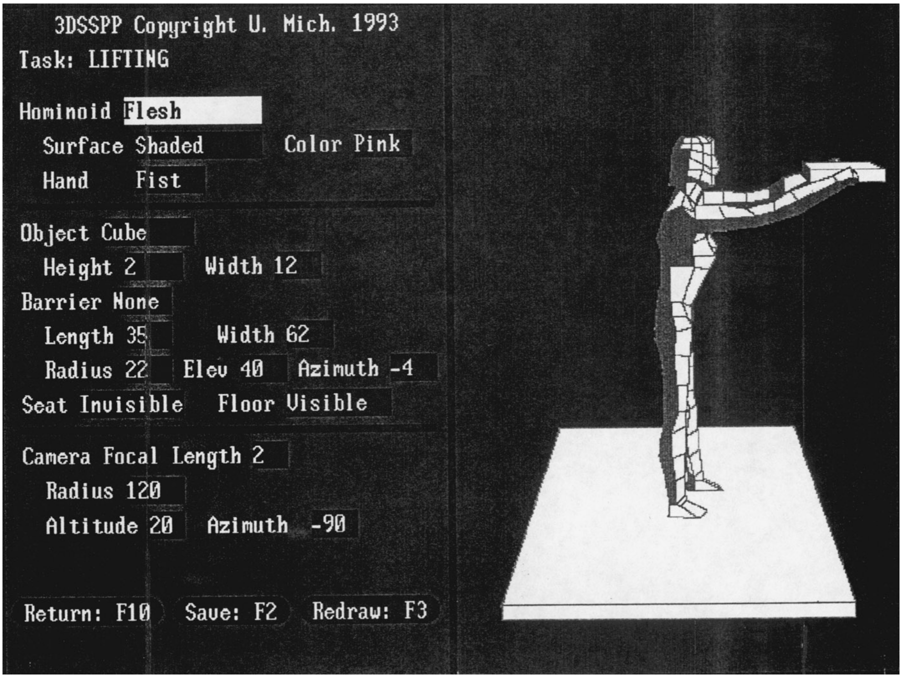
3.3. Computer Simulation of Human Strength Capability

The worker strength exertion capability in heavy manual tasks can be simulated with the help of a microcomputer. Perhaps the best-known microcomputer system developed for work design and analysis concerning human strength is the Three Dimensional Static Strength Program (3D SSPP), developed by the Center for Ergonomics at the University of Michigan and distributed through the Intellectual Properties Office (University of Michigan, 1989). The program can aid in the evaluation of the physical demands of a prescribed job, and is useful as a job design/redesign and evaluation tool. Due to its static nature, the 3D SSPP model assumes negligible effects of accelerations and momentums and is applicable only to slow movements used in manual handling tasks. It is claimed that the 3D SSPP results correlate with average population static strengths at $r = 0.8$, and that the program should not be used as the sole determinant of worker strength performance (University of Michigan, 1989). In their last validation study, Chaffin and Erig (1991) reported that if considerable care is taken to ensure exactness between simulated and actual postures, the prediction error standard deviation would be less than 6% of the mean predicted value. However, 3D SSPP does not allow simulation of dynamic exertions.

The body posture, in 3D SSPP, is defined through five different angles about the joints describing body link locations. The input parameters, in addition to posture data, include percentile of body height and weight for both male and female populations, definition of force parameters (magnitude and direction of load handled in the sagittal plane), and the number of hands used. The output from the model provides the estimation of the percentage values of the population capable of exerting the required muscle forces at the elbow, shoulder, lumbosacral (L5/S1), hip, knee and ankle joints, and calculated back compression force on L5/S1 in relation to NIOSH action limit and maximum permissible limit. The body balance and foot/hip potential is also considered. An illustration of the model output is given in Figure 6.

3.4. Push–Pull Force Limits

Safe push–pull force exertion limits may be interpreted as the maximum force magnitudes that people can exert without injuries (for static exertions) or CTD (for repeated exertions) of the upper extremities under a set of conditions.



3DSSPP Copyright U. Mich. 1993
Task: LIFTING
Hominoid Flesh
Surface Shaded Color Pink
Hand Fist
Object Cube
Height 2 Width 12
Barrier None
Length 35 Width 62
Radius 22 Elev 40 Azimuth -4
Seat Invisible Floor Visible
Camera Focal Length 2
Radius 120
Altitude 20 Azimuth -90

Figure 6 Illustration of Results from the 3D Static Strength Prediction Program of the University of Michigan.

3.4.1. Static Standing Forces

Because many factors influence the magnitude of a static MVC force, it would be wise not to recommend a single value for either push or pull force limits. After reviewing several studies Imrhan (1999), has concluded that average static two-handed MVC push forces have ranged from about 400–620 N in males and 180–335 N in females without bracing of the body, and pull forces from about 310–370 N in males and 180–270 N in females.

3.4.2. Dynamic Standing Forces

Dynamic push forces have ranged from 170 to 430 N in males and 200 to 290 N in females, and pull forces from 225 to 500 N in males and 160 to 180 N in females. As a result of series of researches by Snook and his colleagues (Snook et al. 1970; Snook and Ciriello 1974a; Snook 1978; Ciriello and Snook 1978, 1983; Ciriello et al. 1990), by utilizing psychophysical methodology, Snook and Ciriello (1991) have published the most useful guidelines on maximum initial or sustained push–pull force limits. Partial reproductions of the final four tables are given in Tables 8–11. The forces in are stated as a function of other work-related independent variables for both males and females. These are as follows:

1. Distance of push/pull: 2.1, 7.6, 15.2, 30.5, 45.7, and 61.0 m.
2. Frequency of push/pull: each distance has force limits for one exertion per 8 hr., 30 min, 5 min, and 2 min.
3. Height (vertical distance from floor to hands: 144, 95, 64 cm for males and 135, 89, and 57 for females.
4. The percentage of workers: (10, 25, 50, 75, and 90%) who are capable of sustaining the particular force during a typical 8-hr job.

TABLE 8 Maximum Acceptable Forces of Pull for Females (kg)

		2.1 m Pull							45.7 m Pull				
		6	12	1	2	5	30	8	1	2	5	30	8
Height	Percent	s		min				h	min				h
		Initial Forces											
135	90	13	16	17	18	20	21	22	12	13	14	15	17
	75	16	19	20	21	24	25	26	14	16	17	18	20
	50	19	22	24	25	28	29	31	17	18	20	21	24
	25	21	25	28	29	32	33	35	19	21	23	24	27
	10	24	28	31	32	36	37	39	22	24	25	27	31
57	90	15	17	19	20	22	23	24	13	14	15	17	19
	75	17	20	22	23	26	27	28	16	17	18	20	22
	50	20	24	26	27	30	32	33	18	20	22	23	26
	25	23	27	30	31	35	36	38	21	23	25	27	30
	10	26	31	34	35	39	40	43	24	26	28	30	34
		Sustained Forces											
135	90	6	9	10	10	11	12	15	6	6	7	7	9
	75	8	12	13	14	15	16	20	8	9	9	9	12
	50	10	16	17	18	19	21	25	10	11	11	12	16
	25	13	19	21	21	23	25	31	12	13	14	14	19
	10	15	22	24	25	27	29	36	14	15	16	17	23
57	90	5	8	9	9	10	11	13	5	6	6	6	8
	75	7	11	12	12	13	14	18	7	8	8	8	11
	50	9	14	15	16	17	18	23	9	10	10	11	14
	25	11	17	18	19	21	22	27	11	12	12	13	19
	10	13	20	21	22	24	26	32	12	14	14	15	20

From Snook and Ciriello (1991) with permission from Taylor & Francis Ltd., London, http://www.tandf.co.uk.
Height = vertical distance from floor to hand–object (handle) contact
Percent = percentage of industrial workers capable of exerting the stated forces in work situations.

TABLE 9 Maximum Acceptable Forces of Pull for Females (kg)

		2.1 m Pull							45.7 m Pull				
		6	12	1	2	5	30	8	1	2	5	30	8
Height	Percent	s		min				h	min				h
Initial Forces													
135	90	14	15	17	18	20	21	22	12	13	14	15	17
	75	17	18	21	22	24	25	27	15	16	17	19	21
	50	20	22	25	26	29	30	32	18	19	21	22	25
	25	24	25	29	30	33	35	37	20	22	24	26	29
	10	26	28	33	34	38	39	41	23	25	27	29	33
57	90	11	12	14	14	16	17	18	11	12	12	13	15
	75	14	15	17	17	19	20	21	13	14	15	16	18
	50	16	17	20	21	23	24	25	15	17	18	19	22
	25	19	20	23	24	27	28	30	18	19	21	22	25
	10	21	23	26	27	30	31	33	20	22	23	25	28
Sustained Forces													
135	90	6	8	10	10	11	12	14	5	5	5	6	8
	75	9	12	14	14	16	17	21	7	8	8	8	11
	50	12	16	19	20	21	23	28	9	10	11	11	15
	25	16	20	24	25	27	29	36	11	13	13	14	19
	10	18	23	28	29	32	34	42	14	15	16	17	22
57	90	5	6	8	8	9	9	12	5	5	5	6	7
	75	7	9	11	12	13	14	17	7	7	8	8	11
	50	10	13	15	16	17	18	23	9	10	10	11	15
	25	12	16	19	20	22	23	29	11	13	13	14	19
	10	15	19	23	23	26	28	34	13	15	16	16	22

From Snook and Ciriello (1991) with permission from Taylor & Francis Ltd., London, http://www.tandf.co.uk.
Height = vertical distance from floor to hand–object (handle) contact
Percent = percentage of industrial workers capable of exerting the stated forces in work situations.

3.4.3. One-Handed Force Magnitudes

One-handed forces vary considerably among studies with similar variables and within individual studies depending on test conditions or variables. Generalizations about recommended forces, therefore, are not easy to make. Average static standing-pull forces have ranged from 70 to 134 N and sitting forces from 350 to 540 N. Dynamic pull forces, in almost all studies, have ranged from 170 to 380 N in females and from 335 to 673 N in males when sitting. Average pull forces in males while lying down prone have ranged from 270 to 383 N and push forces from 285 to 330 N (Hunsicker and Greey 1957).

3.4.4. Pinch–Pull Force Magnitudes

Pinching and pulling with one hand while stabilizing the object with the other hand has been observed in male adults to yield forces of 100, 68, and 50 N when using the lateral, chuck, and pulp pinches, respectively (Imrhan and Sundararajan 1992; Imrhan and Alhaery 1994).

4. STATIC EFFORTS AND FATIGUE

4.1. Design Limits for Static Work

Static efforts at work are often fatiguing and cannot be sustained over a long period of time (Rohmert 1960; Monod and Scherrer 1965; Pottier et al. 1969 and Monod 1972). Figure 7 illustrates the relationship between a percentage of the maximum voluntary contraction used and the time duration. This relationship has been determined for arm, leg, and trunk muscles by Rohmert (1960), for an upperlimb pulling action by Caldwell and Smith (1963), and for biceps brachii, triceps brachii, the middle finger flexor, and quadriceps femoris by Monod and Scherrer (1965). The results of these

TABLE 10 Maximum Acceptable Forces of Pull for Males (kg)

Height	Percent	2.1 m Pull							45.7 m Pull				
		6	12	1	2	5	30	8	1	2	5	30	8
		s		min				h	min				h
Initial Forces													
144	90	14	16	18	18	19	19	23	10	11	13	13	16
	75	17	19	22	22	23	24	28	12	14	16	16	20
	50	20	23	26	26	28	28	33	15	16	19	19	24
	25	24	27	31	31	32	33	39	17	19	22	22	28
	10	26	30	34	34	36	37	44	20	22	25	25	31
64	90	22	25	28	28	30	30	36	16	18	21	21	26
	75	27	30	34	34	37	37	44	19	22	25	25	31
	50	32	36	41	41	44	44	53	23	26	30	30	37
	25	37	42	48	48	51	51	61	27	30	35	35	43
	10	42	48	54	54	57	58	69	30	34	39	39	49
Sustained Forces													
144	90	8	10	12	13	15	15	18	6	7	8	9	10
	75	10	13	16	17	19	20	23	7	9	10	11	14
	50	13	16	20	21	23	24	28	9	11	12	14	17
	25	15	20	24	25	28	29	34	11	13	15	17	20
	10	17	22	27	28	32	33	39	12	14	17	19	23
64	90	11	14	17	18	20	21	25	8	9	11	12	15
	75	14	19	23	23	26	27	32	10	12	14	16	19
	50	17	23	28	29	32	34	40	13	15	17	20	23
	25	20	27	33	35	39	40	48	15	18	21	24	28
	10	23	31	38	40	45	46	54	17	20	24	27	32

From Snook and Ciriello (1991). Used with permission by Taylor & Francis Ltd., London, http://www.tandf.co.uk.
Height = vertical distance from floor to hand–object (handle) contact
Percent = percentage of industrial workers capable of exerting the stated forces in work situations.

three studies indicate that the limit time approaches infinity at a force of 8–10% maximum voluntary contraction and converges to zero at 100% of the maximum strength.

As discussed by Kahn and Monod (1989), the maximum duration of static effort or the maximum maintenance time (limit time) varies inversely with the applied force and may be sustained for a long time if the force does not exceed 15–20% of the maximum voluntary contraction (MVC) of the muscle considered. The relation between force and limit time has been defined by Monod (1965) as:

$$t = \frac{k}{(F - f)^n}$$

where t is the limit time (min), F the relative force used (%), f the force (%) for which t tends to infinity (called the critical force), and k and n are constants. Rohmert (1960) subsequently proposed a more elaborate equation:

$$t = -1.5 + \left(\frac{2.1}{F}\right) - \left(\frac{0.6}{F^2}\right) + \left(\frac{0.1}{F^3}\right)$$

In both cases the maximum maintenance time is linked to the force developed by a hyperbolic relation, which applies to all muscles.

4.2. Intermittent Static Work

In the case of intermittent static efforts during which the contraction phases are separated by rest periods of variable absolute and relative duration, the maximum work time, given the relative force used and the relative duration of contraction, can be predicted as follows (Rohmert 1973):

TABLE 11 Maximum Acceptable Forces of Pull for Males (kg)

		2.1 m Pull							45.7 m Pull				
		6	12	1	2	5	30	8	1	2	5	30	8
Height	Percent	s		min				h	min				h
Initial Forces													
	90	20	22	25	25	26	26	31	13	14	16	16	20
	75	26	29	32	32	34	34	41	16	18	21	21	26
144	50	32	36	40	40	42	42	51	20	23	26	26	33
	25	38	43	47	47	50	51	61	24	27	32	32	39
	10	44	49	55	55	58	58	70	28	31	36	36	45
	90	19	22	24	24	25	26	31	12	14	16	16	20
	75	25	28	31	31	33	33	40	16	18	21	21	26
64	50	31	35	39	39	41	41	50	20	22	26	26	32
	25	38	42	46	46	49	50	59	24	27	31	31	39
	10	43	48	53	53	57	57	68	27	31	36	36	44
Sustained Forces													
	90	10	13	15	16	18	18	22	7	8	10	11	13
	75	13	17	21	22	24	25	30	10	11	13	15	18
144	50	17	22	27	28	31	32	38	12	14	17	19	23
	25	21	27	33	34	38	40	47	15	18	21	24	28
	10	25	31	38	40	45	46	54	18	21	24	28	33
	90	10	13	16	16	18	19	23	7	8	9	11	13
	75	4	18	21	22	25	26	31	9	11	12	14	17
64	50	18	23	28	29	32	33	39	12	14	16	18	22
	25	22	28	34	35	39	41	48	14	17	20	23	27
	10	26	32	39	41	46	48	56	17	20	23	26	31

From Snook and Ciriello (1991). Used with permission by Taylor & Francis Ltd., London, http://www.tandf.co.uk.
Height = vertical distance from floor to hand–object (handle) contact
Percent = percentage of industrial workers capable of exerting the stated forces in work situations.

$$t = \frac{k}{(F - f)^{np}}$$

where p is the static contraction time as a percentage of the total time. Rohmert (1962) had devised another method for estimating the minimum duration of rest periods required to avoid fatigue during intermittent static work:

$$t_r = 18\left(\frac{t}{t_{\max}}\right)^{1.4} \times \left(\frac{F}{F_{\max}} - 0.15\right) \times 100\%$$

where t_r is the rest time as a percentage of t, which is the duration of contraction (min). Kahn and Monod (1989) concluded that the main causal factor in the onset of fatigue due to static efforts (isometrically contracting muscles) is local muscle ischemia. Furthermore, the onset of local muscle fatigue can be delayed if changes in recovery time are sufficient to allow restoration of normal blood flow through the muscle.

4.3. Static Efforts of the Arm

As of this writing, only limited guidelines regarding the placement of objects that must be manipulated by the arm have been proposed (Chaffin et al. 1999). Figure 8 depicts the effect of horizontal reach on shoulder muscle fatigue endurance times. This figure illustrates that the workplace must be designed to allow for the upper arm to be held close to the torso. In general, any load-holding tasks should be minimized by the use of fixtures and tool supports. Strasser et al. (1989) showed experimentally that the local muscular strain of the hand–arm–shoulder system is dependent upon the direction of horizontal arm movements. Such strain, dependent on the direction of repetitive manual movements, is of great importance for workplace layout. The authors based their study on the premise

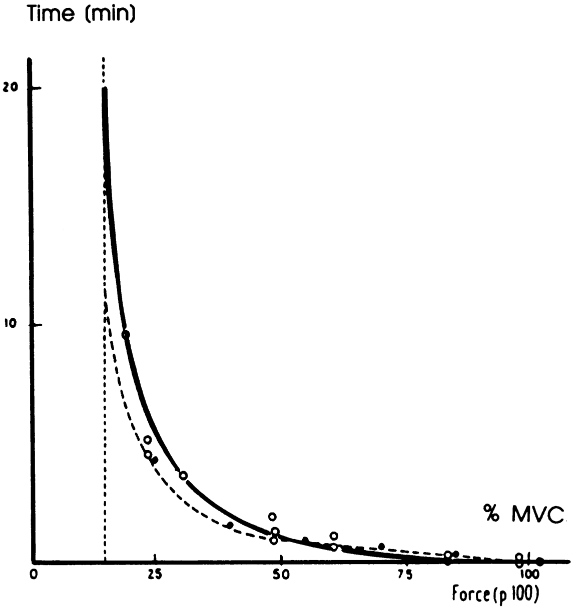


Figure 7 Isometric Muscle Endurance Time as a Function of Percentage of Muscle Strength. (Reproduced with permission from Kahn and Monod, copyright © by Taylor & Francis, http://www.tandf.co.uk 1989.)

that in order to avoid unnecessary strain imposed by unfavorable postures and working directions in repetitive material-handling tasks, patterns of static and dynamic musculoskeletal loads need to be determined. Figure 9 shows the results of this normalization procedure applied to the experimental data. The static components of the EA values within an angle range between 110° and 200° are also

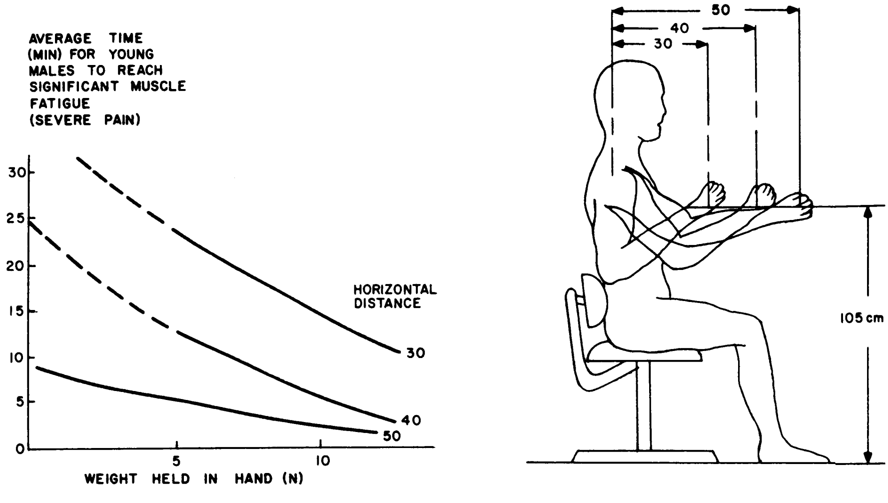


Figure 8 Endurance Time of Shoulder Muscles at Different Arm Reach Postures. (Adapted from Chaffin et al., *Occupational Biomechanics,* 3rd Ed. Copyright © 1999. Reprinted by permission of John Wiley & Sons, Inc., New York.)

