CHAPTER 9
USABILITY

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Not only must tools, equipment, and machines function, but in many cases their effectiveness depends on how well a human can use and operate them. A pair of pliers is useless unless it is held in the human hand; a lathe (if not run automatically) needs an operator to observe the cutting edge, to operate controls, and to feed and unload; maintenance and repair of equipment must be facilitated by proper design.

Of course, fitting tools and work to human capabilities and limitations has always been done, but this was formally established as "work physiology" and "industrial psychology" early in the twentieth century. During the Second World War, "human engineering" was systematically applied to weapon systems, and since then it has been increasingly applied to technical products and human-machine systems. *Ergonomics,* the current generally used term, is rooted in safety and ease of use; its desired outcome is the optimization of work, especially of the interface between the human and the technical product.

Designing for human use is the field of ergonomics, or human (factors) engineering. The term *ergonomics* was coined in 1950 from two Greek words: *ergon* for human work and *nomos* for rules. In the United States, the Human Factors and Ergonomics Society is the professional organization; the worldwide umbrella organization is the International Ergonomics Association, with nearly three dozen national member societies. Courses in ergonomics or human engineering are taught in more than fifty engineering departments (mostly industrial engineering) and psychology departments (engineering psychology) in North American universities.

Books provide encompassing information about ergonomics and its engineering applications; in English, for example, there are publications by Boff, Kaufman, and Thomas [9.1]; Cushman and Rosenberg [9.2]; Eastman Kodak Company [9.3]; Fraser [9.4]; Grandjean [9.5]; Helander [9.6]; Kroemer, Kroemer, and Kroemer-Elbert [9.7], [9.8]; Proctor and Van Zandt [9.9]; Pulat [9.10]; Salvendy [9.11]; Sanders and McCormick [9.12]; Weimer [9.13]; Wilson and Corlett [9.14]; and Woodson, Tillman, and Tillman [9.15]. Furthermore, standards offer practical information, in particular U.S. Military Standards 759 and 1472, as well as more specific issues by the U.S. Air Force, Army, and Navy, and NASA Standard 3000. The American Society of Safety Engineers (ASSE), the Society of Automotive Engineers (SAE), and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) as well as the American National Standards Institute (ANSI) and the Occupational Safety and Health Agency (OSHA) issue ergonomic standards on specific topics. (Addresses are given in the References section.)

9.1 DESIGNING FOR HUMAN BODY SIZE

"Fitting" a hand tool, a machine, or a complex technical system to the operator is very important: Pliers are hard to use if the handles hurt the hand; a caulking gun that has handles so far apart that persons with small hands cannot grasp it is unusable for many; gloves that don't fit won't be used. Tools, machines, and systems can be designed to fit the body, whereas genetic engineering of the body to fit ill-designed equipment is not practical. The axiom is, "Fit tool and task to the human."

Four steps assure that the product or system fit the operator (see Ref. [9.8] for more details):

Step 1. Select those body dimensions that directly relate to equipment dimensions. For example, hand size should be related to handle size; shoulder and hip breadth to an opening through which a repair person must enter; head length and breadth to helmet size; eye height to the height of an object that must be seen, such as a computer display; knee height and hip breadth to the leg room needed by a seated operator.

Step 2. For each of these pairings, decide whether the design must fit only one given body dimension or a range of body dimensions. For example, an opening must be large enough to allow the person with the largest shoulder and hip breadths to pass through, even when wearing bulky clothing and equipment; pliers can come in different sizes to fit either small or large hands; the height of a seat should be adjustable to accommodate persons ranging from short to tall, with different lower leg lengths.

Step 3. Combine all selected design values in a careful drawing, computer model, or mock-up to ascertain that they are compatible. For example, the leg-room clearance height needed for a seated person with long lower legs might be very close to the height of the working object, which is related to elbow height.

Step 4. Determine whether one design will fit all users; if not, several sizes or adjustability are needed. For example, a large opening will allow all users to pass through; work clothes must come in different sizes; pilot seats are adjustable to fit female and male, small and big air crew members.

9.1.1 Available Anthropometric Information

Human body dimensions are measured by anthropometrists. Unfortunately, large surveys of national populations have been performed almost exclusively on soldiers;

very few large civilian groups have been measured in recent years. Thus, the available information is usually derived from soldier anthropometry, and these data are then applied to the adult population in general.

Table 9.1 contains body dimensions of U.S. adults. These numbers have been extracted from recent compilations by Gordon et al. [9.16] and Greiner [9.17], who reported a large number of U.S. Army body dimensions. Some information on the body dimensions of elderly persons, of children, and of pregnant women is available as well—see, for example, tables published recently by Kroemer, Kroemer, and Kroemer-Elbert [9.8] and Roebuck [9.18].

Fortunately, measurements of human body dimensions usually fall into "normal" (Gaussian) distributions which can be described statistically in terms of average (mean) and standard deviation, provided that a sufficient number of people is included in the survey. Hence, one can apply regular parametric statistics.

9.1.2 Use of Percentiles

Percentile values can be determined from anthropometric data. The 50th percentile coincides, in a normal distribution, with the average. Average values for important body dimensions are given in Table 9.1 (in the column labeled 50th percentile), together with the standard deviation. If one multiplies the standard deviation S by the factor k presented in Table 9.2, one can determine percentile values below or above which lie known subsamples. For example, below the 2d percentile are 2 percent of all data and the remaining 98 percent are above; conversely, 98 percent of all data lie below the 98th percentile and 2 percent of all data are above. To determine the 2d percentile, or the 98th percentile, one multiplies the standard deviation of the anthropometric dimensions by the factor 2.06 (as shown in Table 9.2). For the 2d percentile, the product is deducted from the average; it is added to the average in order to determine the 98th percentile. In the range between the 2d and 98th percentiles, 96 percent of all data are contained.

Percentiles serve the designer/engineer in several ways [9.8]. First, they help to establish the portion of a user population that will be able to make (or excluded from making) proper use of a specific piece of equipment. Second, knowledge of percentile values can be used to select subjects for fit tests. Third, any design value or a body dimension can be exactly located on the range for that specific dimension.

9.1.3 Models of Operator Size

Some body dimensions are highly correlated, such as eye height and stature. Other dimensions are practically unrelated, such as stature and hip breadth. In the case of high correlations, one can use one dimension to predict another: If eye height is unknown but stature has been measured, one can predict eye height from stature with high accuracy. However, some height dimensions and almost all width and depth dimensions are practically unrelated to stature; thus, one cannot assume, with sufficient certainty, that a short person must have narrow hips or small wrists, or be of light weight.

Therefore, one must be careful when estimating body dimensions from others. If needed body dimensions are unknown, one has to take specific body size measurements of the equipment operators and product users; it may be necessary to use the expertise of ergonomists or anthropometrists. A common mistake is using "the average person," a phantom who is assumed to possess average dimensions throughout.

TABLE 9.1 Selected Anthrometric Data of the U.S. Adult Population, Females/Males

All values in cm, except weight in kg.