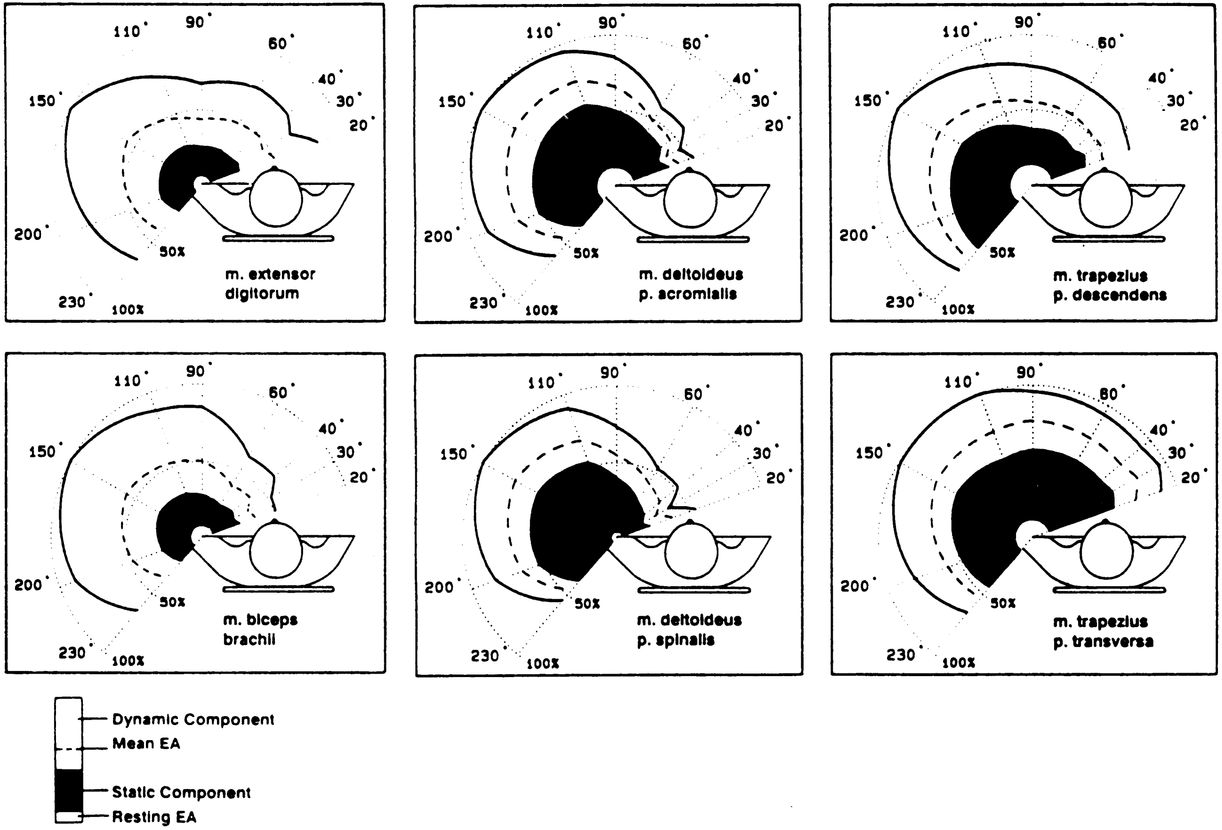


Figure 9 Illustration of Changes in Muscular Effort with the Direction of Contraction at Horizontal Plane. (Reproduced with permission from Strasser et al., copyright © by Taylor & Francis, http://www.tandf.co.uk. 1989.)

significantly higher than those of 20°, 30°, 40°, 60°, and 230°. With regard to the musculature of the shoulder region represented by two recordings of the trapezius (right part of Figure 9), an essentially lower dependence of the muscular strain on the direction of the repetitive horizontal arm movements was observed.

5. WORKPLACE ANALYSIS AND DESIGN

5.1. Evaluation of Working Postures

The posture of the human body at work is influenced by several factors, including workstation layout (heights of the workplace, orientation of tools and work objects), hand tool design, work methods and work habits, visual control and force exertion requirements, and anthropometric characteristics of the workers (Chaffin et al. 1999; Grandjean 1980; Habes and Putz-Anderson, 1985; Corlett et al. 1986; Kilbom et al. 1986; Keyserling 1986; Wallace and Buckle 1987). Poor and unnatural (i.e., not-neutral) working postures have been associated with the onset of fatigue, bodily discomforts and pains, and musculoskeletal disorders (Tichauer 1978; Karhu et al. 1977; and Keyserling et al. 1988). Keyserling (1990) discusses the scientific evidence of such associations. For example, it was shown that trunk flexion, lateral bending, or twisting increases muscle stress and intervetrabral disc pressure, while prolonged sitting or forward bending leads to increased risk of low back pain and muscle fatigue (Chaffin 1973; Schultz et al. 1982; Kelsey and Hochberg 1988). Prolonged elevation of the arms may cause tendonitis (Hagberg 1984), while shoulder extension and elevation may lead to thoracic outlet syndrome (Armstrong 1986). Also, strong association was found between poor neck posture and cervicobrachial disorders (Jonsson et al. 1988).

5.2. Computer-Aided Analysis of Working Postures

Ergonomics provides useful guidelines for evaluation of working postures, especially with respect to identification and quantification of postural stresses and their relation to posture-related work injury. The ultimate goal of such analysis is to improve the workplace design by reducing postural stresses imposed upon the body to the acceptable (safe) levels. Some of the methods used in the past to systematically evaluate work postures by using computerized or semicomputerized techniques are reported by Karhu et al. (1977); Corlett et al. (1979); Holzmann (1982); Keyserling (1986); Pearcy et al. (1987); and Wangenheim and Samuelson (1987). Snijders et al. (1987) introduced devices for measurement of forward bending, lateral bending, and torsion continuously. Ferguson et al. (1992) used a lumbar motion monitor to measure the back motion during asymmetric lifting tasks. The Ovako Working Posture Analysis System (OWAS), which uses predefined standard postures, was first reported by Karhu et al. (1977). The posture targeting technique (1988) and RULA (1996), developed by Corlett et al. (1979), are based on the recording of the positions of the head, trunk, and upper and lower arms.

5.3. Postural Analysis Systems

5.3.1. OWAS

OWAS (the Ovako Working Posture Analyzing System), first reported by Karhu et al. (1977), identifies the most common work postures for the back, arms, and legs and estimates the weight of the loads handled or the extent of the strength (effort). A rating system categorizes 72 different postures in terms of discomfort caused and the effect on health. Back postures are defined as either straight, bent, straight and twisted, or bent and twisted. No specificity (in terms of number of degrees) is provided. This categorization results in the specification of four action categories. The observed posture combinations are classified according to the OWAS method into ordinal scale action categories. The four action categories described here are based on experts' estimates on the health hazards of each work posture or posture combination in the OWAS method on the musculoskeletal system:

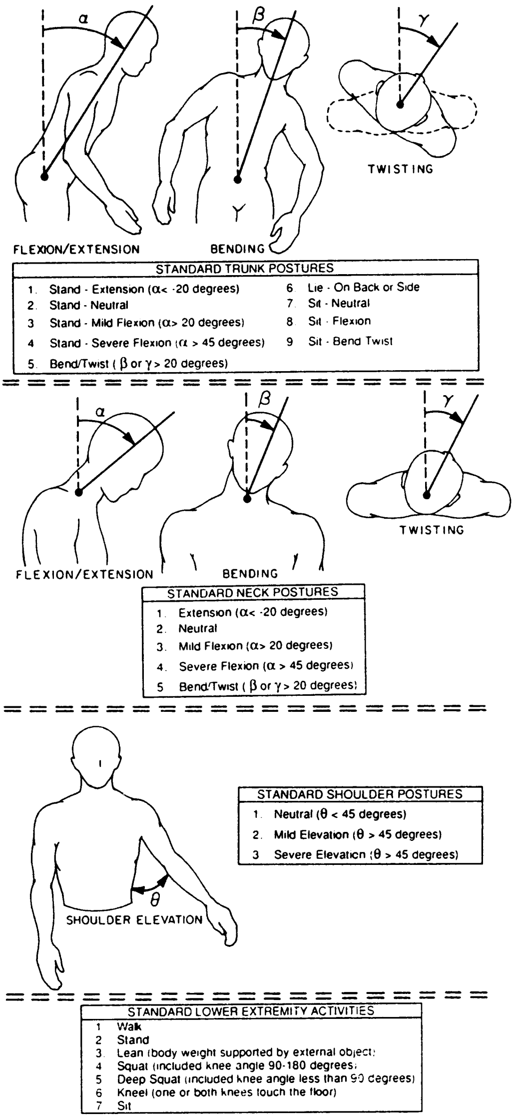
1. Work postures are considered usually with no particular harmful effect on the musculoskeletal system. No actions are needed to change work postures.
2. Work postures have some harmful effect on the musculoskeletal system. Light stress, no immediate action is necessary, but changes should be considered in future planning.
3. Work postures have a distinctly harmful effect on the musculoskeletal system. The working methods involved should be changed as soon as possible.
4. Work postures have an extremely harmful effect on the musculoskeletal system. Immediate solutions should be found to reduce these postures.

OWASCA, a computer-aided visualizing and training software for work posture analysis, was developed using OWAS. OWASCA is intended as OWAS training software (Vayrynen et al. 1990).

The system is also suitable for visualizing the work postures and for the basic analysis of the postures and their loads. The posture is presented with parametric vector using 2D graphics, OWAS codes, and texts. The posture of the back, arms and legs, posture combination, force or effort used, additional postures, and action categories can be studied interactively step by step. The required OWAS skills can be tested by OWASCA. The program shows a random work posture, and the user is asked to identify it. OWASCA describes the errors and gives the numbers of test postures and correct answers (Mattila et al. 1993).

5.3.2. *Standard Posture Model*

A standard system for analyzing and describing postures of the trunk, neck, shoulders, and lower extremities during dynamic work was developed at the University of Michigan (Keyserling 1990) (see Figure 10). Neutral joint postures and their deviations were also defined (Table 12). The postural



STANDARD TRUNK POSTURES	
1. Stand - Extension ($\alpha < -20$ degrees)	6. Lie - On Back or Side
2. Stand - Neutral	7. Sit - Neutral
3. Stand - Mild Flexion ($\alpha > 20$ degrees)	8. Sit - Flexion
4. Stand - Severe Flexion ($\alpha > 45$ degrees)	9. Sit - Bend Twist
5. Bend/Twist (β or $\gamma > 20$ degrees)	

STANDARD NECK POSTURES
1. Extension ($\alpha < -20$ degrees)
2. Neutral
3. Mild Flexion ($\alpha > 20$ degrees)
4. Severe Flexion ($\alpha > 45$ degrees)
5. Bend/Twist (β or $\gamma > 20$ degrees)

STANDARD SHOULDER POSTURES
1. Neutral ($\theta < 45$ degrees)
2. Mild Elevation ($\theta > 45$ degrees)
3. Severe Elevation ($\theta > 45$ degrees)

STANDARD LOWER EXTREMITY ACTIVITIES
1 Walk
2 Stand
3. Lean (body weight supported by external object)
4 Squat (included knee angle 90-180 degrees)
5 Deep Squat (included knee angle less than 90 degrees)
6 Kneel (one or both knees touch the floor)
7 Sit

Figure 10 Illustration of Standard Posture Categories. (Reproduced with permission from Keyserling, copyright © by Taylor & Francis, 1990.)

TABLE 12 Classification of Working Postures That Deviate from Neutral

Body Segment	Neutral Posture	Deviated Posture Description
Trunk	Vertical with no axial twisting	Extended (bent backward more than 20°) Mildly flexed (bent forward between 20 and 40°) Severely flexed (bent forward more than 45°) Bent sideways or twisted more than 20° from the neutral position
Neck		Extended (bent backward more than 20°) Mildly flexed (bent forward between 20 and 45°) Severely flexed (bent forward more than 90°) Bent sideways or twisted more than 20°
Shoulder		Neutral (included angle less than 45°) Mild elevation (included angle between 45 and 90°) Severe elevation (included angle more than 45°)
Lower extremities	(standard postures)	Walk (locomotion while maintaining an upright posture) Stand (free standing with no support other than the feet) Lean (weight partially supported by an external object such as a wall or railing) Squat (knees bent with the included angle between thigh and calf 90–180°) Deep squat (included angle between thigh and calf less than 90°) Kneel (one or both knees contact the floor and support part of the body weight) Sit (body weight primarily supported by the ischial tuberosities)

Adapted from Keyserling 1990.

analysis involves three steps. First, a continuous video recording of the job is obtained. Second, a sequential description of the major tasks required to perform the job is done in a laboratory, with the job being broken into fundamental work elements and their times measured. The third and final step involves collection of the postural data using the common time scale developed from the fundamental work elements. Postural changes are keyed into the system through the preassigned keys corresponding to specific postures. The value of each posture and the time of postural change for a given joint are recorded and stored in a computer. Based on the above data, the system generates a posture profile for each joint, consisting of the total time spent on each standard posture during the work cycle, the range of times spent in each standard posture, the frequency of posture use, and so on. The system can also provide a graph showing postural changes over time for any of the body joints (segments) of interest.

5.4. Acceptability of Working Postures

Analysis of posture must take into consideration not only the spatial elements of the posture, that is, how much is the person flexed, laterally bent, or rotated (twisted), but how long these postures are maintained. Milner et al. (1986) pointed out where an individual is working to the limits of endurance capacity, it has been found that full recovery is not possible within a rest period 12 times the maximum holding time. Full recovery is possible as long as the holding time is a small percentage of maximum handling time.

Bonney et al. (1990) studied tolerability of certain postures and showed that complex postures requiring movement in more than one direction are more uncomfortable than simple postures. Lateral bending produced more discomfort than either flexed or rotated postures and appears to be the least well-tolerated posture. Rotation by itself does not cause significant discomfort. This finding is consistent with epidemiological results of Kelsey and Golden (1988), who hypothesized that twisting along may not produce enough stress to bring about a detectable increase in risk.

Corlett and Manenica (1980) derived estimates for maximum handling times for various postures when performing a no-load task. These recommendations are as follows:

1. Slightly bent forward postures (approx. 15–20°) = 8 min
2. Moderately bent forward posture (approx. 20–60 °) = 3–4 min
3. Severely bent forward postures (greater than about 60°) = approx. 2 min

Colombini et al. (1985) presented criteria on which posture assessments should be based. Postures considered tolerable include (1) those that do not involve feelings of short-term discomfort and (2) those that do not cause long-term morpho-functional complaints. Short-term discomfort is basically the presence of a feeling of fatigue and/or pain affecting any section of the asteo-arthromuscular and ligamentous apparatus appearing in periods lasting minutes, hours, or days.

Miedema et al. (1997) derived the maximum holding times (MHT) of 19 standing postures in terms of percent of shoulder height and percent of arm reach. They also classified such working postures into three categories, depending on the mean value of the MHT: (1) comfortable; (2) moderate; and (3) uncomfortable postures (see Table 13).

Recently, Kee and Karwowski (2001) presented data for the joint angles of isocomfort (JAI) for the whole body in sitting and standing postures, based on perceived joint comfort measures. The JAI value was defined as a boundary indicating joint deviation from neutral (0°), within which the perceived comfort for different body joints is expected to be the same. The JAI values were derived for nine verbal categories of joint comfort using the regression equations representing the relationships between different levels of joint deviation and corresponding comfort scores for each joint motion. The joint angles with marginal comfort levels for most motions around the wrist, elbow, neck, and ankle were similar to the maximum range-of-motion (ROM) values for these joints. However, the isocomfort joint angles with the marginal comfort category for the back and hip motions were much smaller than the maximum ROM values for these joints.

There were no significant differences in percentage of JAI in terms of the corresponding maximum ROM values between standing and sitting postures. The relative marginal comfort index, defined as the ratio between joint angles for marginal comfort and the corresponding maximum ROM values, for hip was the smallest among all joints. This was followed in increasing order of the index for lower back and for shoulder, while the index values for elbow were the largest. This means that hip motions are less comfortable than any other joint motion, while elbow motions are the most comfortable. The relative good comfort index exhibited much smaller values of joint deviation, with most

TABLE 13 MHT and Postural Load Index for the 18 Postures[a]

Posture Categories	MHT (min)	Postural Load Index
Comfortable postures (MHT > 10 min)		
SH/AR = 75/50	37.0	3
75/25	18.0	3
100/50	17.0	3
50/25	14.0	0
125/50	12.0	8
50/50	12.0	0
Moderate postures (5 min $\leq$ MHT $\leq$ 10 min)		
100/25	10.0	7
100/100	9.0	5
75/100	9.0	4
125/100	8.0	8
75/75	6.0	12
50/100	6.0	10
100/75	5.5	8
50/75	5.3	5
Uncomfortable postures (MHT < 5 min)		
25/25	5.0	10
25/50	4.0	10
150/50	3.5	13
25/75	3.3	10
25/100	3.0	13

[a] Posture was defined after Miedema et al. 1997 in terms of % of shoulder height (SH)/% of arm reach (AR).

TABLE 14 Summary of ISO/CEN Draft Standards and Work Items

Ergonomic guiding principles

ISO 6385: 1981-06-00

ENV 26385: 1990-06-00

Ergonomic principles of the design of work systems

EN 614-1: 1995-02-00

Safety of machinery—Ergonomic design principles—Part 1: Terminology and general principles

prEN 614-2: 1997-12-00

Safety of machinery—Ergonomic design principles—Part 2: Interactions between the design of machinery and work tasks

Anthropometry

EN 547-1: 1996-12-00

ISO/DIS 15534-1:1998-04-00

Safety of machinery—Human body measurements—Part 1: Principles for determining the dimensions required for openings for whole body access into machinery for mobile machinery.

EN 547-2: 1996-12-00

ISO/DIS 15534-2:1998-04-00

Safety of machinery—Human body measurements—Part 2: Principles for determining the dimensions required for access openings

EN 547-3: 1996-12-00

ISO/DIS 15534-3:1998-04-00

Safety of machinery—Human body measurements—Part 3: Anthropometric data

ISO 7250: 1996-07-00

EN ISO 7250: 1997-07-00

Basic human body measurements for technological design (ISO 7250:1996)

ISO/DIS 14738: 1997-12-00

prEN ISO 14738: 1997-12-00

Safety of machinery—Anthropometric requirements for the design of workstations at machinery

Ergonomics—Computer manikins, body templates

Under preparation

Selection of persons for testing of anthropometric aspects of industrial products and designs

Under preparation:

Safeguarding crushing points by means of a limitation of the active forces

Under preparation:

Ergonomics—Reach envelopes

Under preparation:

Anthropometric database

Document scope:

The European Standard establishes an anthropometric database for all age groups to be used as the basis for the design of work equipment, workplaces, and workstations at machinery.