Dimensions	Percentile 5th	Percentile 50th	Percentile 95th	Standard deviation
Heights, standing				
Stature ("height")	152.8/164.7	162.94/175.58	173.7/186.6	6.36/6.68
Eye	141.5/152.8	151.61/163.39	162.1/174.3	6.25/6.57
Shoulder (acromion)	124.1/134.2	133.36/144.25	143.2/154.6	5.79/6.20
Elbow	92.6/99.5	99.79/107.25	107.4/115.3	4.48/4.81
Wrist	72.8/77.8	79.03/84.65	85.5/91.5	3.86/4.15
Crotch	70.0/76.4	77.14/83.72	84.6/91.6	4.41/4.62
Overhead fingertip reach (on toes)	200.6/216.7	215.34/132.80	231.3/249.4	9.50/9.99
Heights, sitting				
Sitting height	79.5/85.5	85.20/91.39	91.0/97.2	3.49/3.56
Eye	68.5/73.5	73.87/79.02	79.4/84.8	3.32/3.42
Shoulder (acromion)	50.9/54.9	55.55/59.78	60.4/64.6	2.86/2.96
Elbow rest	17.6/18.4	22.05/23.06	27.1/27.4	2.68/2.72
Knee	47.4/51.4	51.54/55.88	56.0/60.6	2.63/2.79
Popliteal	35.1/39.5	38.94/43.41	42.9/47.6	2.37/2.49
Thigh clearance	14.0/14.9	15.89/16.82	18.0/19.0	1.21/1.26
Depths				
Chest	20.9/21.0	23.94/24.32	27.8/28.0	2.11/2.15
Elbow–fingertip	40.6/44.8	44.35/48.40	48.3/52.5	2.36/2.33
Buttock–knee sitting	54.2/56.9	58.89/61.64	64.0/66.7	2.96/2.99
Buttock–popliteal sitting	44.0/45.8	48.17/50.04	52.8/54.6	2.66/2.66
Thumbtip reach	67.7/73.9	73.46/80.08	79.7/86.7	3.64/3.92
Breadths				
Forearm–forearm	41.5/47.7	46.85/54.61	52.8/62.1	3.47/4.36
Hip, sitting	34.3/32.9	38.45/36.68	43.2/41.2	2.72/2.52
Head dimensions				
Length	17.6/18.5	18.72/19.71	19.8/20.9	0.64/0.71
Breadth	13.7/14.3	14.44/15.17	15.3/16.1	0.49/0.54
Circumference	52.3/54.3	54.62/56.77	57.1/59.4	1.46/1.54
Interpupillary breadth	5.7/5.9	6.23/6.47	6.9/7.1	0.36/0.37
Hand dimensions				
Wrist circumference	14.1/16.2	15.14/17.43	16.3/18.8	0.69/0.82
Length, stylion to tip 3	16.5/17.8	18.07/19.41	19.8/21.1	0.98/0.99
Breadth, metacarpal	7.4/8.4	7.95/9.04	8.6/9.8	0.38/0.42
Circumference, metacarpal	17.3/19.8	18.65/21.39	20.1/23.1	0.86/0.98
Digit 1: breadth, distal joint	1.9/2.2	2.06/2.40	2.3/2.6	0.13/0.13
Length	5.6/6.2	6.35/6.97	7.2/7.8	0.48/0.48
Digit 2: breadth, distal joint	1.5/1.8	1.73/2.01	1.9/2.3	0.12/0.15
Length	6.2/6.7	6.96/7.53	7.7/8.4	0.46/0.49
Digit 3: breadth, distal joint	1.5/1.7	1.71/1.98	1.9/2.2	0.11/0.14
Length	6.9/7.5	7.72/8.38	8.6/9.3	0.51/0.54
Digit 4: breadth, distal joint	1.4/1.6	1.58/1.85	1.8/2.1	0.11/0.14
Length	6.4/7.1	7.22/7.92	8.1/8.8	0.50/0.52
Digit 5: breadth, distal joint	1.3/1.5	1.47/1.74	1.7/2.0	0.11/0.13
Length	5.1/5.7	5.83/6.47	6.6/7.3	0.46/0.49
Foot dimensions				
Length	22.4/24.9	24.44/26.97	26.5/29.2	1.22/1.31
Breadth	8.2/9.2	8.97/10.06	9.8/11.0	0.49/0.53
Lateral malleolus height	5.2/5.8	6.06/6.71	7.0/7.6	0.53/0.55
Weight (kg), U.S. Army	49.6/61.6	62.01/78.49	77.0/98.1	8.35/11.10
Weight (kg), civilians†	39/58†	62.0/78.5†	85/99†	13.8/12.6†

† Estimated (from Kroemer, 1981).

Note that all values (except for civilians' weight) are based on measured, not estimated, data that may be slightly different from values calculated from average plus or minus 1.65 standard deviation.

Source: Adapted from [9.15] and [9.16].

TABLE 9.2 Calculation of Percentiles Using the Average and Multiples of the Standard Deviation

Percentile p associated with			
$x_i = \overline{x} - kS$ (below mean)	$x_j = \overline{x} + kS$ (above mean)	Central percent included in the range x_i to x_j	k
0.5	99.5	99	2.576
1	99	98	2.326
2	98	96	2.06
2.5	97.5	95	1.96
3	97	94	1.88
5	95	90	1.65
10	90	80	1.28
15	85	70	1.04
16.5	83.5	67	1.00
20	80	60	0.84
25	75	50	0.67
37.5	62.5	25	0.32
50	50	0	0

(People who are all 5th, or *n*th, percentile are figments of the imagination as well.) As discussed above, it is necessary to consider ranges of body dimensions, and to ascertain whether correlations exist between sets of body dimensions. For example, there is only a very small statistical correlation (about 0.4) between body height and body weight, contradicting the popular image of ideal height/weight ratios. Several such misleading body-proportion models have been used in the past, including design templates with fixed body proportions or CAD/CAM programs that utilize single-percentile constructs of the human body.

Human bodies come in a variety of sizes and proportions. Information about these is available (see especially Refs. [9.8], [9.16], [9.17], and [9.18]), and this can and must be used by the engineer to assure that the design fits the user.

9.2 DESIGNING FOR HUMAN BODY POSTURE

People seldom do work when lying supine or prone, but such postures do occur—for example, in repair jobs, or in low-seam underground mining. In some fighter airplanes and tanks, or in low-seam mining equipment, pilots or drivers are semireclining. There are also transient or temporary work postures such as kneeling on one or both knees, squatting, or stooping, often in confined spaces such as the cargo holds of aircraft; these postures as well as reaching, bending, and twisting the body should be avoided even in short-term activities to avert fatigue or injury. Proper equipment design is the task of the design engineer; proper equipment use is the responsibility of the manager.

By itself, lying is the least strenuous posture in terms of physical effort as measured by oxygen consumption or heart rate. Yet it is not well suited for performing physical work with the arms and hands because they must be elevated for most activities. Standing is much more energy-consuming, but it allows free use of the arms and hands, and, if one walks around, much space can be covered. Walking facilitates dynamic use of the body and is suitable for the development of fairly large energies and impact forces.

Sitting is, in most respects, between these two postures. Body weight is partially supported by a seat; energy consumption and circulatory strain are higher than when lying, but lower than when standing. Arms and hands can be used freely, although the work space they can cover is more limited than when walking. The energy that can be developed is smaller than when standing, but because of the stability of the trunk when it is supported on the seat, performing finely controlled manipulations is easier. Operation of pedals and controls with the feet is easy in the sitting posture: The feet are fairly mobile, since they are little needed to stabilize the posture and support the body weight.

Sitting and standing are usually thought to involve a more or less "upright" or "erect" trunk. The model of all major body joints at 0, 90, or 180 degrees is used for standardization of body measurements, but it is neither commonly employed, nor even proven to be healthy. Thus, the convenient model of the "0–90–180 posture" at work is just another phantom, like the "average person." In fact, deviations are common, subjectively preferred, and desirable in terms of variations in posture; moving about breaks maintained static muscle efforts and provides physiological stimuli and exercise.

9.2.1 Designing for the Standing Operator

Standing is used as a working posture if sitting is not suitable, either because the operator has to cover a fairly large work area or because very large forces must be exerted with the hands, particularly if these conditions prevail only for a limited period of time. Forcing a person to stand simply because the work object is customarily put high above the floor is usually not a sufficient justification; for example, in automobile assembly, car bodies can be turned or tilted, and parts redesigned, so that the worker does not have to stand and bend in order to reach the work object. Some work stations are designed for standing operators because of a need to exert large forces over large spaces, make strong exertions with visual control, or work with large objects are shown in Fig. 9.1.

People should never be forced to stand still at a work station just because the equipment was originally badly designed or badly placed, as is unfortunately too often the case with drill presses used in continuous work. Also, many other machine tools, such as lathes, have been so constructed that the operator must stand and lean forward to observe the cutting action, and at the same time extend the arms to reach the controls on the machine.

The height of the work station depends largely on the activities to be performed with the hands and the size of the object. In fitting the work station to the operator, the main reference point is the operator's individual elbow height, as further discussed below. The support surface (for example, workbench or table) is determined by the working height of the hands and the size of the object on which the person works.

Sufficient room for the operator's feet must be provided, including toe and knee space to allow him or her to move up close to the work area. Of course, the floor should be flat and free of obstacles; use of platforms to stand on should be avoided, if possible, because the operator may stumble over the edge. While movements of the body associated with dynamic work are, basically, a desirable physiological feature, they should not involve excessive bends and reaches, and especially should not include twisting motions of the trunk; these can cause overexertions and injury, often to the low back [9.8].

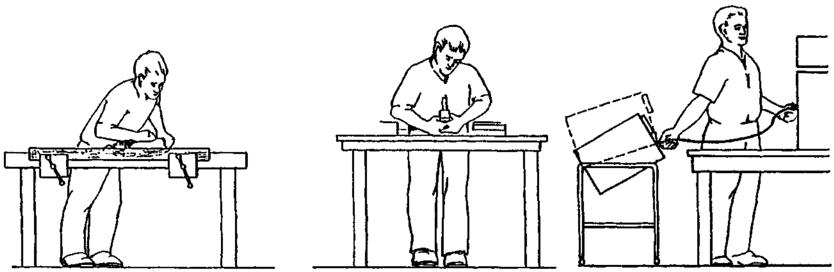


FIGURE 9.1 Work stations designed for standing operators. (With permission from K. H. E. Kroemer, H. B. Kroemer, and K. E. Kroemer-Elbert, (1994), *Ergonomics: How to Design for Ease and Efficiency*. All rights retained by the publisher, Prentice Hall, Englewood Cliffs, NJ.)

9.2.2 Designing for the Sitting Operator

Sitting is a much less stressful posture than standing. It allows better-controlled hand movements, but permits coverage of only a smaller area and exertion of smaller forces with the hands. A sitting person can easily operate controls with the feet and do so, if suitably seated, with much force (see below). When designing a work station for a seated operator, one must particularly consider the free space required for the legs. If this space is severely limited, very uncomfortable and fatiguing body postures result, as shown in Fig. 9.2.

The height of the working area for the hands is mostly determined by elbow height. However, many activities require close visual observation; thus eye height

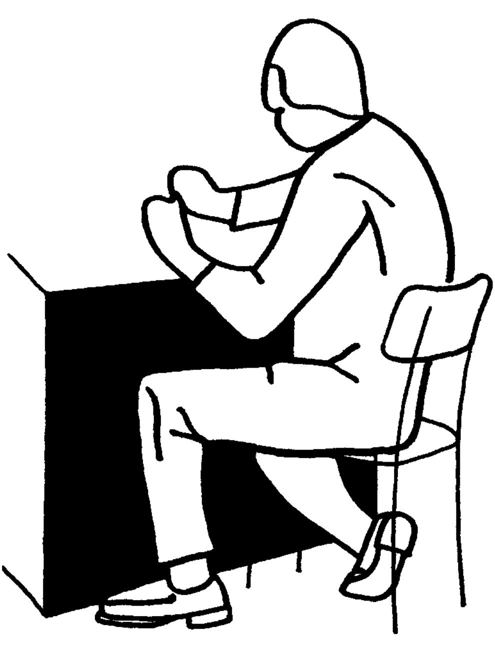


FIGURE 9.2 Missing leg room makes for an awkward sitting posture.

co-determines the proper height of the manipulation area, depending on the operator's preferred visual distance and direction of gaze. The design principles for accommodating a seated person are discussed in more detail later in this chapter. In some work stations, sit-stand transitions are suitable, as shown in Fig. 9.3.

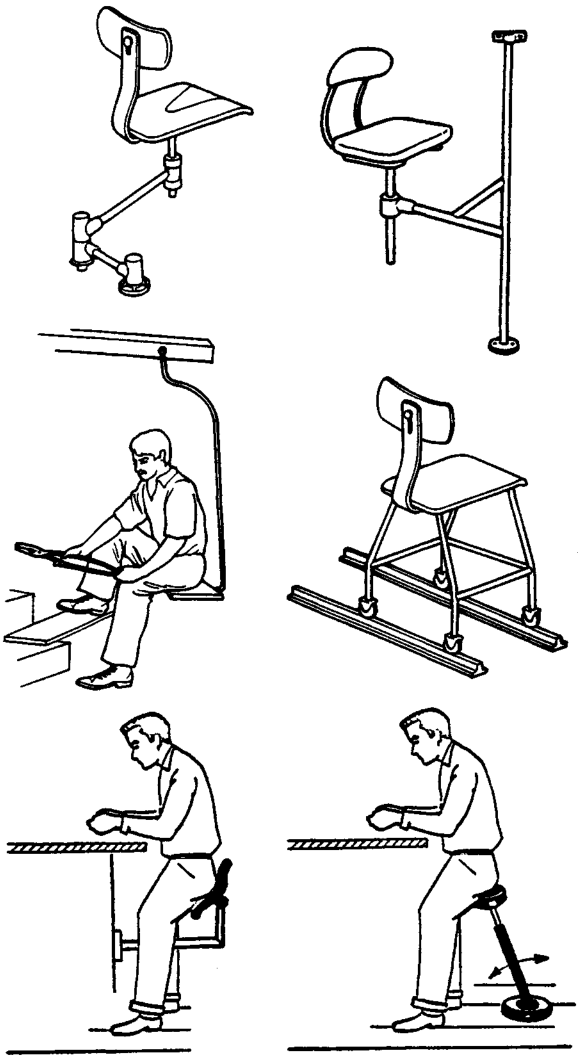


FIGURE 9.3 Stools and body props for sit–stand transitions. (With permission from K. H. E. Kroemer, H. B. Kroemer, and K. E. Kroemer-Elbert, (1994), *Ergonomics: How to Design for Ease and Efficiency*. All rights retained by the publisher, Prentice Hall, Englewood Cliffs, NJ.)

9.3 DESIGNING FOR REACH AND MOBILITY

Reach is the ability to extend hands and arms, or feet and legs, to touch and operate a control. Objects at the periphery of one's reach can just barely be pushed, pulled, turned, but more complex operations can be performed within the reach envelope.

The utmost reach envelope depends on the location of the body joint about which the limb moves; usually, this is the shoulder for hand reaches and the hip for foot reaches. The radius is the length of arm or leg. The contours of reach envelopes are nearly spherical in front and to the sides, and above and below the joint; but to the rear of the body, these envelopes become much reduced, as shown in Figs. 9.4 and 9.5.