Under preparation:

Notation system of anthropometric measurements used in the European Standards EN 547 Part 1 to Part 3

Biomechanics

prEN 1005-1: 1998-12-00

Safety of machinery—Human physical performance—Part 1: Terms and Definitions

prEN 1005-2: 1998-12-00

Safety of machinery—Human physical performance—Part 2: Manual handling of machinery and component parts of machinery

prEN 1005-3: 1998-12-00

Safety of machinery—Human physical performance—Part 3: Recommended force limits for machinery operation

prEN 1005-4: 1998-11-00

Safety of machinery—Human physical performance—Part 4: Evaluation of working postures in relation to machinery

Under preparation:

Safety of machinery—Human physical performance—Part 5: Risk assessment for repetitive handling at high frequency

ISO/DIS 11226; 1999-02-00

Ergonomics—Evaluation of working postures

ISO/DIS 11228-1: 1998-08-00

Ergonomics—Manual handling—Part 1: Lifting and carrying

TABLE 14 (*Continued*)

Under preparation:
Ergonomics—Manual handling—Part 2: Pushing and pulling
Document scope: To be defined
Under preparation:
Ergonomics—Manual Handling—Part 3: Handling, at high repetition of low loads
Document scope: To be defined
Under preparation:
Ergonomic design of control centers—Part 4: Workstation layout and dimensions

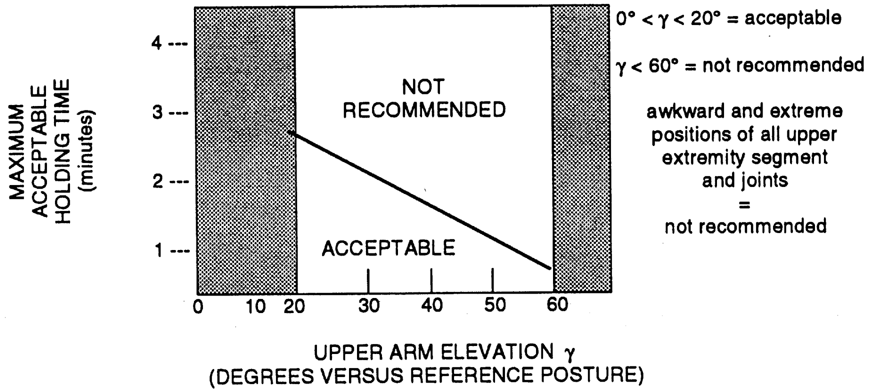
Ergonomics of operability of mobile machines
Under preparation:
Ergonomic design principles for the operability of mobile machinery
Under preparation:

Integrating ergonomic principles for machinery design
Under preparation:
Safety of machinery—Guidance for introducing ergonomic principles and for the drafting of the ergonomics' clauses

The holding time for upper arm elevation can beevaluated as follows.

HOLDING TIME	ACCEPTABLE	NOT RECOMMENDED
> maximum acceptable holding time*		X
≤ maximum acceptable holding time*	X	

- Refer to diagram shown below.

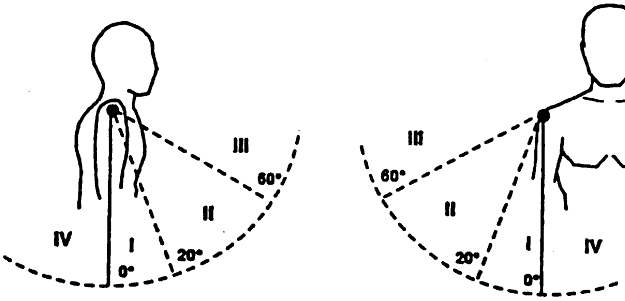


Note: An adequate recovery time should be provided following the holding time for a certain upper arm elevation.

Figure 11 Evaluation of Working Postures (ISO/DIS 11226, 1998).

UPPER ARM ELEVATION

STEP 1 – refer to figure and table below



Upper arm elevation

Evaluation of upper arm elevation

	Static posture	Movement	
		low frequency (<2/minute)	high frequency (≥2/minute)
I*	acceptable	ACCEPTABLE	acceptable
II	conditonally acceptable (step 2A)	acceptable	conditionally acceptable (step 2C)
III	not acceptable	conditionally acceptable (step 2B)	not acceptable
IV	not acceptable	conditionally acceptable (step 2B)	not acceptable

Static posture and high frequency movements (≥ 2 / minute), awkward and extreme positions of all upper extremity segments and joints
=
not acceptable

* It is recommended to strive for working postures with the upper arms hanging down.

STEP 2:
a) acceptable if there is full arm support; if there in so full arm support, acceptability depends on duration of the posture and period of recovery;
b) not acceptable if the machine may be used for long durations;
c) not acceptable if frequency ≥10 / minute and/or if the machine may be used for long durations.

Figure 12 Evaluation of Working Postures in Relation to Machinery (CEN prEN 1005—4, 1997): Upper arm elevation.

index values of less than 40.0. The presented data about joint angles of isocomfort can be used as design guidelines for postural comfort in a variety of human–machine systems.

5.5. International Standards

A list of international standards in the area of anthropometry and biomechanics being developed by ISO is shown in Table 14.

5.5.1. Exposure Assessment of Upper-Limb Repetitive Movements

Recently, Colombini et al. (1999) reported the findings of an international expert group working under auspices of the Technical Committee on Musculoskeletal Disorders of the International Ergonomics Association (IEA) and endorsed by the International Commission on Occupational Health (ICOH). This report provides a set of definitions, criteria, and procedures for assessment of working conditions with respect to exposure of the upper extremities. The document includes two important international standards: Evaluation of Working Postures (ISO/DIS 11226 1998), presented in Figure 11, and Evaluation of Working Postures in Relation to Machinery (CEN prEN 1005—4, 1997): Upper arm elevation, shown in Figure 12.

5.5.2. European Standards for Working Postures During Machinery Operation

The draft proposal of the European (CEN/TC122, WG4/SG5) and the international (ISO TC159/SC3/WG2) standardization document (1993) ''Safety of machinery—human physical performance, Part 4: Working postures during machinery operation,'' specifies criteria of acceptability of working postures vs. exposure times. These criteria are discussed below.

5.5.2.1. General Design Principles Work task and operation should be designed with sufficient physical and mental variation so that the physical load is distributed over various postures and patterns of movements. Designs should accommodate the full range of possible users. To evaluate whether working postures during machinery operation are acceptable, designers should perform a risk assessment, that is, an evaluation of the actual low-varying (static) postures of body segments. The lowest maximum acceptable holding time for the various body segment postures should be determined.

5.5.2.2. Assessment of Trunk Posture An asymmetric trunk posture should be avoided (no trunk axial rotation or trunk lateral flexion). Absence of normal lumbar spine lordosis should be avoided. If the trunk is inclined backward, full support of the lower and upper back should be provided. The forward trunk inclination should be less than 60°, on the condition that the holding time be less than the maximum acceptable holding time for the actual forward trunk inclination, as well as that adequate rest is provided after action (muscle fitness should not be below 80%).

5.5.2.3. Assessment of Head Posture An asymmetric head posture should be avoided (no axial rotation or lateral flexion of the head with respect to the trunk). The head inclination should not be less than trunk inclination (no neck extension). The head inclination should not be larger than the trunk inclination for more than 25° (no extreme neck flexion). If the head is inclined backward, full head support should be provided. The forward head inclination should be less than 25° (if full trunk support is provided), forward inclination should be between less than 85°, on the condition that the holding time should be less than the maximum acceptable holding time for the actual forward head inclination as well as that adequate rest is provided.

5.5.2.4. Assessment of Upper Extremity Posture *Shoulder and upper arm posture.* Upper arm retroflexion and upper-arm adduction should be avoided. Raising the shoulder should be avoided. The upper-arm elevation should be less than 60°, on the condition that the holding time be less than the maximum acceptable holding time for the actual upper-arm elevation as well as that adequate rest be provided after action (muscle fitness should not be below 80%).

Forearm and hand posture. Extreme elbow flexion or extension, extreme forearm pronation or supination, and extreme wrist flexion or extension should be avoided. The hand should be in line with the forearm (no ulnar/radial deviation of the wrist).

6. OCCUPATIONAL BIOMECHANICS

6.1. Definitions

As reviewed by Karwowski (1992), occupational biomechanics is a ''study of the physical interaction of workers with their tools, machines and materials so as to enhance the worker's performance while minimizing the risk of future musculoskeletal disorders'' (Chaffin et al. 1999). There are six methodological areas, or contributing disciplines, important to the development of current knowledge in biomechanics:

1. Kinesiology, or study of human movement, which includes kinematics and kinetics
2. Biomechanical modeling methods, which refer to the forces acting on the human body while a worker is performing well-defined and rather common manual task
3. Mechanical work-capacity evaluation methods in relation to physical capacity of the worker and job demands
4. Bioinstrumentation methods (performance data acquisition and analysis)
5. Classification and time-prediction methods that allow for detailed time analysis of the human work activities and implementation of biomechanics principles to fit the workplace to the worker

6.2. Principles of Mechanics

Biomechanics considers safety and health implications of mechanics, or the study of the action of forces, for the human body (its anatomical and physiological properties) in motion (at work) and at rest. Mechanics, which is based on Newtonian physics, consists of two main areas: statics or the study of the human body at rest or in equilibrium, and dynamics or the study of the human body in motion. Dynamics is further subdivided into two main parts, kinematics and kinetics. Kinematics is concerned with the geometry of motion, including the relationships among displacements, velocities, and accelerations in both translational and rotational movements, without regard to the forces involved. Kinetics, on the other hand, is concerned with forces that act to produce the movements.

The types of forces acting on the human body at any given time are gravitational forces, external forces and ground reaction forces, and muscle forces (Winter 1979). Gravitational forces act downward, through the center of mass of body segments. The external forces are due to the body segment weights and external workload. The forces generated by the muscles are usually expressed as net muscle moments acting upon given joints. It should be noted that body (segment) weight is a (gravitational) force, while body mass is a measure of inertia.

6.3. Biomechanical Analysis

6.3.1. Static Analysis

Static analysis requires consideration of forces and moments of force acting on the body at rest (static equilibrium). A magnitude of the moment of force at the point of rotation is equal to the product of force and the perpendicular distance from the force action line to that point. The moment **(M)** equals force **(F)** times moment arm **(d)**, with unit of measurement (N·m). The static analysis ignores the effects of accelerations, momentum, and friction and is adequate only for analysis of static postures.

The body will be in a static equilibrium state when at rest or dynamic equilibrium when in motion with constant velocity. The translational equilibrium (first condition) of the body (segment) is present when the vector sum of all the forces acting on a body simultaneously is zero ($\Sigma F = 0$). The rotational equilibrium (second condition) of the body is present when the sum of moments about joint is zero ($\Sigma M = 0$). In other words, for the body to be at rest (zero velocity), the sum of all clockwise moments must be equal to the sum of all counterclockwise moments.

6.3.2. Lever Systems

Skeletal muscles of the human body produce movements of the bones about the joints by pulling at their anatomical attachments on the bones across the joints in order to counteract the external forces. This is possible due to three types of lever systems, composed of bones that serve as levers and joints that serve as points of pivot or fulcrums. The lever system consists of an effort force and the resistance force acting at different locations and distances with respect to the fulcrum. The force arm

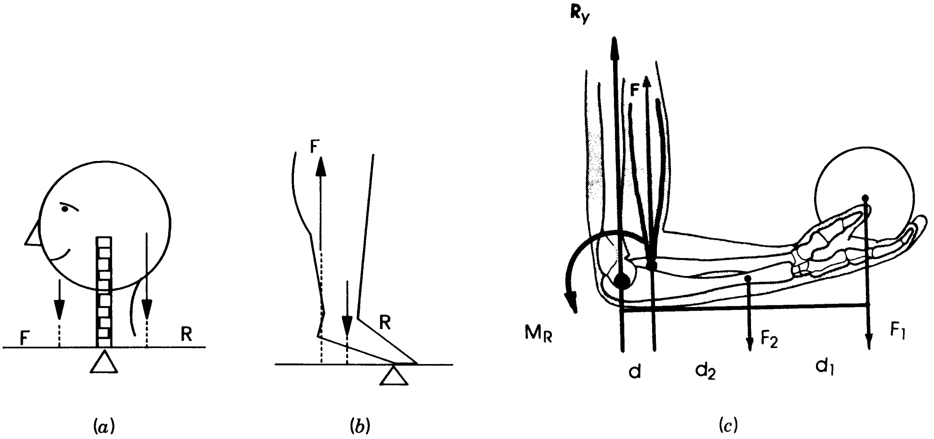


Figure 13 (a) Example of the first-class lever system. (b) Example of the second-class lever system. (c) Example of the third-class lever system and single-segment static analysis. (Adapted from Troup and Edwards, reproduced with permission of the Controller of Her Majesty's Stationery Office)

and the resistance arm are defined as the distance from the fulcrum to the effort force or resistance force, respectively. Mechanical advantage (MA) of the lever system is defined as the ratio between the force arm distance (df) and the resistance arm distance (dr) where MA = df/dr.

In the first class of lever systems, the fulcrum is located between the effort and resistance. Examples include the triceps muscle action of the ulna when the arm is abducted and held over the head, and the splenium muscles, acting to extend the head across the atlanto-occipital joints (Williams and Lissner 1977). The second class of lever systems is one where resistance is located between the fulcrum and the effort, providing for mechanical advantage greater than one. An example of such a lever system is the distribution of forces in the lower leg when raising one's heel off the ground (see Figure 13). In the third class of lever systems, the effort is located between the fulcrum and the resistance, and consequently the mechanical advantage is always less than one, that is, to balance the resistance, the magnitude of effort must be greater than the magnitude of resistance. Many bone lever systems in the human body, for example, the system involved in forearm flexion as illustrated in Figure 13(*c*), are third-class systems.

7. DESIGN OF MANUAL MATERIALS HANDLING TASKS

7.1. Epidemiology of Low-Back Disorders

As reviewed by Ayoub et al. (1997), manual materials-handling (MMH) tasks, which include unaided lifting, lowering, carrying, pushing, pulling, and holding activities, are the principal source of compensable work injuries affecting primarily the low back in the United States (NIOSH 1981; National Academy of Sciences 1985; *Federal Register* 1986; Bigos et al. 1986; Battié et al. 1990). These include a large number of low-back disorders (LBDs) that are due to either cumulative exposure to manual handling of loads over a long period of time or to isolated incidents of overexertion when handling heavy objects (BNA 1988; National Safety Council 1989; Videman et al. 1990). Overexertion injuries in 1985 for the United States accounted for 32.7% of all accidents: lifting objects (15.1%), carrying, holding, etc. (7.8%), and pulling or pushing objects (3.9%). For the period of 1985–1987, back injuries accounted for 22% of all cases and 32% of the compensation costs.

In the United States, about 28.2% of all work injuries involving disability are caused by overexertion, lifting, throwing, folding, carrying, pushing, or pulling loads that weigh less than 50 lb (National Safety Council 1989). The analysis by industry division showed that the highest percent of such injuries occurred in service industries (31.9%), followed by manufacturing (29.4%), transportation and public utility (28.8%), and trade (28.4%). The total time lost due to disabling work injuries was 75 million workdays, while 35 million days were lost due to other accidents. The total work accident cost was $47.1 billion; the average cost per disabling injury was $16,800. Spengler et al. (1986) reported that while low-back injuries comprised only 19% of all injuries incurred by the workers in one of the largest U.S. aircraft companies, they were responsible for 41% of the total injury costs. It is estimated that the economic impact of back injuries in the United States may be as high as 20 billion annually, with compensation costs exceeding $6 billion per year (BNA 1988).

Major components of the MMH system, related risk factors for low-back pain (LBP), and LBDs include worker characteristics, material/container characteristics, task/workplace characteristics, and work practice characteristics (Karwowski et al. 1997). A wide spectrum of work- and individual-related risk factors have been associated with the LBP and LBDs (Riihimäki 1991). However, the precise knowledge about the extent to which these factors are etiologic and the extent to which they are symptom precipitating or symptom aggravating is still limited. Kelsey and Golden (1988) reported that the risk of lumbar disk prolapse for workers who lift more than 11.3 kg (25 lb) more than 25 times a day is over three times greater than for workers who lift lower weights. The OSHA (1982) study also revealed very important information regarding workers perception of the weights lifted at the time of injury. Among the items perceived by the workers as factors contributing to their injuries were lifting too-heavy objects (reported by 36% of the workers) and underestimation of weight of objects before lifting (reported by 14% of the workers).

An important review of epidemiological studies on risk factors of LBP using five comprehensive publications on LBP was made by Hildebrant (1987). A total of 24 work-related factors were found that were regarded by at least one of the reviewed sources as risk indicators of LBP. These risk factors include the following categories:

1. *General:* heavy physical work, work postures in general
2. *Static workload:* static work postures in general, prolonged sitting, standing or stooping, reaching, no variation in work posture
3. *Dynamic workload:* heavy manual handling, lifting (heavy or frequent, unexpected heavy, infrequent, torque), carrying, forward flexion of trunk, rotation of trunk, pushing/pulling
4. *Work environment:* vibration, jolt, slipping/falling
5. *Work content:* monotony, repetitive work, work dissatisfaction

Many of the cross-sectional studies have shown that LBP is related to heavy manual work (Riihimäki 1991). MMH activities, including those that involve sudden body motions, have been associated with LBP (Svensson and Andersson 1983; Frymoyer et al. 1983, Hansson 1989; Bigos et al. 1991). Among the office workers, LBP was most commonly attributed to lifting tasks (Lloyd et al. 1986). An increased risk of herniated disc was also reported in jobs involving heavy lifting combined with body twisting and forward bending (Kelsey et al. 1984). Manual lifting tasks are often associated with adopting nonneutral trunk postures, which also have been related to LBP (Frymoyer et al. 1980; Maeda et al. 1980; Keyserling et al. 1988; Riihimäki et al 1989).

In addition to physical factors, several studies identified a variety of psychological and psychosocial risk factors of LBP that are related to work environment (Damkot et al. 1984; Magora 1973; Svensson and Andersson 1983, 1989; Bigos et al. 1991). However, as pointed out by Riihimäki (1991), since most of the studies have been retrospective in nature, it is difficult to determine whether these factors are antecedents or consequences of back pain (Kelsey et al. 1988), and whether these factors play a role in the etiology of LBDs or only affect the perception of symptoms and sickness behavior.

7.2. MMH Capacity Design Criteria

Workers who perform heavy physical work are subjected not only to forces and stresses from the immediate physical environment but also to mechanical forces generated from within the body. As a result of these forces and stresses, a strain is produced on the worker's musculoskeletal system as well as on other systems such as the cardiopulmonary system. One of the most important issues in the application of ergonomics to work design is to reduce the stresses imposed on the musculoskeletal and cardiopulmonary systems (Ayoub and Mital 1989). Several approaches have been used by different investigators to establish safe handling limits, including the psychophysical approach, the physiological approach, and the biomechanical approach.