The most preferred working areas are sections of the reach envelope in front of the body and close to the body, as shown in Fig. 9.6. For the hands, the preferred areas are directly in front of the chest at about elbow height, with the arm more or less bent. In these areas, motions can be performed most quickly, with best accuracy, and with least effort. (These areas are also suitable for exertion of moderate to large

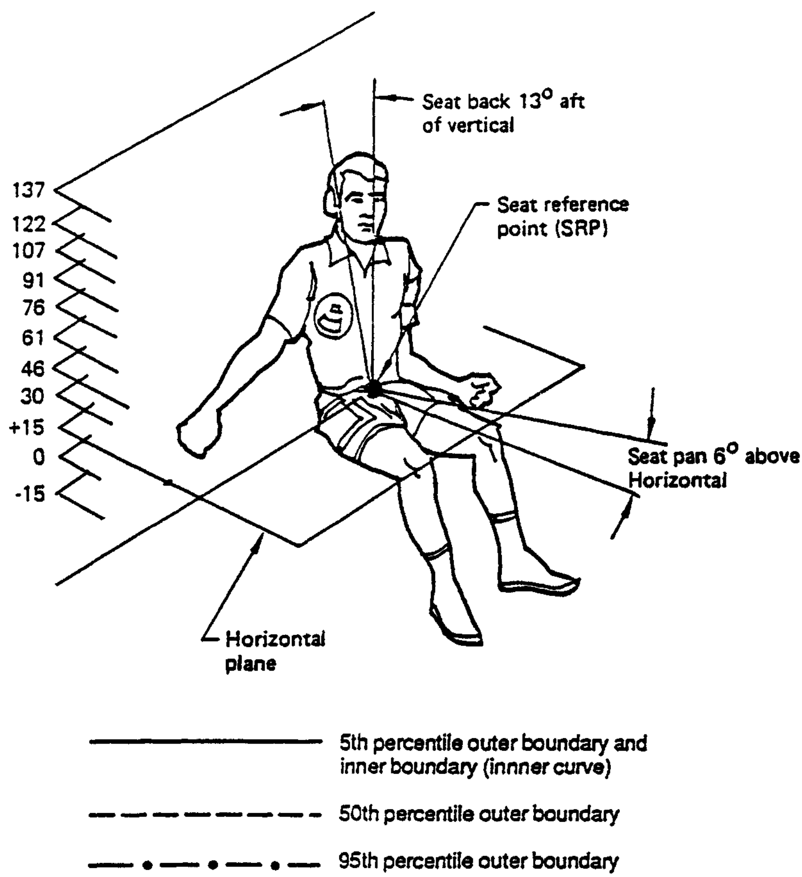
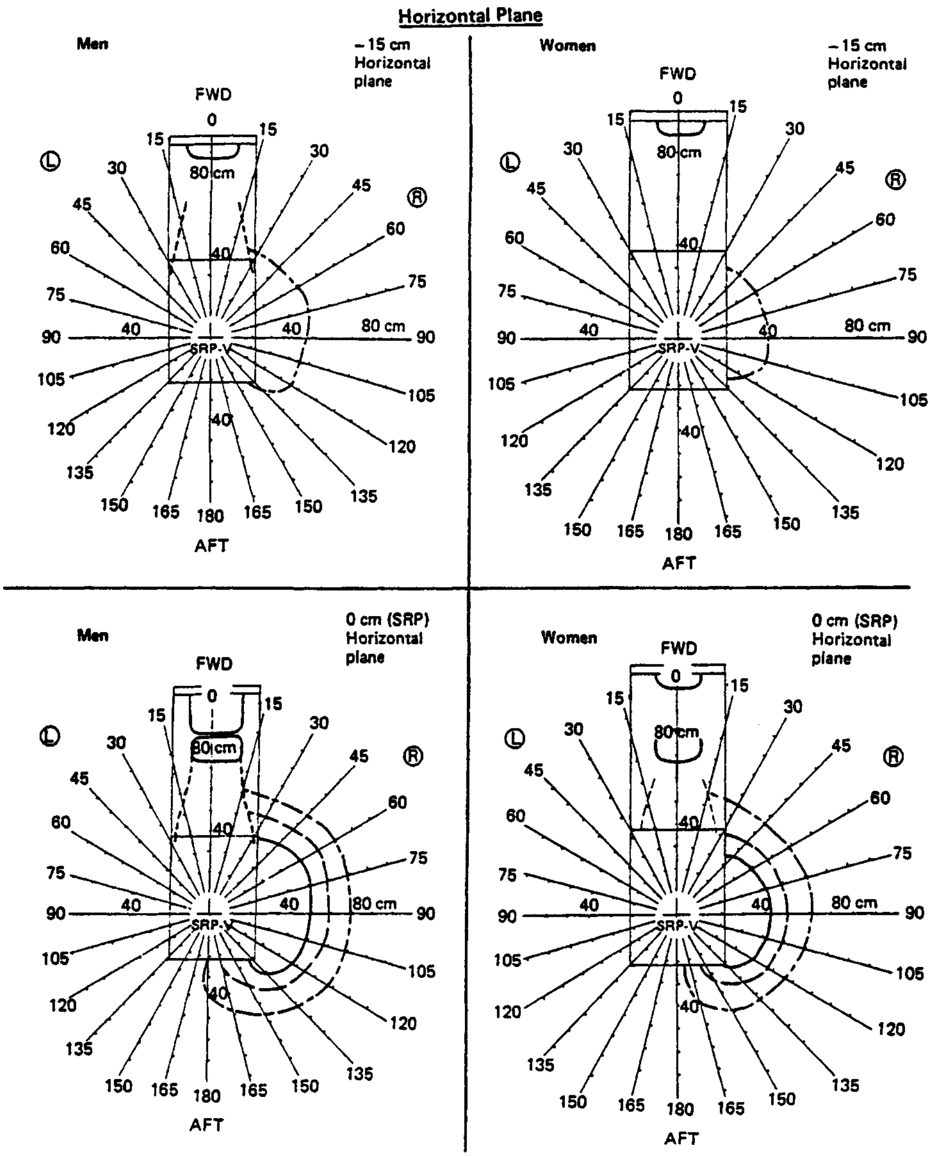