7.3. The Psychophysical Approach

The psychophysical approach relies on the worker's perceived exertion to quantify his or her tolerance level, thereby establishing the maximum acceptable weights or forces (MAW/F) for different MMH activities (e.g., maximum acceptable weight of lift [MAWL]). Psychophysics deals with the relationship between human sensation and their physical stimuli. Borg (1962) and Eisler (1962) found that the perception of both muscular effort and force obey the psychophysical function, where sensation magnitude (S) grows as a power function of the stimulus (I). Stevens (1975) reported the relationship between the strength of the sensation (S) and the intensity of its physical stimulus (I) by the power function:

$$S = k \times I^n$$

where: S = strength of sensation
I = intensity of physical stimulus
k = constant
n = slope of the line, which represents the power function when plotted on log–log coordinates

The use of psychophysics in the study of MMH tasks requires the worker to adjust the weight, force, or frequency in a handling situation until they feel it represents their MAW/F (Asfour et al. 1984; Gamberale and Kilböm 1988; Garg and Banagg 1988; Legg and Myles 1985; Mital et al. 1989; Snook and Ciriello 1991). Psychophysical limits usually refer to weights or forces (MAW/F), although maximum acceptable frequencies have also been established (e.g., Nicholson and Legg 1986; Snook and Ciriello 1991). Despite the relative simplicity of the psychophysical method to determine acceptable limits for manual lifting, which makes this approach quite popular (Karwowski et al 1999), caution should be exercised with respect to interpretation and usability of the currently available design limits and databases.

7.4. MMH Design Databases

One can use already available databases such as the one reported by Snook and Ciriello (1991). Another database was reported by Mital (1992) for symmetrical and asymmetrical lifting, and other databases include work by Ayoub et al. (1978) and Mital (1984). Using such available data replaces conducting a study for every work task and group of workers. Tables provided by the various investigators can be used to estimate the MAW/F for a range of job conditions and work populations. The databases provided in tabular format often make allowances for certain task, workplace, and/or worker characteristics. The use of databases begins with the determination of the various characteristics with which the database is stratified.

7.5. Psychophysical Models

Another method to estimate MAW/F is regression models based on the psychophysical data. Most of these models predict MAWL. The design data presented here are based upon the database of Snook and Ciriello (1991). Table 15 provides Snook and Ciriello's (1991) two-handed lifting data for males and females, as modified by Mital et al. (1993). Those values that were modified have been identified. The data in these tables were modified so that a job severity index value of 1.5 is not exceeded, which corresponds to 27.24 kg. Likewise, a spinal compression value that, on average, provides a margin of safety for the back of 30% was used for the biomechanical criterion, yielding a maximum load of 27.24 for males and 20 kg for females. Finally, the physiological criterion of energy expenditure was used. The limits selected were 4 kcal/min for males and 3 kcal/min for females for an 8-hr working day (Mital et al. 1993). The design data for maximal acceptable weights for two-handed pushing/pulling tasks, maximal acceptable weights for carrying tasks, and maximal acceptable holding times can be found in Snook and Ciriello (1991) and Mital et al. (1993). The maximal acceptable weights for manual handling in unusual postures are presented by Smith et al. (1992).

7.6. The Physiological Approach

The physiological approach is concerned with the physiological response of the body to MMH tasks. During the performance of work, physiological changes take place within the body. Changes in work methods, performance level, or certain environmental factors are usually reflected in the stress levels of the worker and may be evaluated by physiological methods. The basis of the physiological approach to risk assessment is the comparison of the physiological responses of the body to the stress of performing a task with levels of permissible physiological limits. Many physiological studies of MMH tended to concentrate on whole body indicators of fatigue such as heart rate, energy expenditure, blood lactate, or oxygen consumption as a result of the workload. Mital et al. (1993) arrived at the same conclusion as Petrofsky and Lind, that is, that the physiological criteria for lifting activities for males should be approximately 4 kcal/min and 3 kcal/min for females.

The energy cost of manual handling activities can be estimated based on the physiological response of the body to the load, that is, by modeling the physiological cost using work and worker characteristics. The estimates obtained from such models are then compared to the literature recommendations of permissible limits. Garg et al. (1978) report metabolic cost models. Although currently in need of update, they still provide a more comprehensive and flexible set of physiological cost models as a function of the task variables. The basic form of the Garg et al. model is:

$$E_{\text{job}} = \left(\sum_{i=1}^{N_p} (\mathrm{E}_{\text{post-}i} \times T_i) + \sum_{i=1}^{N_t} \mathrm{E}_{\text{task-}i} \right) \div T$$

where: E_{job} = average energy expenditure rate of the job (kcal/min)
$E_{\text{post-}i}$ = metabolic energy expenditure rate due to maintenance of ith posture (kcal/min)
T_i = time duration of ith posture (min)
N_p = total number of body postures employed in the job
$E_{\text{task-}i}$ = net metabolic energy expenditure of the ith task in steady state (kcal)
N_t = total number of tasks in the given job
T = time duration of the job (min)

Different models require different input data, but typically most of these models involve input information regarding task type, load weight/force, load size, height, frequency, and worker characteristics, which include body weight and gender.

7.7. The Biomechanical Approach

The biomechanical approach focuses on the establishment of tissue tolerance limits of the body, especially the spine (e.g., compressive and shear force limits tolerated by the lumbar spine). The levels of stresses imposed on the body are compared to permissible levels of biomechanical stresses, measured by, for example, peak joint moments, peak compressive force on the lumbar spine, and peak shear forces on the lumbar spine. Other measures include mechanical energy, average and integrated moments or forces over the lifting, and MMH activity times (Andersson 1985; Gagnon and Smyth 1990; Kumar 1990). Methods used to estimate the permissible level of stress in biomechanics for MMH include strength testing, lumbar tissue failure, and the epidemiological relationship between biomechanical stress and injury.

Tissue failure studies are based on cadaver tissue strength. Generally, the research has focused on the ultimate compressive strength of the lumbar spine. Studies and literature reviews by Brinckmann et al. (1989) and Jäger and Luttmann (1991) indicate that the ultimate compressive strength of

TABLE 15 Recommended Weight of Lift (kg) for Male (Female) Industrial Workers for Two-Handed Symmetrical Lifting for Eight Hours

		Floor to 80 cm Height							
		Frequency of Lift							
Cont. Size		1/8 hr	1/30 min	1/5 min	1/min	4/min	8/min	12/min	16/min
75 cm	90	17 (12)	14 (9)	14 (8)	11(7)	9 (7)	7 (6)	6 (5)	4.5 (4)
	75	24 (14)	21 (11)	20 (10)	16 (9)	13 (9)	10.5 (8)	9 (7)	7 (6)
	50	27* (17)	27* (13)	27 (12)	22 (11)	17 (10)	14 (9)	12 (8)	9.5 (7)
	25	27* (20*)	27* (15)	27* (14)	27* (13)	21 (12)	17.5 (11)	15 (9)	12 (7)
	10	27* (20*)	27* (17)	27* (16)	27* (14)	25 (14)	20.5 (13)	18 (11)	14.5 (9)
49 cm	90	20 (13)	17 (9)	16 (8)	13 (8)	10 (8)	7 (7)	7 (6)	6.5 (5)
	75	27* (16)	24 (12)	24 (10)	19 (10)	14 (9)	10 (8)	10 (7)	9 (6)
	50	27* (19)	27* (14)	27* (13)	26 (12)	19 (11)	15 (10)	12.5 (9)	10 (8)
	25	27* (20*)	27* (17)	27* (15)	27* (14)	24 (13)	18.5 (11)	15 (10)	12 (8)
	10	27* (20*)	27* (19)	27* (17)	27* (15)	28 (15)	22 (13)	17.5 (11)	15 (9)
34 cm	90	23 (15)	19 (11)	19 (10)	15 (9)	11 (9)	7 (8)	7 (7)	6.5 (7)
	75	27* (19)	27* (14)	27* (13)	22 (12)	17 (11)	10 (9)	10 (8)	9.5 (7)
	50	27* (20*)	27* (17)	27* (16)	27* (14)	22 (13)	15 (11)	14 (10)	12 (8)
	25	27* (20*)	27* (20*)	27* (18)	27* (17)	27* (15)	20 (13)	17 (12)	14 (10)
	10	27* (20*)	27* (20*)	27* (20*)	27* (19)	27* (18)	25 (15)	21 (13)	15 (11)
75 cm	90	15 (10)	13 (7.5)	13 (6.5)	10 (6)	8 (6)	6 (5)	6 (4)	4 (3)
	75	22 (12)	20 (9)	19 (8)	14.5 (7.5)	12 (7.5)	10 (6.5)	9 (6)	7 (5)
	50	27* (14)	25 (11)	24 (10)	20 (9)	15 (8)	13 (7.5)	11 (6.5)	9 (6)
	25	27* (17)	27* (12.5)	27* (11.5)	24.5 (11)	18 (10)	15 (9)	12 (7.5)	11 (6.5)
	10	27* (19)	27* (14)	27* (13)	27* (11.5)	22 (11.5)	19 (11)	16 (9)	13 (8)
49 cm	90	18 (11)	16 (7.5)	15 (6.5)	12.5 (6.5)	9 (6.5)	6 (6)	6 (5)	5 (4)
	75	27 (13)	22.5 (10)	22.5 (8)	18 (8)	14 (7.5)	10 (6.5)	9 (6)	8 (5)
	50	27* (16)	27* (11.5)	27* (11)	24 (10)	18 (9)	14 (8)	12 (7.5)	10 (6.5)
	25	27* (17)	27* (14)	27* (12.5)	27* (11.5)	22 (11)	18 (9.5)	14 (8)	11 (7)
	10	27* (19)	27* (16)	27* (14)	27* (12.5)	27 (12.5)	21 (11)	17 (9)	14 (7.5)
34 cm	90	22 (12.5)	18 (9)	18 (8)	14 (7.5)	11 (7.5)	6 (6.5)	6 (6)	5 (5)
	75	27* (16)	26 (11.5)	25 (11)	21 (10)	16 (9)	10 (8)	9 (6.5))	8 (5.5)
	50	27* (19)	27* (14)	27* (13)	27* (11.5)	22 (11)	14 (9.5)	12 (8)	10 (7)
	25	27* (20*)	27* (17)	27* (15)	27* (14)	27 (12.5)	20 (11)	14 (10)	11 (9)
	10	27* (20*)	27* (19)	27* (17)	27* (16)	27* (15)	21 (13)	17 (11)	14 (9)

TABLE 15 (*Continued*)

Floor to 80 cm Height									
		Frequency of Lift							
Cont. Size		1/8 hr	1/30 min	1/5 min	1/min	4/min	8/min	12/min	16/min
75 cm	90	15 (9)	12 (6)	12 (6)	9.5 (5)	8 (5)	6 (4.5)	5 (4)	3 (3)
	75	21 (11)	18 (8)	17 (7)	14 (7)	11 (7)	9 (6)	8 (5)	6 (4.5)
	50	27* (12.5)	24 (10)	23 (9)	19 (8)	15 (7)	12 (7)	10 (6)	8 (5.5)
	25	27* (15)	27* (11)	27* (10)	24 (10)	18 (9)	14 (8)	12 (7)	9 (6)
	10	27* (17)	27* (12.5)	27* (12)	27* (10)	22 (10)	18 (10)	15 (8)	12 (7)
49 cm	90	17 (10)	15 (7)	14 (6)	11 (6)	9 (6)	6 (5.5)	6 (4.5)	4 (3.5)
	75	24 (12)	21 (9)	21 (7)	16 (7)	12 (7)	9 (6)	9 (5)	7 (4.5)
	50	27* (14)	27* (10)	27* (10)	22 (9)	16 (8)	14 (7)	12 (7)	10 (6)
	25	27* (15)	27* (12)	27* (11)	27* (10)	20 (10)	17 (8.5)	14 (7)	11 (6.5)
	10	27* (17)	27* (14)	27* (12)	27* (11)	23 (11)	20 (10)	17 (8)	14 (7)
34 cm	90	20 (11)	16 (8)	16 (7)	13 (7)	9 (7)	6 (6)	6 (5)	4 (4.5)
	75	27* (14)	24 (10)	24 (10)	19 (9)	15 (8)	9 (7)	9 (6)	7 (5)
	50	27* (17)	27* (12)	27* (12)	26 (10)	19 (10)	14 (8.5)	12 (7)	10 (6)
	25	27* (20)	27* (15)	27* (13.5)	27* (12)	23 (11)	20 (10)	14 (9)	11 (8)
	10	27* (20*)	27* (17)	27* (15)	27* (14)	27* (13.5)	24 (12)	17 (10)	14 (8)
75 cm	90	19 (13)	18 (11)	16 (10)	15 (9)	13 (8)	7 (6)	6 (6)	5 (5)
	75	25 (15)	23 (13)	21 (12)	20 (11)	17 (9)	8 (7)	8 (7)	7 (6)
	50	27* (17)	27* (15)	26 (14)	25 (13)	21 (11)	12 (9)	11 (9)	9 (8)
	25	27* (20)	27* (17)	27* (16)	27* (14)	26 (12)	17 (11)	13 (10)	12 (9)
	10	27* (20*)	27* (19)	27* (17)	27* (16)	27* (14)	23 (12.5)	20 (11)	16 (9.5)
49 cm	90	19 (13)	18 (11)	16 (10)	15 (9)	13 (8)	7 (6)	6 (6)	5 (5)
	75	25 (15)	23 (13)	21 (12)	20 (11)	17 (9)	8 (7)	8 (7)	7 (6)
	50	27* (17)	27* (15)	26 (14)	25 (13)	21 (11)	12 (9)	11 (9)	9 (8)
	25	27* (20)	27* (17)	27* (16)	27* (14)	26 (12)	17 (11)	13 (10)	12 (9)
	10	27* (20*)	27* (19)	27* (17)	27* (16)	27* (14)	23 (12.5)	20 (11)	16 (9.5)
34 cm	90	22 (14)	20 (12)	18 (11)	17 (10)	14 (9)	7 (7)	6 (6.5)	5 (6.5)
	75	27* (17)	26 (14)	23 (13)	22 (12)	18 (11)	8 (8.5)	8 (8.5)	7 (8)
	50	27* (19)	27* (17)	27* (15)	27* (14)	23 (13)	12 (11)	11 (10)	9 (8.5)
	25	27* (20*)	27* (19)	27* (17)	27* (16)	27 (14)	17 (13.5)	13 (11.5)	12 (11)
	10	27* (20*)	27* (20*)	27* (19)	27* (18)	27* (16)	24 (14.5)	21 (13)	16 (11.5)

	90	16 (11)	15 (9.5)	13 (9)	12 (8)	11 (7)	7 (5)	6 (5)	5 (4.5)
	75	22 (13)	20 (11)	18 (10.5)	17 (9.5)	15 (8)	8 (6)	8 (6)	6 (5)
75 cm	50	27* (15)	25 (13)	23 (12)	21 (11)	19 (10)	12 (8)	11 (8)	8 (7)
	25	27* (17.5)	27* (15)	27 (14)	26 (12)	23 (10.5)	17 (10)	13 (9)	11 (8)
	10	27* (19)	27* (17)	27* (15)	27* (14)	27 (12)	22 (11)	18 (10)	13 (8)
	90	16 (11)	15 (9.5)	13 (9)	12 (8)	11 (7)	7 (6)	6 (5)	5 (4.5)
	75	22 (13)	20 (11)	18 (10.5)	17 (9.5)	15 (8)	8 (6)	8 (6)	6 (5)
49 cm	50	27* (15)	25 (13)	23 (12)	21 (11)	19 (10)	12 (8)	11 (8)	8 (7)
	25	27* (17.5)	27* (15)	27 (14)	26 (12)	23 (10.5)	17 (10)	13 (9)	11 (8)
	10	27* (19)	27* (17)	27* (15)	27* (14)	27 (12)	22 (11)	18 (10)	13 (8)
	90	18 (12)	17 (10.5)	15 (10)	14 (9)	12 (8)	7 (6)	6 (6)	5 (6)
	75	24 (15)	22 (12)	20 (11)	19(10.5)	16 (10)	8 (7.5)	8 (7.5)	7 (7)
34 cm	50	27* (17)	27* (15)	25 (13)	24 (12)	20 (11)	12 (10)	11 (9)	9 (7.5)
	25	27* (19)	27* (17)	27* (15)	27* (14)	24 (12)	20 (11)	16 (10)	12 (10)
	10	27* (20*)	27* (19)	27* (17)	27* (16)	27* (14)	22 (13)	18 (11)	13 (10)
	90	15 (9)	14 (8)	12 (7)	12 (7)	9 (7)	7 (5)	6 (4)	4 (3)
	75	20 (11)	18 (9)	15 (9)	15 (8)	12 (8)	9 (6)	8 (5)	6 (4)
75 cm	50	25 (13)	23 (11)	20 (10)	19 (9)	16 (9)	12 (8)	10 (7)	7 (6)
	25	27* (14)	27 (12)	25 (11)	23 (10)	19 (10)	15 (9)	12 (8)	10 (7)
	10	27* (16)	27* (14)	27* (13)	27 (12)	22 (11)	17 (10)	13 (9)	12 (8)
	90	18 (10)	16 (9)	14 (8)	14 (7)	11 (7)	7 (5)	7 (4)	5 (3)
	75	23 (12)	21 (10)	19 (9)	18 (9)	14 (8)	9 (6)	8 (5)	6 (4)
49 cm	50	27* (14)	27 (12)	24 (11)	23 (10)	18 (9)	12 (8)	10 (7)	9 (6)
	25	27* (15)	27* (13)	27* (12)	27* (11)	21 (10)	15 (9)	12 (8)	10 (7)
	10	27* (17)	27* (15)	27* (14)	27* (13)	25 (11)	17 (10)	13 (9)	11 (8)
	90	20 (12)	18 (11)	17 (10)	16 (9)	13 (8)	7 (6)	6 (6)	5 (6)
	75	26 (14)	24 (12)	22 (11)	21 (11)	17 (9)	9 (7)	8 (7)	8 (7)
34 cm	50	27* (17)	27* (14)	27* (13)	26 (12)	21 (11)	12 (9)	11 (9)	10 (8)
	25	27* (19)	27* (16)	27* (15)	27* (14)	25 (12)	15 (11)	14 (10)	13 (9)
	10	27* (20*)	27* (18)	27* (16)	27* (15)	27* (14)	17 (12)	16 (11)	15 (9.5)

Adapted from Mital et al. 1993b.
* Weight limited by biomechanical design criterion (3930 N spinal compression for males, 2689 N for females).
Weight limited by physiological design criterion (4 kcal / min for males, 3 kcal / min for females).
()—Values in parentheses are for females
hr = hours; min. = minute(s)

cadaver lumbar segments varies from approximately 800 N to approximately 13,000 N. Jäger and Luttman (1991) report a mean failure for compression at 5,700 N for males with a standard deviation of 2600 N. For females, this failure limit was found to be 3900 N with a standard deviation of approximately 1500 N. In addition, several factors influence the compressive strength of the spinal column, including age, gender, specimen cross-section, lumbar level, and structure of the disc or vertebral body. The ultimate compressive strength of various components of the spine can be estimated with following regression model (Jäger and Luttman 1991):

$$\begin{aligned}\text{Compressive strength (kN)} = {} & (7.65 + 1.18\,G) - (0.502 + 0.382\,G)\,A \\ & + (0.035 + 0.127\,G)\,C - 0.167\,L - 0.89\,S\end{aligned}$$

where: G = gender (0 for female; 1 for male)
A = decades (e.g., 30 years = 3, 60 = 6)
L = lumbar level (0 for L5/S1; incremental values for each lumbar disc or vertebra)
C = cross-section (cm^2)
S = structure (0 for disc; 1 for vertebra)

It should be noted that statically determined tolerances may overestimate compressive tolerances (Jäger and Luttman 1992b). Modeling studies by Potvin et al. (1991) suggest that erector spinae oblique elements could contribute about 500 N sagittal shear to leave only 200 N sagittal shear for discs and facets to counter. According to Farfan (1983), the facet joints are capable of absorbing 3,100 N to 3,600 N while the discs support less than 900 N.

Due to the complexity of dynamic biomechanical models, assessment of the effects of lifting on the musculoskeletal system has most frequently been done with the aid of static models. Many lifting motions, which are dynamic in nature, appear to have substantial inertia components. McGill and Norman (1985) also compared the low-back moments during lifting when determined dynamically and statically. They found that the dynamic model resulted in peak L4/L5 moments 19% higher on the average, with a maximum difference of 52%, than those determined from the static model. Given the complexity of the human body and the simplicity of the biomechanical models, values from these models can only be estimates and are best used for comparison purposes rather than suggesting absolute values (Delleman et al. 1992).

7.8. Revised NIOSH (1991) Lifting Equation

The 1991 revised lifting equation has been expanded beyond the previous guideline and can be applied to a larger percentage of lifting tasks (Waters et al. 1993). The recommended weight limit (RWL) was designed to protect 90% of the mixed (male/female) industrial working population against LBP. The 1991 equation is based on three main components: standard lifting location, load constant, and risk factor multipliers. The standard lifting location (SLL) serves as the 3D reference point for evaluating the parameters defining the worker's lifting posture. The SLL for the 1981 Guide was defined as a vertical height of 75 cm and a horizontal distance of 15 cm with respect to the midpoint between the ankles. The horizontal factor for the SLL was increased from 15 cm to 25 cm displacement for the 1991 equation. This was done in view of recent findings that showed 25 cm as the minimum horizontal distance in lifting that did not interfere with the front of the body. This distance was also found to be used most often by workers (Garg and Badger 1986; Garg 1989).

The load constant (LC) refers to a maximum weight value for the SLL. For the revised equation, the load constant was reduced from 40 kg to 23 kg. The reduction in the load constant was driven in part by the need to increase the 1981 horizontal displacement value from a 15-cm to a 25-cm displacement for the 1991 equation (noted above in item 1). Table 16 shows definitions of the relevant terms utilized by the 1991 equation. The RWL is the product of the load constant and six multipliers:

$$\text{RWL (kg)} = LC \times HM \times VM \times DM \times AM \times FM \times CM$$

The multipliers (M) are defined in terms of the related risk factors, including the horizontal location (HM), vertical location (VM), vertical travel distance (DM), coupling (CM), frequency of lift (FM), and asymmetry angle (AM). The multipliers for frequency and coupling are defined using relevant tables. In addition to lifting frequency, the work duration and vertical distance factors are used to compute the frequency multiplier (see Table 17). Table 18 shows the coupling multiplier (CM), while Table 19 provides information about the coupling classification.

The horizontal location (H) is measured from the midpoint of the line joining the inner ankle bones to a point projected on the floor directly below the midpoint of the hand grasps (i.e., load center). If significant control is required at the destination (i.e., precision placement), then H should be measured at both the origin and destination of the lift. This procedure is required if there is a need to: (1) regrasp the load near the destination of the lift, (2) momentarily hold the object at the

TABLE 16 Terms of the 1991 NIOSH Equation

Multiplier	Formula (cm)
Load constant	$LC = 23$ kg
Horizontal	$HM = 25/H$
Vertical	$VM = 1 - (\,0.003 \mid V - 75 \mid\,)$
Distance	$DM = 0.82 + 4.5/D$
Asymmetry	$AM = 1 - 0.0032\ A$
Frequency	FM (see Table 147)
Coupling	CM (see Table 148)

H = the horizontal distance of the hands from the midpoint of the ankles, measured at the origin & destination of the lift (cm).

V = the vertical distance of the hands from the floor, measured at the origin and destination of the lift (cm).

D = the vertical travel distance between the origin and destination of the lift (cm).

A = the angle of asymmetry—angular displacement of the load from the sagittal plane, measured at the origin and destination of the lift (degrees).

F = average frequency of lift (lifts/minute).

C = load coupling, the degree to which appropriate handles, devices, or lifting surfaces are present to assist lifting and reduce the possibility of dropping the load.

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destination, or (3) position or guide the load at the destination. If the distance is less than 10 in (25 cm), then *H* should be set to 10 in (25 cm).

The vertical location (*V*) is defined as the vertical height of the hands above the floor and is measured vertically from the floor to the midpoint between the hand grasps, as defined by the large middle knuckle. The vertical location is limited by the floor surface and the upper limit of vertical reach for lifting (i.e., 70 in or 175 cm).

The vertical travel distance variable (*D*) is defined as the vertical travel distance of the hands between the origin and destination of the lift. For lifting tasks, *D* can be computed by subtracting the vertical location (*V*) at the origin of the lift from the corresponding *V* at the destination of the

TABLE 17 Frequency Multipliers for the 1991 Lifting Equation

Frequency Lifts (min)	Continuous Work Duration					
	< 8 hours		< 2 hours		< 1 hour	
	$V < 75$	$V > 75$	$V < 75$	$V > 75$	$V < 75$	$V > 75$
0.2	0.85	0.85	0.95	0.95	1.00	1.00
0.5	0.81	0.81	0.92	0.92	0.97	0.97
1	0.75	0.75	0.88	0.88	0.94	0.94
2	0.65	0.65	0.84	0.84	0.91	0.91
3	0.55	0.55	0.79	0.79	0.88	0.88
4	0.45	0.45	0.72	0.72	0.84	0.84
5	0.35	0.35	0.60	0.60	0.80	0.80
6	0.27	0.27	0.50	0.50	0.75	0.75
7	0.22	0.22	0.42	0.42	0.70	0.70
8	0.18	0.18	0.35	0.35	0.60	0.60
9	–	0.15	0.30	0.30	0.52	0.52
10	–	0.13	0.26	0.26	0.45	0.45
11	–	–	–	0.23	0.41	0.41
12	–	–	–	0.21	0.37	0.37
13	–	–	–	–	–	0.34
14	–	–	–	–	–	0.31
15	–	–	–	–	–	0.28

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TABLE 18 The Coupling Multipliers for the 1991 Lifting Equation

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

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lift. For lowering tasks, D is equal to V at the origin minus V at the destination. The variable (D) is assumed to be at least 10 in (25 cm) and no greater than 70 in (175 cm). If the vertical travel distance is less than 10 in (25 cm), then D should be set to 10 in (25 cm).

The asymmetry angle A is limited to the range of 0° to 135°. If $A > 135°$, then AM is set equal to zero, which results in a RWL of 0. The asymmetry multiplier (AM) is $1 - (0.0032A)$. The AM has a maximum value of 1.0 when the load is lifted directly in front of the body and a minimum value of 0.57 at 135° of asymmetry.

The frequency multiplier (FM) is defined by (1) the number of lifts per minute (frequency), (2) the amount of time engaged in the lifting activity (duration), and (3) the vertical height of the lift from the floor. Lifting frequency (F) refers to the average number of lifts made per minute, as measured over a 15-min period. Lifting duration is classified into three categories: short duration,

TABLE 19 Coupling Classification

Good coupling

1. For containers of optimal design, such as some boxes, crates, etc., a "Good" hand-to-object coupling would be defined as handles or hand-hold cutouts of optimal design
2. For loose parts or irregular objects that are not usually containerized, such as castings, stock, and supply materials, a "Good" hand-to-object coupling would be defined as a comfortable grip in which the hand can be easily wrapped around the object.

Fair coupling

1. For containers of optimal design, a "Fair" hand-to-object coupling would be defined as handles or hand-hold cut-outs of less than optimal design.
2. For containers of optimal design with no handles or hand-hold cutouts or for loose parts or irregular objects, a "Fair" hand-to-object coupling is defined as a grip in which the hand can be flexed about 90°.

Poor coupling

1. Containers of less than optimal design or loose parts or irregular objects that are bulky, hard to handle, or have sharp edges.
2. Lifting nonrigid bags (i.e., bags that sag in the middle).

Notes:

1. An optimal handle design has 0.75–1.5 in (1.9–3.8 cm) diameter, ≥ 4.5 in (11.5 cm) length, 2 in (5 cm) clearance, cylindrical shape, and a smooth, nonslip surface.
2. An optimal hand-hold cutout has the following approximate characteristics: ≥ 1.5 in (3.8 cm) height, 4.5 in (11.5 cm) length, semioval shape, ≥ 2 in (5 cm) clearance, smooth nonslip surface, and ≥ 0.25 in (0.60 cm) container thickness (e.g., double-thickness cardboard).
3. An optimal container design has ≤ 16 in (40 cm) frontal length, ≥ 12 in (30 cm) height, and a smooth nonslip surface.
4. A worker should be capable of clamping the fingers at nearly 90° under the container, such as required when lifting a cardboard box from the floor.
5. A container is considered less than optimal if it has a frontal length > 16 in (40 cm), height > 12 in (30 cm), rough or slippery surfaces, sharp edges, asymmetric center of mass, unstable contents, or requires the use of gloves. A loose object is considered bulky if the load cannot easily be balanced between the hand grasps.
6. A worker should be able to wrap the hand comfortably around the object without causing excessive wrist deviations or awkward postures, and the grip should not require excessive force.

After Waters et al. 1994. Courtesy of the U.S. Department of Health and Human Services.

moderate duration, and long duration. These categories are based on the pattern of continuous work-time and recovery-time (i.e., light work) periods.

A continuous work-time period is defined as a period of uninterrupted work. Recovery time is defined as the duration of light work activity following a period of continuous lifting. Short duration defines lifting tasks that have a work duration of one hour or less, followed by a recovery time equal to 1.2 times the work time. Moderate duration defines lifting tasks that have a duration of more than one hour, but not more than two hours, followed by a recovery period of at least 0.3 times the work time. Long duration defines lifting tasks that have a duration of between two and eight hours, with standard industrial rest allowances (e.g., morning, lunch, and afternoon rest breaks).

The lifting index (LI) provides a relative estimate of the physical stress associated with a manual lifting job and is equal to the load weight divided by the RWL. According to Waters et al. (1994), the RWL and LI can be used to guide ergonomic design in several ways:

1. The individual multipliers can be used to identify specific job-related problems. The general redesign guidelines related to specific multipliers are shown in Table 20.
2. The RWL can be used to guide the redesign of existing manual lifting jobs or to design new manual lifting jobs.
3. The LI can be used to estimate the relative magnitude of physical stress for a task or job. The greater the LI, the smaller the fraction of workers capable of safely sustaining the level of activity.
4. The LI can be used to prioritize ergonomic redesign. A series of suspected hazardous jobs could be rank ordered according to the LI and a control strategy could be developed according to the rank ordering (i.e., jobs with lifting indices about 1.0 or higher would benefit the most from redesign).

The 1991 equation should not be used if any of the following conditions occur: lifting/lowering with one hand; lifting/lowering for over eight hours, lifting/lowering while seated or kneeling; lifting/lowering in a restricted workspace, lifting/lowering unstable objects; lifting/lowering while carrying, pushing, or pulling; lifting/lowering with wheelbarrows or shovels; lifting/lowering with high-speed motion (faster than about 30 in/sec); lifting/lowering with unreasonable foot/floor coupling (<0.4 coefficient of friction between the sole and the floor); lifting/lowering in an unfavorable environment (i.e., temperature significantly outside 66–79°F (19–26°C) range; relative humidity outside 35–50% range).

7.9. Computer Simulation of the Revised NIOSH Lifting Equation (1991)

One way to investigate the practical implications of the 1991 lifting equation for industry is to determine the likely results of the equation when applying a realistic and practical range of values

TABLE 20 General Design/Redesign Suggestions for Manual Lifting Tasks

If HM is less than 1.0	Bring the load closer to the worker by removing any horizontal barriers or reducing the size of the object. Lifts near the floor should be avoided; if unavoidable, the object should fit easily between the legs.
If VM is less than 1.0	Raise/lower the origin/destination of the lift. Avoid lifting near the floor or above the shoulders.
If DM is less than 1.0	Reduce the vertical distance between the origin and the destination of the lift.
If AM is less than 1.0	Move the origin and destination of the lift closer together to reduce the angle of twist, or move the origin and destination further apart to force the worker to turn the feet and step, rather than twist the body.
If FM is less than 1.0	Reduce the lifting frequency rate, reduce the lifting duration, or provide longer recovery periods (i.e., light work period).
If CM is less than 1.0	Improve the hand-to-object coupling by providing optimal containers with handles or hand-hold cutouts, or improve the hand-holds for irregular objects.
If the RWL at the destination is less than at the origin	Eliminate the need for significant control of the object at the destination by redesigning the job or modifying the container/object characteristics.

As recommended by Waters et al. 1994. Courtesy of the U.S. Department of Health and Human Services.

for the risk factors (Karwowski 1992). This can be done using modern computer simulation techniques in order to examine the behavior of the 1991 NIOSH equation under a broad range of conditions. Karwowski and Gaddie (1995) simulated the 1991 equation using SLAM II (Pritsker 1986), a simulation language for alternative modeling, as the product of the six independent factor multipliers represented as attributes of an entity flowing through the network. For this purpose, probability distributions for all the relevant risk factors were defined and a digital simulation of the revised equation was performed.

As much as possible, the probability distributions for these factors were chosen to be representative of the real industrial workplace (Ciriello et al. 1990; Brokaw 1992; Karwowski and Brokaw 1992; Marras et al. 1993). Except for the vertical travel distance factor, coupling, and asymmetry multipliers, all factors were defined using either normal or lognormal distributions. For all the factors defined as having lognormal distributions, the procedure was developed to adjust for the required range of real values whenever necessary. The SLAM II computer simulation was run for a total of 100,000 trials, that is, randomly selected scenarios that realistically define the industrial tasks in terms of the 1991 equation. Descriptive statistical data were collected for all the input (lifting) factors, the respective multipliers, and the resulting recommended weight limits. The input factor distributions were examined in order to verify the intended distributions.

The results showed that for all lifting conditions examined, the distribution of recommended weight limit values had a mean of 7.22 kg and a standard deviation of 2.09 kg. In 95% of all cases, the RWL was at or below the value of 10.5 kg (about 23.1 lb). In 99.5% of all cases, the RWL value was at or below 12.5 kg (27.5 lb). That implies that when the LI is set to 1.0 for task design or evaluation purposes, only 0.5% of the (simulated) industrial lifting tasks would have the RWLs greater than 12.5 kg. Taking into account the lifting task duration, in the 99.5% of the simulated cases, the RWL values were equal to or were lower than 13.0 kg (28.6 lb) for up to one hour of lifting task exposure, 12.5 kg (or 27.5 lb) for less than two hours of exposure, and 10.5 kg (23.1 lb) for lifting over an eight-hour shift.

From a practical point of view, these values define simple and straightforward lifting limits, that is, the threshold RWL values (TRWL) that can be used by practitioners for the purpose of immediate and easy-to-perform risk assessment of manual lifting tasks performed in industry. Because the 1991 equation is designed to ensure that the RWL will not exceed the acceptable lifting capability of 99% of male workers and 75% of female workers, this amounts to protecting about 90% of the industrial workers if there is a 50/50 split between males and females. The TRWL value of 27.5 lb can then be used for immediate risk assessment of manual lifting tasks performed in industry. If this value is exceeded, then a more thorough examination of the identified tasks, as well as evaluation of physical capacity of the exposed workers, should be performed.

7.10. Prevention of LBDs in Industry

The application of ergonomic principles to the design of MMH tasks is one of the most effective approaches to controlling the incidence and severity of LBDs (Ayoub et al. 1997). The goal of ergonomic job design is to reduce the ratio of task demands to worker capability to an acceptable level (see Figure 14). The application of ergonomic principles to task and workplace design permanently reduces stresses. Such changes are preferable to altering other aspects of the MMH system, such as work practices. For example, worker training may be ineffective if practices trained are not reinforced and refreshed (Kroemer 1992), whereas altering the workplace is a lasting physical intervention

7.10.1. Job Severity Index

The job severity index (JSI) is a time- and frequency-weighted ratio of worker capacity to job demands. Worker capacity is predicted with the models developed by Ayoub et al. (1978), which use isometric strength and anthropometric data to predict psychophysical lifting capacity. JSI and each of the components are defined below.

$$\mathrm{JSI} = \sum_{i=1}^{n} \frac{\mathrm{hours}_i \times \mathrm{days}_i}{\mathrm{hours}_t \times \mathrm{days}_t} \sum_{j=1}^{m_i} \left[\frac{F_j}{F_i} \times \frac{\mathrm{WT}_j}{\mathrm{CAP}_j} \right]$$

where: n =number of task groups

hours_i = exposure hours/day for group i

days_i = exposure days/week for group i

hours_t = total hours/day for job

days_t = total days/week for job

m_i = number of tasks in group i

WT_j = maximum required weight of lift for task j

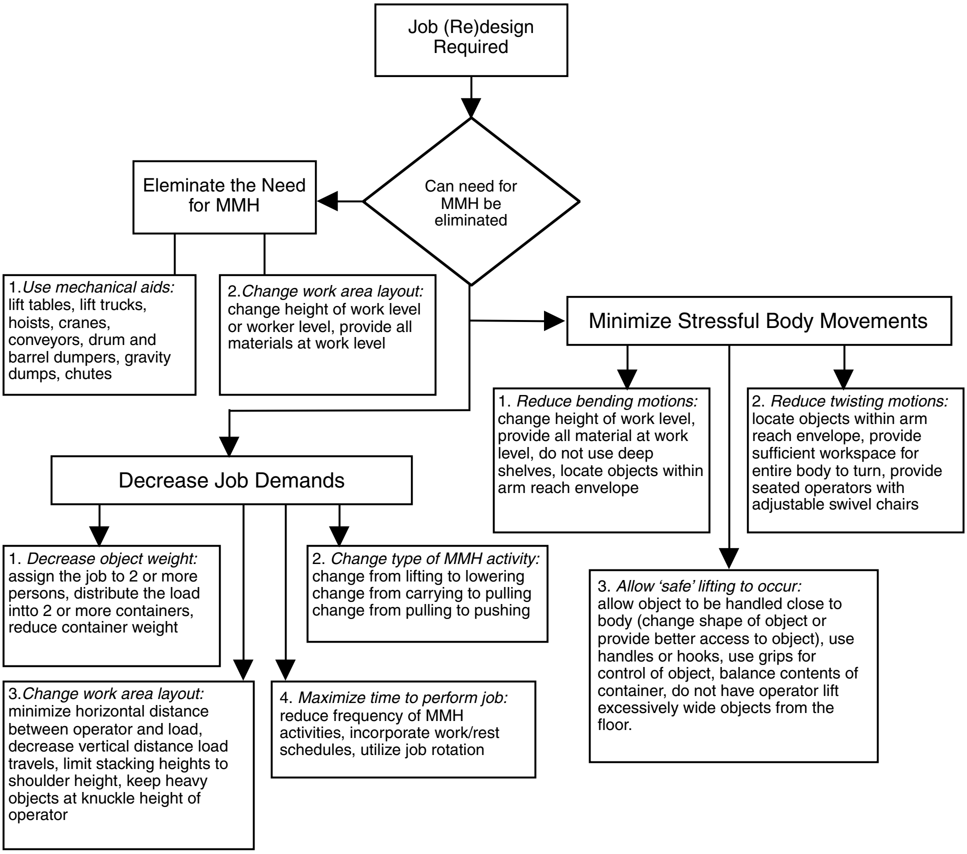

Figure 14 Summary of Ergonomic Approaches to MMH Task (re)design. (Adapted from Ayoub 1982 and Ayoub et al. 1983)

CAP_j = the adjusted capacity of the person working at task j
F_j = lifting frequency for task j
F_i = total lifting frequency for group i

$$= \sum_{j=1}^{m_i} F_j$$

Liles et al. (1984) performed a field study to determine the relationship between JSI and the incidence and severity of LBDs. A total of 453 subjects was included in the study. The results of the field study indicated that both incidence and severity of recordable back injuries rose rapidly at values of JSI greater than 1.5. The denominator for the incidence and severity rates is 100 full-time employees, that is, 200,000 exposure hours. JSI can be reduced to a desirable level by increasing worker capacity (e.g., selecting a worker with higher capacity) or altering task and job parameters to reduce JSI to an acceptable level.