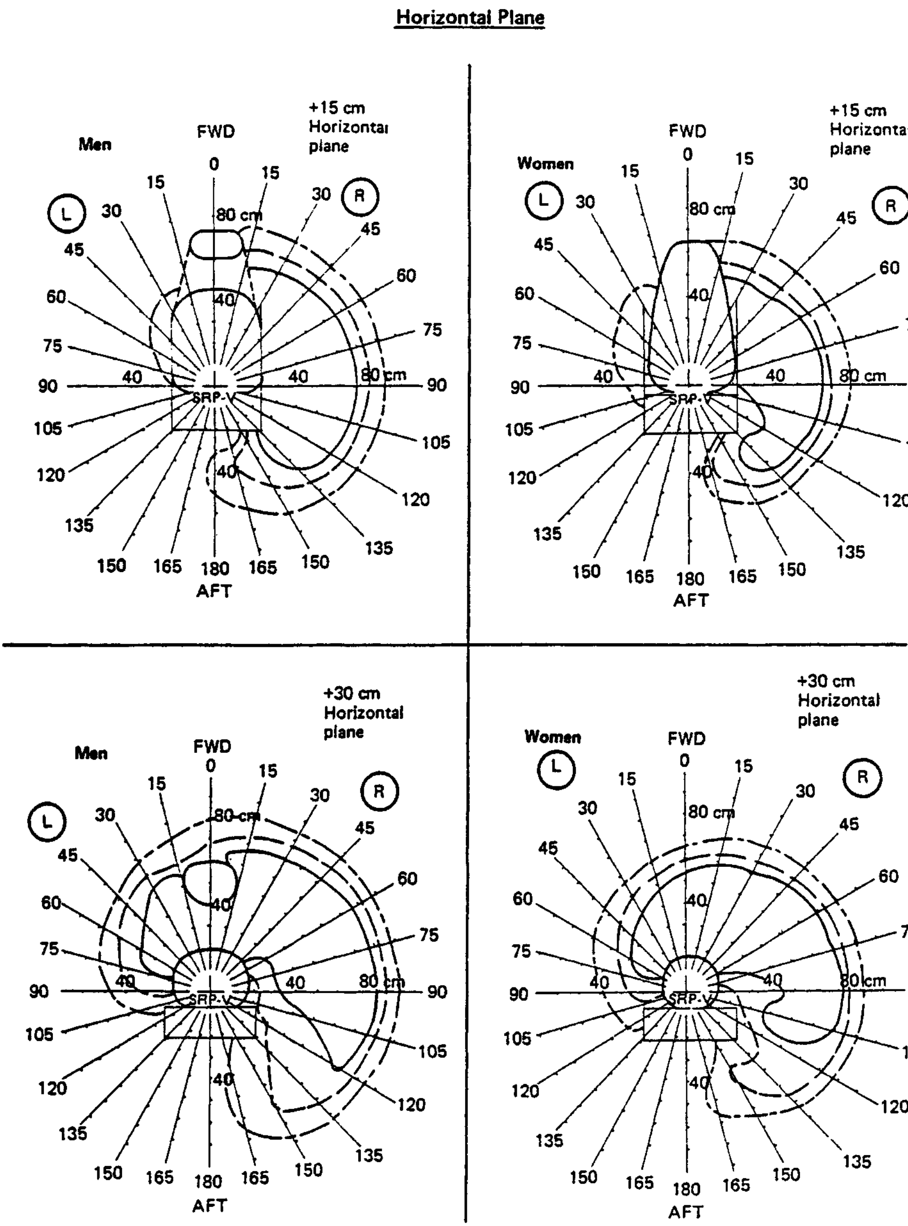
FIGURE 9.4 Reference planes for reaches. (Adapted from NASA STD 3000.)



(a)

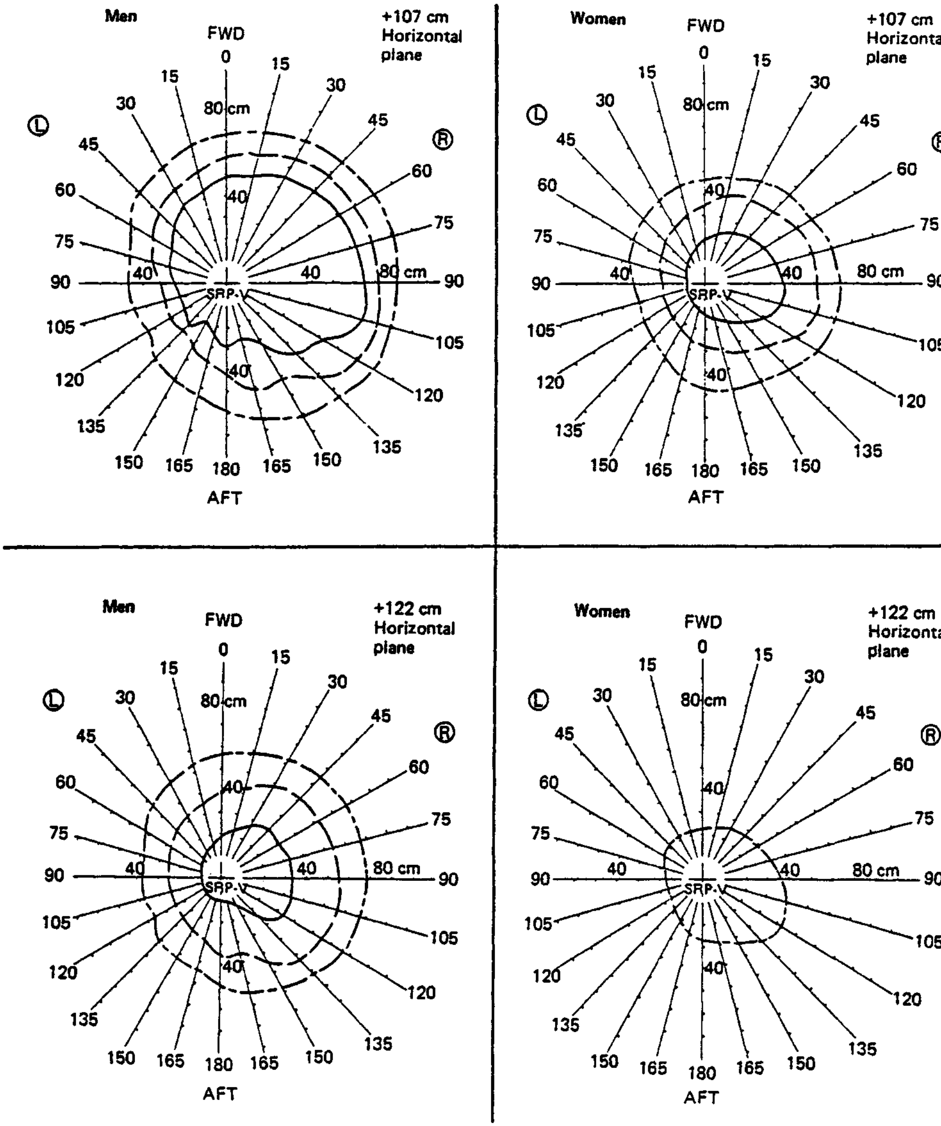
FIGURE 9.5 Examples of reach envelopes of seated operators. (Adapted from NASA STD 3000.)

hand forces, as discussed in the next section.) For the feet, the most suitable area for a seated operator is slightly below and in front of the knees—that is, with a knee angle of about 90 to 120 degrees. This is an area in which relatively fast and accurate foot motions can be made. (Foot forces in this posture are only small to moderate, however; see below.)



(b)

FIGURE 9.5 (*Continued*) Examples of reach envelopes of seated operators. (Adapted from NASA STD 3000.)



(c)

FIGURE 9.5 (*Continued*) Examples of reach envelopes of seated operators. (Adapted from NASA STD 3000.)

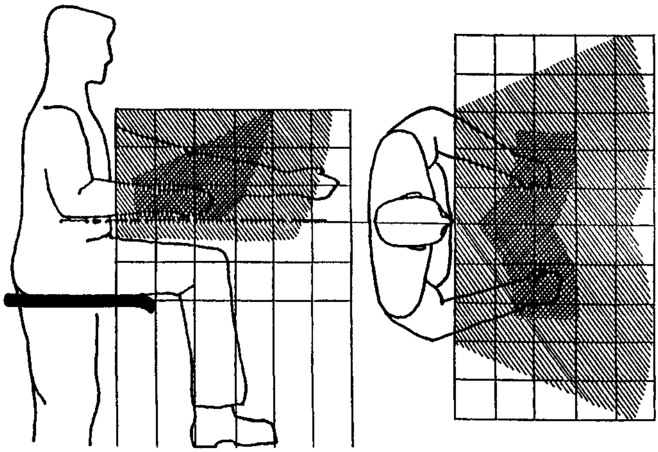


FIGURE 9.6 The normal and preferred (cross-hatched) work space for the hands. (With permission from K. H. E. Kroemer, H. B. Kroemer, and K. E. Kroemer-Elbert, (1994), *Ergonomics: How to Design for Ease and Efficiency*. All rights retained by the publisher, Prentice Hall, Englewood Cliffs, NJ.)