7.10.2. Dynamic Model for Prediction of LBDs in Industry

Marras et al. (1993) performed a retrospective study to determine the relationships between workplace factors and trunk motion factors and LBD occurrence. A logistic regression analysis was performed to provide a model used to estimate the probability of high-risk LBD membership. High-risk jobs were defined as jobs having incidence rates of 12 or more injuries per 200,000 hours of exposure. The regressors included in the model were lift rate (lifts/hr), average twisting velocity (deg/sec), maximum moment (Nm), maximum sagittal flexion (degrees), and maximum lateral velocity (deg/sec). The above model can be used to guide workplace design changes because the probability of high-risk LBD membership can be computed before and after design changes. For example, maximum moment could be reduced by decreasing the load weight or the maximum horizontal distance between the load and the lumbar spine, and the associated decrease in high-risk membership probability can be estimated. The model is considerably different from the models discussed above in that LBD risk is not assumed to be related to individual capacity.

8. WORK-RELATED MUSCULOSKELETAL DISORDERS OF THE UPPER EXTREMITY

8.1. Characteristics of Musculoskeletal Disorders

The National Institute of Occupational Safety and Health (NIOSH 1997) states that musculoskeletal disorders, which include disorders of the back, trunk, upper extremity, neck, and lower extremity are one of the 10 leading work-related illnesses and injuries in the United States. Praemer et al, (1992) report that work-related upper-extremity disorders (WUEDs), which are formally defined by the Bureau of Labor Statistics (BLS) as cumulative trauma illnesses, account for 11.0 % of all work-related musculoskeletal disorders (illnesses). For comparison, occupational low-back disorders account for more than 51.0% of all WRMDs. According to BLS (1995), the cumulative trauma illnesses of upper extremity accounted for more than 60% of the occupational illnesses reported in 1993. These work-related illnesses, which include hearing impairments due to occupational noise exposure, represent 6.0% of all reportable work-related injuries and illnesses (Marras 1996).

As reviewed by Karwowski and Marras (1997), work-related musculoskeletal disorders currently account for one-third of all occupational injuries and illnesses reported to the Bureau of Labor Statistics (BLS) by employers every year. These disorders thus constitute the largest job-related injury and illness problem in the United States today. According to OSHA (1999), in 1997 employers reported a total of 626,000 lost workday disorders to the BLS, and these disorders accounted for $1 of every $3 spent for workers' compensation in that year. Employers pay more than $15–20 billion in workers' compensation costs for these disorders every year, and other expenses associated with MSDs may increase this total to $45–54 billion a year.

Such statistics can be linked to several occupational risk factors, including the increased production rates leading to thousands of repetitive movements every day, widespread use of computer keyboards, higher percentage of women and older workers in the workforce, better record keeping of reportable illnesses and injuries on the job by employers, greater employee awareness of WUEDs and their relation to the working conditions, and a marked shift in social policy regarding recognition and compensation of the occupational injuries and ilnesses.

8.2. Definitions

Work-related musculoskeletal disorders (WRMDs) are those disorders and diseases of the musculoskeletal system which have a proven or hypothetical work related causal component (Kuorinka and Forcier 1995). Musculoskeletal disorders are pathological entities in which the functions of the musculoskeletal system are disturbed or abnormal, while diseases are pathological entities with observable impairments in body configuration and function. Although WUEDs are a heterogeneous group of disorders, and the current state of knowledge does not allow for a general description of the course of these disorders, it is possible nevertheless to identify a group of so-called generic risk factors, including biomechanical factors, such as static and dynamic loading on the body and posture, cognitive demands, and organizational and psychosocial factors, for which there is an ample evidence of work-relatedness and higher risk of developing the WUEDs.

Generic risk factors, which typically interact and cumulate to form cascading cycles, are assumed to be directly responsible for the pathophysiological phenonmena that depend on location, intensity, temporal variation, duration, and repetitivness of the generic risk factors (Kuorinka and Forcier 1995). It is also proposed that both insufficient and exccessive loading on the musculoskeletal system have deleterious effects and that the pathophysiological process is dependent upon individual characteristics with respect to body responses, coping mechanisms, and adaptation to risk factors.

Musculoskeletal disorders can be defined by combining the separate meanings for each word (Putz-Anderson 1993). *Cumulative* indicates that these disorders develop gradually over periods of time as a result of repeated stresses. The cumulative concept is based on the assumption that each repetition of an activity produces some trauma or wear and tear on the tissues and joints of the particular body part. The term *trauma* indicates bodily injury from mechanical stresses, while *disorders* refer to physical ailments. The above definition also stipulates a simple cause-and-effect model for CTD development. According to such a model, because the human body needs sufficient intervals of rest time between episodes of repeated strains to repair itself, if the recovery time is insufficient, combined with high repetition of forceful and awkward postures, the worker is at higher risk of developing a CTD. In the context of the generic model for prevention shown in Figure 15, the above

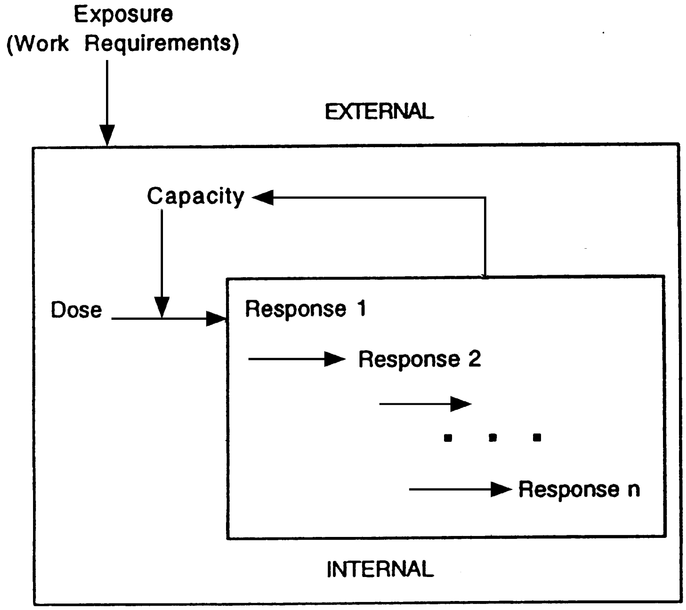

Figure 15 A Conceptual Model for Development of WMSDs proposed by Armstrong et al. (1993). Reproduced with permission from Finnish Institute of Occupational Health.

definition is primarily oriented towards biomechanical risk factors for WUEDs and is, therefore, incomplete. Table 21 presents a summary of the potential risk factors for work-related musculoskeletal disorders.

8.3. Conceptual Models for Development of WRMDs

According to the World Health Organization (WHO 1985), an occupational disease is a disease for which there is a direct cause-and-effect relationship between hazard and disease (e.g., asbestos–

TABLE 21 Potential Risk Factors for Development of Work-Related Musculoskeletal Disorders

1. Physical strength requirements
2. Biomechanical stressors (dynamic and static)
3. Endurance requirement and physiological costs of work
4. Motion factors:
    a. repetitive movement rates
    b. reach distances (functional, extended, and repetitive)
    c. motion times and efficiency
5. Postural factors:
    a. characteristics and range of motion
    b. joint deviations
    c. static loading
    d. awkward postures
6. Work duration factors:
    a. rate/work/rest ratios
    b. stressful task assignments
7. Work organization demands:
    a. work pace/time pressures
    b. machine/team pacing
    c. overtime demands
    d. monotony of work

asbestosis). Work-related diseases are defined as multifactorial when the work environment and the performance of work contribute significantly to the causation of disease (WHO 1985). Work-related diseases can be partially caused by adverse work conditions. However, personal characteristics, environmental, and sociocultural factors are also recognized as risk factors for these diseases.

The scientific evidence of work-relatedness of musculoskeletal disorders has been firmly established by numerous epidemiologic studies conducted over the last 25 years of research in the field (NIOSH 1997). It has also been noted that the incidence and prevalence of musculoskeletal disorders in the reference populations were low, but not zero, most likely indicating the nonwork-related causes of these disorders. It was also documented that such variables as cultural differences, psychosocial and economic factors, which may influence one's perception and tolerance of pain and consequently affect the willingness to report musculoskeletal problems, may have significant impact on the progressions from disorder to work disability (WHO 1985; Leino 1989).

Armstrong et al. (1993) developed a conceptual model for the pathogenesis of work-related musculoskeletal disorders. The model is based on the set of four cascading and interacting state variables of exposure, dose, capacity, and response, which are measures of the system state at any given time. The response at one level can act as dose at the next level (see Figure 15). Furthermore, it is assumed that a response to one or more doses can diminish or increase the capacity for responding to successive doses. This conceptual model for development of WRMDs reflects the multifactorial nature of work-related upper-extremity disorders and the complex nature of the interactions between exposure, dose, capacity, and response variables. The proposed model also reflects the complexity of interactions among the physiological, mechanical, individual, and psychosocial risk factors.

In the proposed model, exposure refers to the external factors (i.e., work requirements) that produce the internal dose (i.e., tissue loads and metabolic demands and factors). Workplace organization and hand tool design characteristics are examples of such external factors that can determine work postures and define loads on the affected tissues or velocity of muscular contractions. Dose is defined by a set of mechanical, physiological, or psychological factors that in some way disturb an internal state of the affected worker. Mechanical disturbance factors may include tissue forces and deformations produced as a result of exertion or movement of the body.

Physiological disturbances are such factors as consumption of metabolic substrates or tissue damage, while the psychological disturbance factors are those related to, for example, anxiety about work or inadequate social support. Changes in the state variables of the worker are defined by the model as responses. A response is an effect of the dose caused by exposure. For example, hand exertion can cause elastic deformation of tendons and changes in tissue composition and/or shape, which in turn may result in hand discomfort. The dose–response time relationship implies that the effect of a dose can be immediate or the response may be delayed for a long periods of time.

The proposed model stipulates that system changes (responses) can also result in either increased dose tolerance (adaptation) or reduced dose tolerance lowering the system capacity. Capacity is defined as the worker's ability (physical or psychological) to resist system destabilization due to various doses. While capacity can be reduced or enhanced by previous doses and responses, it is assumed that most individuals are able to adapt to certain types and levels of physical activity.

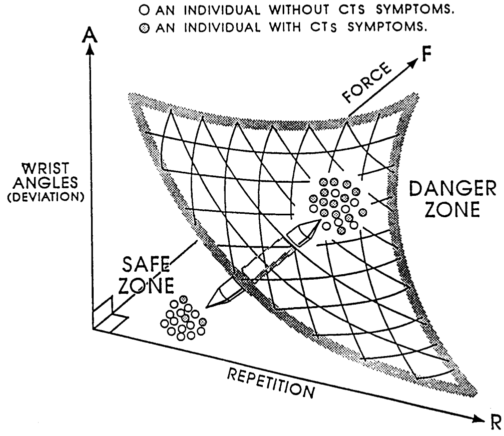

Figure 16 Conceptual CTS Model. (Adapted from Tanaka and McGlothlin 1999, reprinted with permission from Elsevier Science.)

Muscles, for example, can develop increased aerobic or anaerobic metabolic capacity. Furthermore, muscular responses are characterized in the model as a series of cascading mechanical and physiological events. The local changes (system responses), such as deformation and the yielding of connective tissues within the muscle, are conveyed to the central nervous system by sensory afferent nerves and cause corresponding sensations to effort and discomfort, often referred to as perceived fatigue.

The main purpose of the dose-response model is to account for the factors and processes that result in WRMDs in order to specify acceptable limits with respect to work design parameters for a given individual. The proposed model should be useful in the design of studies on the etiology and pathomechanisms of work-related musculoskeletal disorders, as well as in the planning and evaluation of preventive programs. The model should complement the epidemiologic studies, which focus on associations between the top and bottom of the cascade with physical workload, psychological demands, and environmental risk factors of work at one end and the manifestations of symptoms, diseases, or disabilities at the other.

Recently, Tanaka and McGlothlin (1999) updated their 3D heuristic dose–response model for repetitive manual work risk factors using the epidemiologic finding. Their earlier model for the postulated relationships between the risk factors for carpal tunnel syndrome (CTS) (for description see Karwowski and Marras 1997) was modified by including the time exposure factor. This was based on examination of prevalence of CTS data for 1988 from the National Health Review Survey (NHIS) and the Occupational Health Supplement (OHS). The authors found that compared to the nonexposed population, the prevalence (P) of CTS among the people exposed to bending/twisting of the hands/wrists many times an hour increased by several times regardless of the length of daily hours exposed. The prevalence of CTS was then defined as follows:

$$P = k \times I \times T = k \{aF \times bR \times e^{cA}\} T$$

where: P = prevalence of CTS
I = intensity
K = constant
a, b, c = coefficients
F = force
R = repetition
A = joint angles
T = time duration

The proposed model indicates that high-intensity work (involving high force, high repetition, and/or high joint deviation) should not be performed for a long period of time, but low-intensity work may be performed for a longer period. The 3D representation of the relationships between the risk factors for CTS is illustrated in Figures 16 and 17.

8.4. Causal Mechanism for Development of WUEDs

As reviewed by Armstrong et al. (1993), work-related muscle disorders are likely to occur when a muscle is fatigued repeatedly without sufficient allowance for recovery. An important factor in development of such disorders is motor control of the working muscle. Hägg (1991) postulates that the recruitment pattern of the motor neurons can occur according to the size principle, where the small units are activated at low forces. Given that the same units can be recruited continuously during a given work task, even if the relative load on the muscle is low, the active low-threshold motor units can work close to their maximal capacity and consequently maybe at a high risk of being damaged. It has also been shown that muscle tension due to excessive mental load can cause an overload on some specific muscle fibers (Westgaard and Bjørkland 1987). Karwowski et al. (1994) showed that cognitive aspects of computer-related task design affect the postural dynamics of the operators and the related levels of perceived postural discomfort. Finally, Edwards (1988) hypothesizes that occupational mucle pain might be a consequence of a conflict between motor control of the postural activity and control needed for rhythmic movement or skilled manipulations. In other words, the primary cause of work-related muscular pain and injury may be altered motor control, resulting in imbalance between harmonious motor unit recruitment relaxation of mucles not directly involved in the activity.

As discussed by Armstrong et al. (1993), poor ergonomic design of tools with respect to weight, shape, and size can impose extreme wrist positions and high forces on the worker's musculoskeletal system. Holding heavier objects requires an increased power grip and high tension in the finger flexor tendons, causing increased pressure in the carpal tunnel. Furthermore, the tasks that induce hand and arm vibration cause an involuntary increase in power grip through a reflex of the strength receptors. Vibration can also cause protein leakage from the blood vessels in the nerve trunks and result in

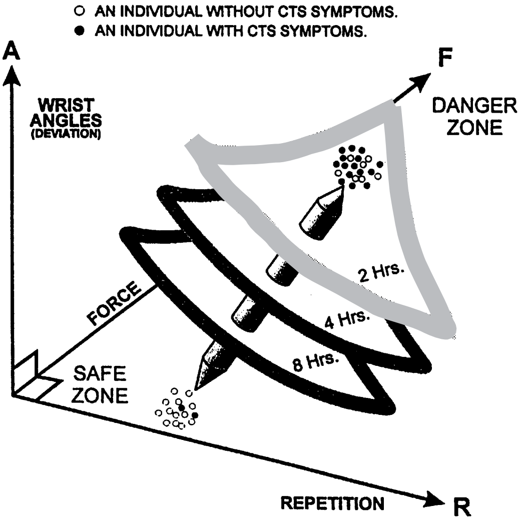

Figure 17 Three-Dimensional Illustration of the conceptual CTS Model with Time Exposure Factor. (Adapted from Tanaka and McGlothlin 1999, reprinted with permission from Elsevier Science.)

TABLE 22 Relationship between Physical Stresses and WRMD Risk Factors (ANSI Z-365)

Physical Stress	Magnitude	Repetition rate	Duration
Force	Forceful exertions and motions	Repetitive exertions	Sustained exertions
Joint angle	Extreme postures and motions	Repetitive motions	Sustained postures
Recovery	Insufficient resting level	Insufficient pauses or breaks	Insufficient rest time
Vibration	High vibration level	Repeated vibration exposure	Long vibration exposure
Temperature	Cold temperature	Repeated cold exposure	Long cold exposure

edema and increased pressure in the nerve trunks and therefore also result in edema and increased pressure in the nerve (Lundborg et al. 1987).

8.5. Musculoskeletal Disorders: Occupational Risk Factors

A risk factor is defined as an attribute or exposure that increases the probability of a disease or disorder (Putz-Anderson, 1988). Biomechanical risk factors for musculoskeletal disorders include repetitive and sustained exertions, awkward postures, and application of high mechanical forces. Vibration and cold environments may also accelerate the development of musculoskeletal disorders. Typical tools that can be used to identify the potential for development of musculoskeletal disorders include conducting work-methods analyses and checklists designed to itemize undesirable work site conditions or worker activities that contribute to injury. Since most of manual work requires the active use of the arms and hands, the structures of the upper extremities are particularly vulnerable to soft tissue injury. WUEDs are typically associated with repetitive manual tasks with forceful exertions, such as those performed at assembly lines, or when using hand tools, computer keyboards and other devices, or operating machinery. These tasks impose repeated stresses to the upper body, that is, the muscles, tendons, ligaments, nerve tissues, and neurovascular structures. There are three basic types of WRDs to the upper extremity: tendon disorder (such as tendonitis), nerve disorder (such as carpal tunnel syndrome), and neurovascular disorder (such as thoracic outlet syndrome or vibration–Raynaud's syndrome). The main biomechanical risk factors of musculoskeletal disorders are presented in Table 22.

9. ERGONOMICS DESIGN TO REDUCE WUEDs

In order to reduce the extent of work-related musculoskeletal injuries, progress in four methodologic areas is expected (NIOSH 1986):

1. Identifying accurately the biomechanical hazards
2. Developing effective health-promotion and hazard-control interventions
3. Changing management concepts and operational policies with respect to expected work performance
4. Devising strategies for disseminating knowledge on control technology and promoting their application through incentives

From the occupational safety and health perspective, the current state of ergonomics knowledge allows for management of musculoskeletal disorders in order to minimize human suffering, potential for disability, and the related workers' compensation costs. Ergonomics can help to:

1. Identify working conditions under which musculoskeletal disorders might occur
2. Develop engineering design measures aimed at elimination or reduction of the known job risk factors
3. Identify the affected worker population and target it for early medical and work intervention efforts

The musculoskeletal disorders-related job risk factors, which often overlap, typically involve a combination of poorly designed work methods, workstations, and hand tools and high production demands. Furthermore, while perfect solutions are rarely available, the job redesign decisions may often require some design trade-offs (Putz-Anderson 1992). In view of the above, the ergonomic intervention should allow:

1. Performing a thorough job analysis to determine the nature of specific problems
2. Evaluating and selecting the most appropriate intervention(s)
3. Developing and applying conservative treatment (implementing the intervention), on a limited scale if possible
4. Monitoring progress
5. Adjust or refining the intervention as needed

9.1. Quantitative Models for Development of WUEDs

It is generally recognized that force, repetition, posture, recovery time, duration of exposure, static muscular work, use of the hand as a tool, and type of grasp are important factors in the causation of WUEDs (Armstrong et al. 1987; Keyserling et al. 1993). Additional job factors that may increase the risk of WUEDs, in combination with the other factors, include cold temperature, use of gloves, and use of vibrating tools. Given the above knowledge, even if limited and in need of more comprehensive validation, it is currently possible to develop quantitative methodologies for ergonomics practitioners in order to discriminate between safe and hazardous jobs in terms of workers being at increased risk of developing the WUEDs. Such models are described below.