Mobility (often also called flexibility) refers to the range of motion that can be achieved about a body articulation. The boundaries are measured by angles from a known reference position (often, but not always, the so-called neutral position) as the difference between the smallest and largest angular excursions by a body segment about its body-next (proximal) articulation. Extremes of such displacements in body joints are described and listed in Table 9.3.

Specific zones of preference, convenience, or expediency need to be defined for each given condition and task; they will normally fall in the crosshatched areas of Figs. 9.6 and 9.7. For unusual or seldom done tasks, controls and tools can be located away from those normally preferred zones. In fact, in some cases one purposely locates objects outside those zones, beyond restrictive guards, walls, or other barriers, so that a "safe distance" between a danger point and the body is achieved, as shown in Fig. 9.8.

9.4 DESIGNING FOR HUMAN FORCE AND POWER

In energy terms, the human is very inefficient at doing heavy physical work; in most of our daily tasks, our energy efficiency is only about 5 percent. The human body also is not built for large force exertions, but rather for the exertion of fast, exact, well-controlled movements. Nevertheless, there are occasions at work on which the human must generate large torques or forces; however, these should be required only occasionally and for short periods of time. Biomechanically and psychologically, the human body is better able to perform rhythmic dynamic work, such as walking, pedaling, or turning a hand crank or lever, than to perform continual efforts with little or no movement. Static efforts (called *isometric* in physiological terminology) quickly lead to fatigue; for example, a human can maintain a maximal muscle

TABLE 9.3 Mobility in Body Joints, Measured in Angle Degrees Between Extreme Positions

		5th Percentile		50th Percentile		95th Percentile		Difference†	
Joint	Movement	Female	Male	Female	Male	Female	Male	Female	Male
Neck	Ventral flexion	34.0	25.0	51.5	43.0	69.0	60.0	+8.5	
	Dorsal flexion	47.5	38.0	70.5	56.5	93.5	74.0	+14.0	
	Right rotation	67.0	56.0	81.0	74.0	95.0	85.0	+7.0	
	Left rotation	64.0	67.5	77.0	77.0	90.0	85.0	NS	
Shoulder	Flexion	169.5	161.0	184.5	178.0	199.5	193.5	+6.5	
	Extension	47.0	41.5	66.0	57.5	85.0	76.0	+8.5	
	Adduction	37.5	36.0	52.5	50.5	67.5	63.0	NS	
	Abduction	106.0	106.0	122.5	123.5	139.0	140.0	NS	
	Medial rotation	94.0	68.5	110.5	95.0	127.0	114.0	+15.5	
	Lateral rotation	19.5	16.0	37.0	31.5	54.5	46.0	+5.5	
Elbow-forearm	Flexion	135.5	122.5	148.0	138.0	160.5	150.0	+10.0	
	Supination	87.0	86.0	108.5	107.5	130.0	135.0	NS	
	Pronation	63.0	42.5	81.0	65.0	99.0	86.5	+16.0	
Wrist	Extension	56.5	47.0	72.0	62.0	87.5	76.0	+10.0	
	Flexion	53.5	50.5	71.5	67.5	89.5	85.0	+4.0	
	Adduction	16.5	14.0	26.5	22.0	36.5	30.0	+4.5	
	Abduction	19.0	22.0	28.0	30.5	37.0	40.0	−2.5	
Hip	Flexion	103.0	95.0	125.0	109.5	147.0	130.0	+15.5	
	Adduction	27.0	15.5	38.5	26.0	50.0	39.0	+12.5	
	Abduction	47.0	38.0	66.0	59.0	85.0	81.0	+7.0	
	Medial rotation (prone)	30.5	30.0	44.5	46.0	58.5	62.5	NS	
	Lateral rotation (prone)	29.0	21.5	45.5	33.0	62.0	46.0	+12.5	
	Medial rotation (sitting)	20.5	18.0	32.0	28.0	43.5	43.0	+4.0	
	Lateral rotation (sitting)	20.5	18.0	33.0	26.5	45.5	37.0	+6.5	
Knee	Flexion (standing)	99.5	87.0	113.5	103.5	127.5	122.0	+10.0	
	Flexion (prone)	116.0	99.5	130.0	117.0	144.0	130.0	+13.0	
	Medial rotation	18.5	14.5	31.5	23.0	44.5	35.0	+8.5	
	Lateral rotation	28.5	21.0	43.5	33.5	58.5	48.0	+10.0	
Ankle	Flexion	13.0	18.0	23.0	29.0	33.0	34.0	−6.0	
	Extension	30.5	21.0	41.0	35.5	51.5	51.5	+5.5	
	Adduction	13.0	15.0	23.5	25.0	34.0	38.0	NS	
	Abduction	11.5	11.0	24.0	19.0	36.5	30.0	+5.0	

† Listed are only differences at the 50th percentile, and if significant ($\alpha < 0.5$).
Source: With permission from Ref. [9.7]. All rights reserved by the publisher, Van Nostrand Reinhold.

exertion for only a few seconds, and even half of the maximally possible contraction can be endured for only about a minute. This explains why it is so difficult to work with the hands overhead or to keep one's back bent.

Unfortunately, most of the existing information on human strength comes from measurements made under static (isometric) conditions, mostly because dynamic conditions are difficult to control experimentally. However, an increasing amount of information on dynamic exertions of force, energy, and power is becoming available; one needs to check the ergonomic literature for emerging information.

9.4.1 Foot Strength

Maximal static body forces are exerted with the foot by an operator who is sitting on a chair with a solid backrest [9.8], [9.12]. The backrest provides resistance to the force exerted with the foot, especially when the operator is pushing forward at about seat height, with the leg almost fully extended. Forces directed more downward are

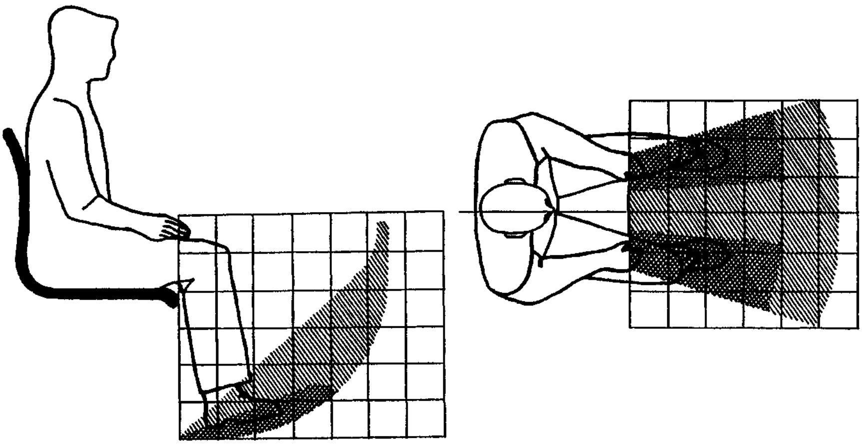


FIGURE 9.7 The normal and preferred (cross-hatched) work space for the feet. (With permission from K. H. E. Kroemer, H. B. Kroemer, and K. E. Kroemer-Elbert, (1994), *Ergonomics: How to Design for Ease and Efficiency*. All rights retained by the publisher, Prentice Hall, Englewood Cliffs, NJ.)

weaker and are limited by the counterforce provided by the body mass (according to Newton's third law, "action equals reaction") of the operator. Figure 9.9 illustrates these conditions.

Except for brief and occasional exertions, one should not expect a standing person to exert force with the foot because the body must be balanced on the other foot alone while doing so.

9.4.2 Hand Strength

Force exertion with the hands is weaker than that with the feet, but the effort is, as a rule, better controlled and more exact. (Yet, consider the driver of an automobile, who customarily controls the speed of the vehicle via pedals.) The strength of arm exertion depends on the direction of force and the location of the handle with respect to the body [9.8], [9.13]. Figure 9.10 provides detailed information; in some cases the force is largest with the arm extended, in other cases with the arm bent. (Note that the numbers given in Fig. 9.10 are 5th-percentile values.) In terms of the preferred working area for the hands and feet discussed earlier, it is obvious that in many cases the largest exertions of strength are at or near the periphery of the reach envelope.

9.4.3 Whole-Body Strength

The weakest link in the chain of force vectors transmitted from the point of application (e.g., the hand) through the body to the point of reactive resistance (e.g., the foot) determines the possible output of the human body. Figure 9.11 presents static forces that have been exerted horizontally by males. These figures show, again, the dependence of strength on location of the object, on body posture, on the kind of reaction force provided (Newton's third law), and, of course, on individual strength.

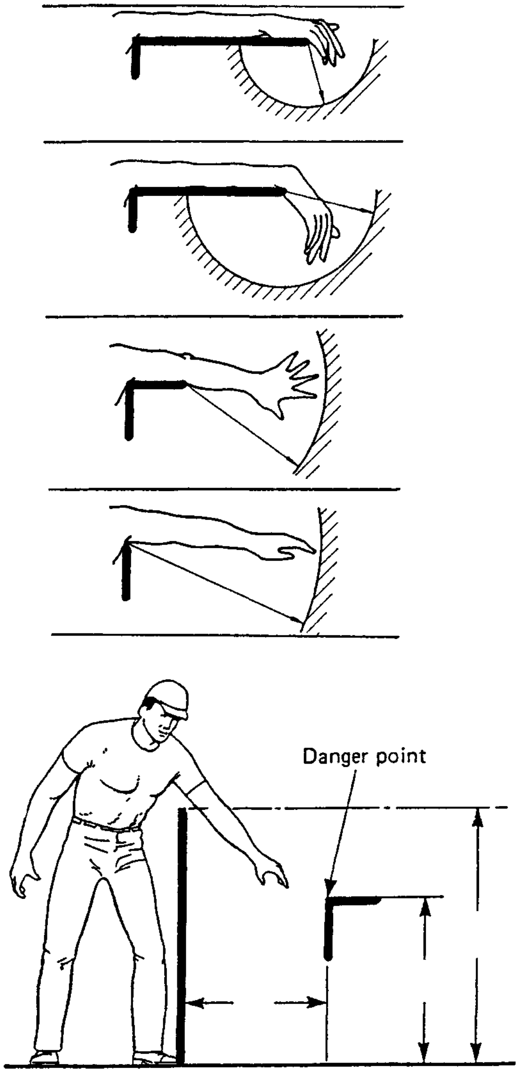


FIGURE 9.8 Examples of "safe distances". (With permission from K. H. E. Kroemer, H. B. Kroemer, and K. E. Kroemer-Elbert, (1994), *Ergonomics: How to Design for Ease and Efficiency.* All rights retained by the publisher, Prentice Hall, Englewood Cliffs, NJ.)

More information about human strengths, such as that of the fingers and thumb of the hand or of the hand, and of the forces and torques involved in the operation of specific controls is available in the ergonomic literature. This has been compiled most recently by Kroemer, Kroemer, and Kroemer-Elbert [9.8] and by Weimer [9.13]; military standards also provide such information.

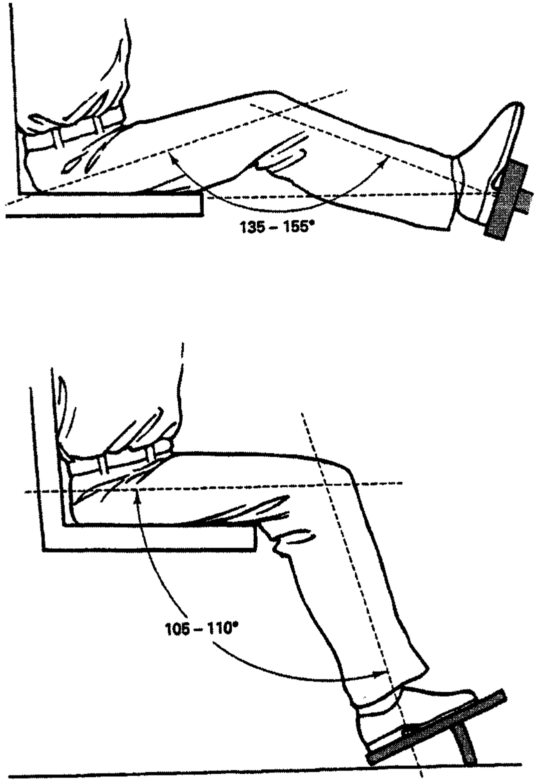
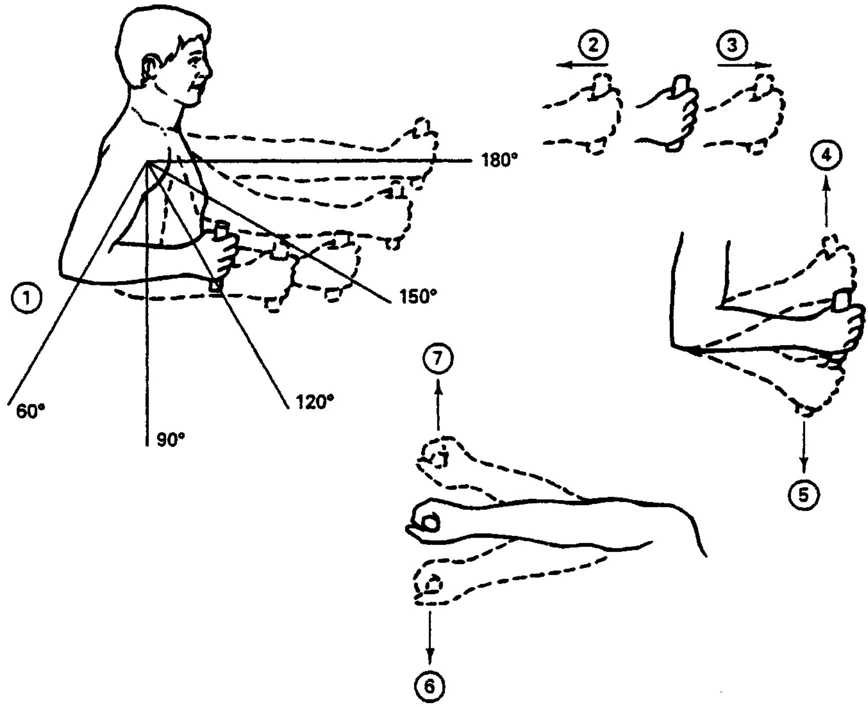


FIGURE 9.9 A sitting operator can exert the largest foot forces in the forward direction, with the leg almost extended and the seat back providing resistance. A downward directed force with a bent knee is weaker, but more comfortable. (Adapted form VanCott and Kinkade, 1972.)