9.2. Semiquantitative Job-Analysis Methodology for Wrist/Hand Disorders

Moore and Garg (1995) developed a semiquantitative job analysis methodology (SJAM) for identifying industrial jobs associated with distal upper-extremity (wrist/hand) disorders. An existing body of knowledge and theory of the physiology, biomechanics, and epidemiology of distal upper-extremity disorders was used for that purpose. The proposed methodology involves the measurement or estimation of six task variables:

1. Intensity of exertion
2. Duration of exertion per cycle
3. Efforts per minute
4. Wrist posture
5. Speed of exertion
6. Duration of task per day

An ordinal rating is assigned for each of the variables according to the exposure data. The proposed strain index is the product of these six multipliers assigned to each of the variables.

The strain index methodology aims to discriminate between jobs that expose workers to risk factors (task variables) that cause WUEDs and jobs that do not. However, the strain index is not designed to identify jobs associated with an increased risk of any single specific disorder. It is anticipated that jobs identified as in the high-risk category by the strain index will exhibit higher levels of WUEDs among workers who currently perform or historically performed those jobs that are believed to be hazardous. Large-scale studies are needed to validate and update the proposed methodology. The strain index has the following limitations in terms of its application:

1. There are some disorders of the distal upper extremity that should not be predicted by the strain index, such as hand–arm vibration syndrome (HAVS) and hypothenar hammer syndrome.
2. The strain index has not been developed to predict increased risk for distal upper-extremity disorders to uncertain etiology or relationship to work. Examples include ganglion cysts, osteoarthritis, avascular necrosis of carpal bones, and ulnar nerve entrapment at the elbow.
3. The strain index has not been developed to predict disorders outside of the distal upper extremity, such as disorders of the shoulder, shoulder girdle, neck, or back.

The following major principles have been derived from the physiological model of localized muscle fatigue:

1. The primary task variables are intensity of exertion, duration of exertion, and duration of recovery.
2. Intensity of exertion refers to the force required to perform a task one time. It is characterized as a percentage of maximal strength.
3. Duration of exertion describes how long an exertion is applied. The sum of duration of exertion and duration of recovery is the cycle time of one exertional cycle.
4. Wrist posture, type of grasp, and speed of work are considered via their effects of maximal strength.
5. The relationship between strain on the body (endurance time) and intensity of exertion is nonlinear.

The following are the major principles derived from the epidemiological literature:

1. The primary task variable associated with an increased prevalence or incidence of distal upper-extremity disorders are intensity of exertion (force), repetition rate, and percentage of recovery time per cycle.
2. Intensity of exertion was the most important task variable in two of the three studies explicitly mentioned. The majority (or all) of the morbidity was related to disorders of the muscle–tendon unit. The third study, which considered only CTS, found that repetition was more important than forcefulness (Silverstein et al. 1987).
3. Wrist posture may not be an independent risk factor. It may contribute to an increased incidence of distal upper-extremity disorders when combined with intensity of exertion.
4. The roles of other task variables have not been clearly established epidemiologically; therefore, one has to rely on biomechanical and physiological principles to explain their relationship to upper-extremity disorders, if any.

Moore and Garg (1994) compared exposure factors for jobs associated with WUEDs to jobs without prevalence of such disorders. They found that the intensity of exertion, estimated as a percentage of maximal strength and adjusted for wrist posture and speed of work, was the major discriminating factor. The relationship between the incidence rate for distal upper-extremity disorder and the job risk factors was defined as follows:

$$\mathrm{IE} = \frac{30 \times F^2}{\mathrm{RT}^{0.6}}$$

where: IR = incidence rate (per 100 workers per year)
F = intensity of exertion (%MS)
RT = recovery time (percentage of cycle time)

The proposed concept of the strain index is a semiquantitative job analysis methodology that results in a numerical score that is believed to correlate with the risk of developing distal upper-extremity disorders. The SI score represents the product of six multipliers that correspond to six task variables. These variables:

TABLE 23 Rating Criteria for Strain Index

Rating	Intensity of Exertion	Duration of Exertion (% of Cycle)	Efforts/Minute	Hand–Wrist Posture	Speed of Work	Duration per Day (h)
1	Light	<10	<4	Very good	Very slow	≥ 1
2	Somewhat hard	10–29	4–8	Good	Slow	1–2
3	Hard	30–49	9–14	Fair	Fair	2–4
4	Very hard	50–79	15–19	Bad	Fast	2–8
5	Near maximal	≤ 80	≤ 20	Very bad	Very fast	≤ 8

Adapted from Moore and Garg 1995.

1. Intensity of exertion
2. Duration of exertion
3. Exertions per minute
4. Hand–wrist posture
5. Speed of work
6. Duration of task per day

These ratings, applied to model variables, are presented in Table 23. The multipliers for each task variable related to these ratings are shown in Table 24. The strain index score as the product of all six multipliers is defined as follows:

$$\begin{aligned}\text{Strain index (SI)} &= (\text{intensity of exertion multiplier})\\ &\times (\text{duration of exertion multiplier})\\ &\times (\text{exertions per minute multiplier})\\ &\times (\text{posture multiplier}) \times (\text{speed of work multiplier})\\ &\times (\text{duration per day multiplier})\end{aligned}$$

Intensity of exertion, the most critical variable of SI, is an estimate of the force requirements of a task and is defined as the percentage of maximum strength required to perform the task once. As such, the intensity of exertion is related to physiological stress (percentage of maximal strength) and biomechanical stresses (tensile load) on the muscle–tendon units of the distal upper extremity. The intensity of exertion is estimated by an observer using verbal descriptors and assigned corresponding rating values (1, 2, 3, 4, or 5). The multiplier values are defined based on the rating score raised to a power of 1.6 in order to reflect the nonlinear nature of the relationship between intensity of exertion and manifestations of strain according to the psychophysical theory. The multipliers for other task variables are modifiers to the intensity of exertion multiplier.

Duration of exertion is defined as the percentage of time an exertion is applied per cycle. The terms cycle and cycle time refer to the exertional cycle and average exertional cycle time, respectively. Duration of recovery per cycle is equal to the exertional cycle time minus the duration of exertion per cycle. The duration of exertion is the average duration of exertion per exertional cycle (calculated by dividing all durations of a series of exertions by the number of observed exertions). The percentage

TABLE 24 Multiplier Table for Strain Index

Rating	Intensity of Exertion	Duration of Exertion (% of Cycle)	Efforts/Minute	Hand–Wrist Posture	Speed of Work	Duration per Day (h)
1	1	0.5	0.5	1.0	1.0	0.25
2	3	1.0	1.0	1.0	1.0	0.50
3	6	1.5	1.5	1.5	1.0	0.75
4	9	2.0	2.0	2.0	1.5	1.00
5	13	3.0[a]	3.0	3.0	2.0	1.50

Adapted from Moore and Garg 1995.

[a] If duration of exertion is 100%, then the efforts/minute multiplier should be set to 3.0.

TABLE 25 An Example to Demonstrate the Procedure for Calculating SI Score

	Intensity of Exertion	Duration of Exertion (% of Cycle)	Efforts/Minute	Posture	Speed of Work	Duration per Day (h)
Exposure dose	Somewhat hard	60%	12	Fair	Fair	4–8
Ratings	2	4	3	3	3	4
Multiplier	3.0	2.0	1.5	1.5	1.0	1.0
SI Score = 3.0 × 2.0 × 1.5 × 1.5 × 1.0 × 1.0 = 13.5						

Adapted from Moore and Garg 1995.

duration of exertion is calculated by dividing the average duration of exertion per cycle by the average exertional cycle time, then multiplying the result by 100. (See equation below.) The calculated percentage duration of exertion is compared to the ranges and assigned the appropriate rating. The corresponding multipliers are identified using Table 23.

$$\%\text{duration of exertion} = \frac{(\text{average duration of exertion per cycle})}{(\text{average exertional cycle time})}$$

Efforts per minute is the number of exertions per minute (i.e., repetitiveness) and is synonymous with frequency. Efforts per minute are measured by counting the number of exertions that occur during a representative observation period (as described for determining the average exertional cycle time). The measured results are compared to the ranges shown in Table 23 and given the corresponding ratings. The multipliers are defined in Table 24.

Posture refers to the anatomical position of the wrist or hand relative to neutral position and is rated qualitatively using verbal anchors. As shown in Table 23, posture has four relevant ratings. Postures that are ‘‘very good’’ or ‘‘good’’ are essentially neutral and have multipliers of 1.0. Hand or wrist postures progressively deviate beyond the neutral range to extremes, graded as ‘‘fair,’’ ‘‘bad,’’ and ‘‘very bad.’’

Speed of work estimates perceived pace of the task or job and is subjectively estimated by a job analyst or ergonomics team. Once a verbal anchor is selected, a rating is assigned.

Duration of task per day is defined as a total time that a task is performed per day. As such, this variable reflects the beneficial effects of task diversity such as job rotation and the adverse effects of prolonged activity such as overtime. Duration of task per day is measured in hours and assigned a rating according to Table 23.

Application of the strain index involves five steps:

1. Collecting data
2. Assigning rating values
3. Determining multipliers
4. Calculating the SI score
5. Interpreting the results

TABLE 26 Maximum Acceptable Forces for Female Wrist Flexion (Power Grip) (N)

Percentage of Population	Repetition Rate				
	2/min	5/min	10/min	15/min	20/min
90	14.9	14.9	13.5	12.0	10.2
75	23.2	23.2	20.9	18.6	15.8
50	32.3	32.3	29.0	26.0	22.1
25	41.5	41.5	37.2	33.5	28.4
10	49.8	49.8	44.6	40.1	34.0

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TABLE 27 Maximum Acceptable Forces for Female Wrist Flexion (Pinch Grip) (N)

Percentage of Population	Repetition Rate				
	2/min	5/min	10/min	15/min	20/min
90	9.2	8.5	7.4	7.4	6.0
75	14.2	13.2	11.5	11.5	9.3
50	19.8	18.4	16.0	16.0	12.9
25	25.4	23.6	20.6	20.6	16.6
10	30.5	28.3	24.6	24.6	19.8

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The values of intensity of exertion, hand–wrist posture, and speed of work are estimated using the verbal descriptors in Table 23. The values of percentage duration of exertion per cycle, efforts per minute, and duration per day are based on measurements and counts. Theses values are then compared to the appropriate column in Table 24 and assigned a rating. The calculations of SI are shown in Table 25.

9.3. Psychophysical Models: The Maximum Acceptable Wrist Torque

Snook et al. (1995) used the psychophysical approach to determine the maximum acceptable forces for various types and frequencies for repetitive wrist motion, grips, and repetition rates that would not result in significant changes in wrist strength, tactile sensitivity, or number of symptoms reported by the female subjects. Three levels of wrist motion were used:

1. Flexion motion with a power grip
2. Flexion motion with a pinch grip
3. Extension motion with a power grip

The dependent variables were maximum acceptable wrist torque, maximum isometric wrist strength, tactile sensitivity, and symptoms. The maximum acceptable wrist torque (MAWT) was defined as the number of Newton meters of resistance set in the brake by the participants (averaged and recorded every minute). The data for maximum acceptable wrist torques for the two-days-per-week exposure were used to estimate the maximum acceptable torques for different repetitions of wrist flexion (power grip) and different percentages of the population. This was done by using the adjusted means and coefficients of variation from the two-days-per-week exposure. The original torque values were converted into forces by dividing each torque by the average length of the handle lever (0.081 m).

The estimated values for the maximum acceptable forces for female wrist flexion (power grip) are shown in Table 26. Similarily, the estimated maximum acceptable forces were developed for wrist flexion (pinch grip, see Table 27) and wrist extension (power grip, see Table 28). The torques were converted into forces by dividing by 0.081 m for the power grip and 0.123m for the pinch grip. Snook et al. (1995) note that the estimated values of the maximum acceptable wrist torque do not apply to any other tasks and wrist positions than those that were used in the study.

TABLE 28 Maximum Acceptable Forces for Female Wrist Extension (Power Grip) (N)

Percentage of Population	Repetition Rate				
	2/min	5/min	10/min	15/min	20/min
90	8.8	8.8	7.8	6.9	5.4
75	13.6	13.6	12.1	10.9	8.5
50	18.9	18.9	16.8	15.1	11.9
25	24.2	24.2	21.5	19.3	15.2
10	29.0	29.0	25.8	23.2	18.3

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10. MANAGEMENT OF MUSCULOSKELETAL DISORDERS

10.1. Ergonomic Guidelines

Most of the current guidelines for control of musculoskeletal disorders at work aim to reduce the extent of movements at the joints, reduce excessive force levels, and reduce the exposure to highly repetitive and stereotyped movements. For example, some of the common methods to control for wrist posture, which is believed one of the risk factors for carpal tunnel syndrome, are altering the geometry of tool or controls (e.g., bending the tool or handle), changing the location/positioning of the part, and changing the position of the worker in relation to the work object. In order to control for the extent of force required to perform a task, one can reduce the force required through tool and fixture redesign, distribute the application of force, or increase the mechanical advantage of the (muscle) lever system.

It has been shown that in the dynamic tasks involving upper extremities, the posture of the hand itself has very little predictive power for the risk of musculoskeletal disorders. Rather, it is the velocity and acceleration of the joint that significantly differentiate the musculoskeletal disorders risk levels (Schoenmarklin and Marras 1990). This is because the tendon force, which is a risk factor of musculoskeletal disorders, is affected by wrist acceleration. The acceleration of the wrist in a dynamic task requires transmission of the forearm forces to the tendons. Some of this force is lost to friction against the ligaments and bones in the carpal tunnel. This frictional force can irritate the tendons' synovial membranes and cause tenosynovitis or carpal tunnel syndrom (CTS). These new research results clearly demonstrate the importance of dynamic components in assessing CTD risk of highly repetitive jobs.

With respect to task repetitivness, it is believed today that jobs with a cycle time of less than 30 seconds and a fundamental cycle that exceeds 50% of the total cycle (exposure) time lead to increased risk of musculoskeletal disorders. Because of neurophysiological needs of the working muscles, adequate rest pauses (determined based on scientific knowledge on the physiology of muscular fatigue and recovery) should be scheduled to provide relief for the most active muscles used on the job. Furthermore, reduction in task repetition can be achieved by, for example, by task enlargement (increasing variety of tasks to perform), increase in the job cycle time, and work mechanization and automation.

The expected benefits of reduced musculoskeletal disorders problems in industry are improved productivity and quality of work products, enhanced safety and health of employees, higher employee morale, and accommodation of people with alternative physical abilities. Strategies for managing musculoskeletal disorders at work should focus on prevention efforts and should include, at the plant level, employee education, ergonomic job redesign, and other early intervention efforts, including engineering design technologies such as workplace reengineering, active and passive surveillance. At the macro-level, management of musculoskeletal disorders should aim to provide adequate occupational health care provisions, legislation, and industry-wide standardization.

10.2. Administrative and Engineering Controls

The recommendations for prevention of musculoskeletal disorders can be classified as either primarily administrative, that is, focusing on personnel solutions, or engineering, that is, focusing on redesigning tools, workstations, and jobs (Putz-Anderson 1988). In general, administrative controls are those actions to be taken by the management that limit the potentially harmful effects of a physically stressful job on individual workers. Administrative controls, which are focused on workers, refer to modification of existing personnel functions such as worker training, job rotation, and matching employees to job assignments.

Workplace design to prevent repetitive strain injury should be directed toward fulfilling the following recommendations:

1. Permit several different working postures.
2. Place controls, tools, and materials between waist and shoulder height for ease of reach and operation.
3. Use jigs and fixtures for holding purposes.
4. Resequence jobs to reduce the repetition.
5. Automate highly repetitive operations.
6. Allow self-pacing of work whenever feasible.
7. Allow frequent (voluntary and mandatory) rest breaks.

The following guidelines should be followed (for details see Putz-Anderson 1988):

1. Make sure the center of gravity of the tool is located close to the body and the tool is balanced.
2. Use power tools to reduce the force and repetition required.
3. Redesign the straight tool handle; bend it as necessary to preserve the neutral posture of the wrist.
4. Use tools with pistol grips and straight grips, respectively, where the tool axis in use is horizontal and vertical (or when the direction of force is perpendicular to the workplace).
5. Avoid tools that require working with the flexed wrist and extended arm at the same time or call for the flexion of distal phalanges (last joints) of the fingers.
6. Minimize the tool weight; suspend all tools heavier than 20 N (or 2 kg of force) by a counterbalancing harness.
7. Align the tool's center of gravity with the center of the grasping hand.
8. Use special-purpose tools that facilitate fitting the task to the worker (avoid standard off the-shelf tools for specific repetitive operations).
9. Design tools so that workers can use them with either hand.
10. Use power grip where power is needed and precision grip for precise tasks.
11. The handles and grips should be cylindrical or oval with a diameter of 3.0–4.5 cm (for precise operations the recommended diameter is 0.5–1.2 cm).
12. The minimum handle diameter should be 10.0 cm, and 11.5–12.0 cm is preferable.
13. A handle span of 5.0–6.7 cm can be used by male and female workers.
14. Triggers on power tools should be at least 5.1 cm wide, allowing their activation by two or three fingers.
15. Avoid form-fitting handles that cannot be easily adjusted.
16. Provide handles that are nonporous, nonslip and nonconductive (thermally and electrically).

11. JOB ANALYSIS AND DESIGN

According to ANSI Z-365 (1995), job analysis and design serve two common purposes:

1. To identify potential work-related risk factors associated with musculoskeletal disorders after they are reported
2. To assist in identifying work-related factors associated with musculoskeletal disorders before they occur

Detailed job analysis consists of analyzing the job at the element or micro-level. These analyses involve breaking down the job into component actions, measuring and quantifying risk factors, and identifying the problems and conditions contributing to each risk factor. Job surveys, on the other hand, are used for establishing work relatedness, prioritizing jobs for further analysis, or proactive risk factors surveillance. Such survey methods may include facility walk-throughs, worker interviews, risk-factor checklists, and team problem-solving approaches.

11.1. Risk Factors and Definitions

The risk factors are job attributes or exposures that increase probability of the occurrence of work-related musculoskeletal disorders. The WRMD risk factors are present at varying levels for different jobs and tasks. It should be noted that these risk factors are not necessarily causation factors of WRMDs. Also, the mere presence of a risk factor does not necessarily mean that a worker performing a job is at excessive risk of injury. (The relationship between physical stresses and WRMD risk factors is shown in Table 22.) Generally, the greater the exposure to a single risk factor or combination of factors, the greater the risk of a WRMD. Furthermore, the more risk factors that are present, the higher the risk of injury. According to ANSI Z-365 (1995), this interaction between risk factors may have a multiplicative rather than an additive effect. However, these risk factors may pose minimal risk of injury if sufficient exposure is not present or if sufficient recovery time is provided. It is known that changes in the levels of risk factors will result in changes in the risk of WRMDs. Therefore, a reduction in WRMD risk factors should reduce the risk for WRMDs. Figure 18 shows the flow chart for the ergonomics rule for control of MSDs at the workplace proposed by OSHA (2000).

11.2. Work Organization Risk Factors

The mechanisms by which poor work organization could increase the risk for WUEDs include modifying the extent of exposure to other risk factors (physical and environmental) and modifying the

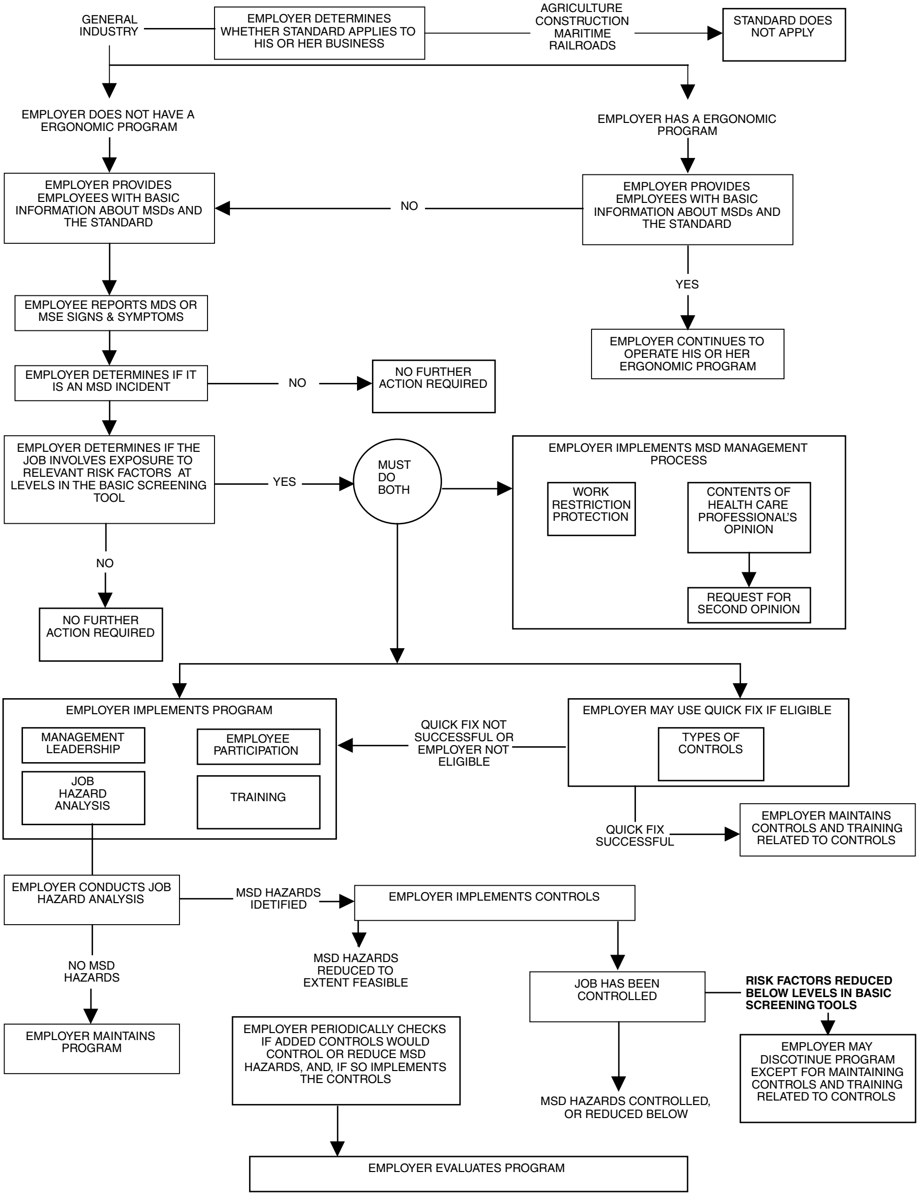

Figure 18 The Proposed OSHA Ergonomics Rule Flow Chart for Control of MSDs at the Workplace. (Modified after OSHA 2000)

stress response of the individual, thereby increasing the risk associated with a given level of exposure (ANSI 1995). Specific work organization factors that have been shown to fall into at least one of these categories include (but are not limited to):

1. Wage incentives
2. Machine-paced work
3. Workplace conflicts of many types

4. Absence of worker decision latitude
5. Time pressures and work overload
6. Unaccustomed work during training periods or after return from long-term leave

11.3. Procedures for Job Analysis and Design

Job analysis should be performed at a sufficient level of detail to identify potential work-related risk factors associated with WRMDs and include the following steps:

1. Collection of the pertinent information for all jobs and associated work methods
2. Interview of the representative sample of the affected workers
3. Breakdown of the jobs into tasks or elements
4. Description of the component actions of each task or element
5. Measurement and quantification of WRMD risk factors
6. Identification of the risk factors for each task or element
7. Identification of the problems contributing to risk factors
8. Summary of the problem areas and needs for intervention for all jobs and associated new work methods

12. SURVEILLANCE FOR JOB ANALYSIS AND DESIGN

12.1. Provisions of the ANSI Z-365 (1999) Draft Standard

Working Draft ANSI Z-365 includes sections on:

1. *Surveillance* of musculoskeletal disorders, including:
    - **(a)** Worker reports
    - **(b)** Analysis of existing records and surveys
    - **(c)** Job surveys/proactive entry into the process
2. *Job analysis and design,* including:
    - **(a)** Description of work
    - **(b)** Definitions of risk factors
    - **(c)** Risk-factor measurement, quantification, and interaction

12.2. Musculoskeletal Disorder Surveillance

As discussed in ANSI Z-365 (1999), surveillance is defined as the ongoing systematic collection, analysis, and interpretation of health and exposure data in the process of describing and monitoring work-related cumulative trauma disorders. Surveillance is used to determine when and where job analysis is needed and where ergonomic interventions may be warranted.

A surveillance system can be used in any workplace to evaluate cumulative trauma disorders (musculoskeletal disorders) in the working population. Surveillance is defined as ‘‘the ongoing systematic collection, analysis and interpretation of health and exposure data in the process of describing and monitoring a health event. Surveillance data are used to determine the need for occupational safety and health action and to plan, implement and evaluate ergonomic interventions and programs’’ (Klaucke 1988). Health and job risk-factor surveillance provide employers and employees with a means of systematically evaluating musculoskeletal disorders and workplace ergonomic risk factors by monitoring trends over time. This information can be used for planning, implementing, and continually evaluating ergonomic interventions. Therefore, incidence (rate of new cases), prevalence (rate of existing cases), and parameters that may be used in estimating severity must be defined.

12.3. Worker Reports (Case-Initiated Entry into the Process)

Follow-up to medical/first aid reports or worker symptoms consists of collecting and following employee medical reports through the medical management process.

12.4. Analysis of Existing Records and Survey (Past Case(s)-Initiated Entry into the Process)

Analysis of existing records and surveys consists of reviewing existing databases, principally collected for other purposes, to identify incidents and patterns of work-related cumulative trauma disorders. It can help determine and prioritize the jobs to be further analyzed using job analysis. There are three types of existing records and survey analyses:

1. Initial analysis of upper-limb WRMDs reported over the last 24–36 months
2. Ongoing trend analysis of past cases
3. Health surveys

12.5. Job Surveys (Proactive Entry into the Process)

The aim of proactive job surveys is to identify specific jobs and processes that may put employees at risk of developing WRMDs. Job surveys are typically performed after the jobs identified by the previous two surveillance components have been rectified. Job surveys of all jobs or a sample of representatives should be performed. Analysis of existing records will be used to estimate the potential magnitude of the problem in the workplace. The number of employees in each job, department, or similar population will be determined first. Then the incidence rates will be calculated on the basis of hours worked, as follows:

$$\text{Incidence (new case) rate (IR)} = \frac{\text{\# of new cases during time} \times 200{,}000}{\text{Total hours worked during time}}$$

This is equivalent to the number of new cases per 100 worker years. Workplace-wide incidence rates (IRs) will be calculated for all cumulative trauma disorders and by body location for each department, process, or type of job. (If specific work hours are not readily available, the number of full-time equivalent employees in each area multiplied by 2000 hours will be used to obtain the denominator.) Severity rates (SRs) traditionally use the number of lost workdays rather than the number of cases in the numerator. Prevalence rates (PRs) are the number of existing cases per 200,000 hours or the percentage of workers with the condition (new cases plus old cases that are still active).

12.6. ANSI Z-365 Evaluation Tools for Control of WRMDs

Some of the research evaluation tools defined by the ANSI Z-365 Draft Standard for the purpose of surveillance and job analysis include the following:

1. Proactive job survey (checklist #1)
2. Quick check risk factor checklist (checklist #2)
3. Symptom survey (questionnaire)
4. Posture discomfort survey
5. History of present illness recording form

12.7. Analysis and Interpretation of Surveillance Data

Surveillance data can be analyzed and interpreted to study possible associations between the WRMD surveillance data and the risk-factor surveillance data. The two principal goals of the analysis are to help identify patterns in the data that reflect large and stable differences between jobs or departments and to target and evaluate intervention strategies. This analysis can be done on the number of existing WRMD cases (cross-sectional analysis) or on the number of new WRMD cases in a retrospective and prospective fashion (retrospective and prospective analysis).

The simplest way to assess the association between risk factors and WRMDs is to calculate odds ratios (Table 29). To do this, the prevalence data obtained in health surveillance are linked with the data obtained in risk-factor surveillance. The data used can be those obtained with symptom ques-

TABLE 29 Examples of Odds Ratio Calculations for a Firm of 140 Employees

		WRMDs		
		Present	Not Present	Total
Risk factor				
	Present	15 (*A*)	25 (*B*)	40 (*A* + *B*)
	Not present	15 (*C*)	85 (*D*)	100 (*C* + *D*)
	Total	30 (*A* + *C*)	110 (*B* + *D*)	140 (N)

Number in each cell indicates the count of employees with or without WRMD and the risk factor.
Odds ratio (OR) = $(A \times D)/(B \times C) = (15 \times 85)/(25 \times 15) = 3.4$

tionnaires (active level 1 health surveillance) and risk-factor checklists (level 1 active risk-factor surveillance). Each risk factor could be examined in turn to see whether it has an association with the development of WRMDs. In the example shown here, one risk factor at a time is selected (overhead work for more than four hours).

Using the data obtained in surveillance the following numbers of employees are counted:

- Employees with WRMDs and exposed to more than four hours of overhead work (15 workers)
- Employees with WRMDs and not exposed to more than four hours of overhead work (15 workers)
- Employees without WRMDs and exposed to more than four hours of overhead work (25 workers)
- Employees without WRMDs and not exposed to more than four hours of overhead work (85 workers)

The overall prevalence rate (PR), that is, rate of existing cases, for the firm is 30/140, or 21.4%. The prevalence rate for those exposed to the risk factor is 37.5% (15/40) compared to 15.0% (15/100) for those not exposed. The risk of having a WRMD depending on exposures to the risk factor, the odds ratio, can be calculated using the number of existing cases of WRMD (prevalence). In the above example, those exposed to the risk factor have 3.4 times the odds of having the WRMD than those not exposed to the risk factor. An odds ratio of greater than 1 indicates higher risk. Such ratios can be monitored over time to assess the effectiveness of the ergonomics program in reducing the risk of WRMDs, and a variety of statistical tests can be used to assess the patterns seen in the data.

13. ERGONOMICS PROGRAMS IN INDUSTRY

An important component of musculoskeletal disorders management efforts is development of a well-structured and comprehensive ergonomic program. According to Alexander and Orr (1992), the basic components of such a program should include:

1. Health and risk-factor surveillance
2. Job analysis and improvement
3. Medical management
4. Training
5. Program evaluation

An excellent program must include participation of all levels of management, medical, safety and health personnel, labor unions, engineering, facility planners, and workers and contain the following elements:

1. Routine (monthly or quarterly) reviews of the OSHA log for patterns of injury and illness and using of special computer programs to identify problem areas.
2. Workplace audits for ergonomic problems are a routine part of the organization’s culture (more than one audit annually for each operating area). Problems identified in this manner are dealt with quickly.
3. List maintained of most critical problems—jobs with job title clearly identified. Knowledge of these problem jobs is widespread, including knowledge by management and the workers.
4. Use of both engineering solutions and administrative controls and seeking to use engineering solutions for long-term solutions.
5. Design engineering is aware of ergonomic considerations and actively builds them into new or reengineered designs. People are an important design consideration.
6. Frequent refresher training for the site-appointed ergonomists in ergonomics and access to short courses and seminars.

14. PROPOSED OSHA ERGONOMICS REGULATIONS

The National Research Council/National Academy of Sciences of the United States recently concluded that there is a clear relationship between musculoskeletal disorders and work and between ergonomic interventions and a decrease in such disorders. According to the Academy, research demonstrates that specific interventions can reduce the reported rate of musculoskeletal disorders for workers who perform high-risk tasks (National Research Council 1998). The effective and universal standard for dealing with the work-related hazards should significantly reduce the risk to WRMDS to employees.

The high prevalence of work-related musculoskeletal disorders, has motivated the Occupational Safety and Health Administration (OSHA) to focus on standardization efforts. Recently, OSHA announced the initiation of rulemaking under Section 6(b) of the Occupational Safety and Health Act of 1970, 29 U.S.C. 655, to amend Part 1910 of Title 29 of the Code of Federal Regulations and requested information relevant to preventing, eliminating, and reducing occupational exposure to ergonomic hazards.

According to OSHA (2000), the proposed standard is needed to bring this protection to the remaining employees in general industry workplaces that are at significant risk of incurring a work-related musculoskeletal disorder but are currently without ergonomics programs. A substantial body of scientific evidence supports OSHA's effort to provide workers with ergonomic protection. This evidence strongly supports two basic conclusions: (1) there is a positive relationship between work-related musculoskeletal disorders and workplace risk factors, and (2) ergonomics programs and specific ergonomic interventions can reduce these injuries.

14.1. Main Provisions of the Draft Ergonomics Standard

The standard applies to employers in general industry whose employees work in manufacturing jobs or manual handling jobs or report musculoskeletal disorders (MSDs) that meet the criteria of the standard (see Figure 18). The standard applies to the following jobs:

1. Manufacturing jobs. Manufacturing jobs are production jobs in which employees perform the physical work activities of producing a product and in which these activities make up a significant amount of their work time;
2. Manual handling jobs. Manual handling jobs are jobs in which employees perform forceful lifting/lowering, pushing/pulling, or carrying. Manual handling jobs include only those jobs in which forceful manual handling is a core element of the employee's job; and
3. Jobs with a musculoskeletal disorder. Jobs with an MSD are those jobs in which an employee reports an MSD that meets all of these criteria:
   - **(a)** The MSD is reported after the effective date;
   - **(b)** The MSD is an ''OSHA recordable MSD,'' or one that would be recordable if the employer was required to keep OSHA injury and illness records; and
   - **(c)** The MSD also meets the screening criteria.

The proposed standard covers only those OSHA-recordable MSDs that also meet these screening criteria:

1. The physical work activities and conditions in the job are reasonably likely to cause or contribute to the type of MSD reported; and
2. These activities and conditions are a core element of the job and/or make up a significant amount of the employee's work time.

The standard applies only to the jobs specified in Section 1910.901, not to the entire workplace or to other workplaces in the company. The standard does not apply to agriculture, construction, or maritime operations. In the proposed standard, a full ergonomics program consists of these six program elements:

1. Management leadership and employee participation
2. Hazard information and reporting
3. Job hazard analysis and control
4. Training
5. MSD management
6. Program evaluation

According to the standard, the employer must:

1. Implement the first two elements of the ergonomics program (management leadership and employee participation, and hazard information and reporting) even if no MSD has occurred in those jobs.
2. Implement the other program elements when either of the following occurs in those jobs (unless one eliminates MSD hazards using the quick fix option

- **(a)** A covered MSD is reported; or
- **(b)** Persistent MSD symptoms are reported plus:
  - **(i)** The employer has knowledge that an MSD hazard exists in the job;
  - **(ii)** Physical work activities and conditions in the job are reasonably likely to cause or contribute to the type of MSD symptoms reported; and
  - **(iii)** These activities and conditions are a core element of the job and/or make up a significant amount of the employee's work time.

In other jobs in general industry, the employer should comply with all of the program elements in the standard when a covered MSD is reported (unless the MSD hazards are eliminated using the quick fix option). The employer should do the following to quick fix a problem job:

1. Promptly make available the MSD management
2. Consult with employee(s) in the problem job about the physical work activities or conditions of the job they associate with the difficulties, observe the employee(s) performing the job to identify whether any risk factors are present, and ask employee(s) for recommendations for eliminating the MSD hazard
3. Put in quick fix controls within 90 days after the covered MSD is identified and check the job within the next 30 days to determine whether the controls have eliminated the hazard
4. Keep a record of the quick fix controls
5. Provide the hazard information the standard requires to employee(s) in the problem job within the 90-day period

The employer should set up the complete ergonomics program if either the quick fix controls do not eliminate the MSD hazards within the quick fix deadline (120 days) or another covered MSD is reported in that job within 36 months.

The employer should demonstrate management leadership of your ergonomics program. Employees (and their designated representatives) must have ways to report MSD signs and MSD symptoms, get responses to reports; and be involved in developing, implementing, and evaluating each element of your program. The employer should not have policies or practices that discourage employees from participating in the program or from reporting MSDs signs or symptoms. The employer also should:

1. Assign and communicate responsibilities for setting up and managing the ergonomics program so managers, supervisors, and employees know what you expect of them and how you will hold them accountable for meeting those responsibilities
2. Provide those persons with the authority, resources, information, and training necessary to meet their responsibilities
3. Examine your existing policies and practices to ensure that they encourage and do not discourage reporting and participation in the ergonomics program
4. Communicate periodically with employees about the program and their concerns about MSDs

According to the proposed standard, the employees (and their designated representatives) must have a way to report MSD signs and symptoms; prompt responses to their reports; access to the standard and to information about the ergonomics program; and ways to be involved in developing, implementing, and evaluating each element of the ergonomics program.

The employer should set up a way for employees to report MSD signs and symptoms and get prompt responses. The employer should evaluate employee reports of MSD signs and symptoms to determine whether a covered MSD has occurred. The employer should periodically provide information to employees that explains how to identify and report MSD signs and symptoms. The employer should also provide this information to current and new employees about common MSD hazards, the signs and symptoms of MSDs and the importance of reporting them early, how to report the signs and symptoms, and a summary of the requirements of the standard.

14.2. Job Hazard Analysis and Control

According to the Draft Standard, the employer should analyze the problem job to identify the ergonomic risk factors that result in MSD hazards. The employer should eliminate the MSD hazards, reduce them to the extent feasible, or materially reduce them using the incremental abatement process in the standard. If the MSD hazards only pose a risk to the employee with the covered MSD, the job hazard analysis and control can be limited to that individual employee's job. In such a case, the employer should:

1. Include in the job-hazard analysis all of the employees in the problem job or those who represent the range of physical capabilities of employees in the job.
2. Ask the employees whether performing the job poses physical difficulties and, if so, which physical work activities or conditions of the job they associate with the difficulties.
3. Observe the employees performing the job to identify which of the physical work activities, workplace conditions, and ergonomic risk factors are present.
4. Evaluate the ergonomic risk factors in the job to determine the MSD hazards associated with the covered MSD. As necessary, evaluate the duration, frequency, and magnitude of employee exposure to the risk factors.

The proposed engineering controls include physical changes to a job that eliminate or materially reduce the presence of MSD hazards. Examples of engineering controls for MSD hazards include changing, modifying, or redesigning workstations, tools, facilities, equipment, materials, and processes. Administrative controls are changes in the way that work in a job is assigned or scheduled that reduce the magnitude, frequency, or duration of exposure to ergonomic risk factors. Examples of administrative controls for MSD hazards include employee rotation, job task enlargement, alternative tasks, and employer-authorized changes in work pace.

Finally, it should be noted that the OSHA's Final Ergonomic Program Standard took effect on January 16, 2001.

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