9.5 DESIGNING FOR FAST AND ACCURATE CONTROL ACTIVATION

Different controls are appropriate for hand or foot operation, and for transmission of different amounts of energies and forces. Selection criteria depend on the purposes of control operation, such as

- Activation or shutting down of equipment, as with an on-off control
- Choosing among "discrete settings," as in ratcheting a control knob or putting the shift selector into one of several positions
- Making "quantitative settings," such as selecting a temperature on a thermostat (however, this may be a special case of a discrete setting)
- Applying "continuous control," as in turning a steering wheel in a vehicle
- Entering data, as on a computer keyboard



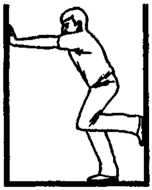
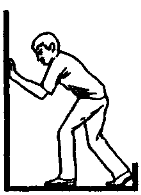
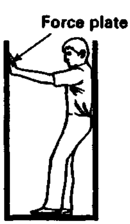
Fifth-percentile arm strength (N) exerted by sitting men													
(1)	(2)		(3)		(4)		(5)		(6)		(7)		
elbow flexion (deg)	Pull		Push		Up		Down		In		Out		
	Left	Right	L	R	L	R	L	R	L	R	L	R
180	222	231	187	222	40	62	58	76	58	89	36	62
150	187	249	133	187	67	80	80	89	67	89	36	67
120	151	187	116	160	76	107	93	116	89	98	45	67
90	142	165	98	160	76	89	93	116	71	80	45	71
60	116	107	96	151	67	89	80	89	76	89	53	71

FIGURE 9.10 Hand forces exerted with the arm in different positions. (Adapted form MIL-HBK 759.)

Most ergonomic recommendations for selection and arrangements of controls (and displays) have been derived from existing devices and western stereotypes (action-effect expectations)—see Refs. [9.2], [9.8], [9.11], [9.12], [9.13], and [9.14]. Thus, for new types of controls and tasks, tradition may not apply.

9.5.1 Control Selection

In general, controls shall be selected for their functional usefulness. The major rules are:

	Force-plate[1] height	Distance[2]	Force, N Mean	Force, N SD
	50	80	664	177
	50	100	772	216
	50	120	780	165
	70	80	716	162
	70	100	731	233
	70	120	820	138
	90	80	625	147
	90	100	678	195
	90	120	863	141
	Percent of shoulder height		Both hands	
	60	70	761	172
	60	80	854	177
	60	90	792	141
	70	60	580	110
	70	70	698	124
	70	80	729	140
	80	60	521	130
	80	70	620	129
	80	80	636	133
	Percent of shoulder height			
	70	70	623	147
	70	80	688	154
	70	90	586	132
	80	70	545	127
	80	80	543	123
	80	90	533	81
	90	70	433	95
	90	80	448	93
	90	90	485	80
	Percent of shoulder height		Both hands	
			Both hands	
	100 percent of shoulder height	50	581	143
		60	667	160
		70	981	271
		80	1285	398
		90	980	302
		100	646	254
			Preferred hand	
		50	262	67
		60	298	71
		70	360	98
		80	520	142
		90	494	169
		100	427	173
		Percent of thumb-tip reach*		
	100 percent of shoulder height	50	367	136
		60	346	125
		70	519	164
		80	707	190
		90	325	132
		Percent of span**		

[1]Height of the center of the force plate – 20 cm high by 26 cm long – upon which force is applied.
[2]Horizontal distance between the vertical surface of the force plate and the opposing vertical surface (wall or footrest, respectively) against which the subjects brace themselves.

*Thumb-tip reach – distance from backrest to tip of subject's thumb as arm and hand are extended forward.
**Span – the maximal distance between a person's fingertips when arms and hands are extended to each side.

FIGURE 9.11 Whole-body strength exerted in various postures. (Adapted from NASA STD 3000, using data measured by the author.)

- The control type shall be compatible with common expectations. Thus, one would use a pushbutton or a toggle switch to turn on a light, not a rotary knob.
- The size of the control and its motion characteristics shall be compatible with past experience and practice. Thus, one would expect to have a fairly large steering wheel for two-handed operation in an automobile, not a small rotary or linear control.
- The direction of operation shall be compatible with stereotypical or common expectations. This means that an on control is pushed or pulled, not turned to the left.
- The control shall be "safe" against inadvertent, false, or excessive operation.

Accordingly, the information contained in Tables 9.4, 9.5, and 9.6 is helpful in selecting proper controls.

More detailed information, such as about the proper control size, spacing, location on control panels, and association with displays, is contained in the ergonomic literature, especially in standards and in design compilations by Cushman and Rosenberg [9.2], Kroemer, Kroemer, and Kroemer-Elbert [9.8], and Woodson, Tillman, and Tillman [9.15].

TABLE 9.4 Control Movements and Expected Effects

	Direction of Control Movement											
Function	Up	Right	Forward	Clockwise	Press,† Squeeze	Down	Left	Rearward	Back	Counter-clockwise	Pull†	Push‡
On	1§	1	1	1	2	1§	—	—	—	—	1	—
Off	—	—	—	—	—	1	2	2	—	1	—	2
Right	—	1	—	2	—	—	—	—	—	—	—	—
Left	—	—	—	—	—	—	1	—	2	—	—	—
Raise	1	—	—	—	—	—	—	2	—	—	—	—
Lower	—	—	2	—	—	1	—	—	—	—	—	—
Retract	2	—	—	—	—	—	—	1	—	—	2	—
Extend	—	—	1	—	—	2	—	—	—	—	—	2
Increase	2	2	1	2	—	—	—	—	—	—	—	—
Decrease	—	—	—	—	—	2	2	1	—	2	—	—
Open Valve	—	—	—	—	—	—	—	—	—	1	—	—
Close Valve	—	—	—	1	—	—	—	—	—	—	—	—

1 = most preferred; 2 = less preferred.
† With trigger-type control.
‡ With push-pull switch.
§ Up in United States, down in Europe.
Source: Modified from K. H. E. Kroemer, "Ergonomics," chap. 13 in B. A. Plog (ed.), *Fundamentals of Industrial Hygiene,* 3d ed., 1988, pp. 521–539, with permission by the publisher, National Safety Council, Chicago.

9.5.2 Avoiding Inadvertent Operation

There are design procedures to guard against inadvertent control activation [9.2]:

- Locate and orient the control in such a way that the operator is unlikely to strike it or move it accidentally in the normal sequence of operations.
- Recess or shield the control or surround it by physical barriers.
- Cover or guard the control by providing a cover, a pin, a lock, or some other device that must be removed or broken before the control can be operated.

TABLE 9.5 Control-Effect Relations of Common Hand Controls

Effect	Keylock	Toggle switch	Push-button	Bar knob	Round knob	Thumbwheel Discrete	Thumbwheel Continuous	Crank	Rocker switch	Lever	Joystick or ball	Legend switch	Slide†
Select ON/OFF	1	1	1	3	—	—	—	—	1	—	—	1	1
Select ON/STANDBY/OFF	—	2	1	1	—	—	—	—	—	1	—	1	1
Select OFF/MODE 1/MODE 2	—	3	2	1	—	—	—	—	—	1	—	1	1
Select one function of several related functions	—	2	1	—	—	—	—	—	2	—	—	—	3
Select one of three or more discrete alternatives	—	—	—	1	—	—	—	—	—	—	—	—	1
Select operating condition	—	1	1	2	—	—	—	—	1	1	—	1	2
Engage or disengage	—	—	—	—	—	—	—	—	—	1	—	—	—
Select one of mutually exclusive functions	—	—	1	—	—	—	—	—	—	—	—	1	—
Set value on scale	—	—	—	—	1	—	2	3	—	3	3	—	1
Select value in discrete steps	—	—	1	1	—	1	—	—	—	—	—	—	1

1 = most preferred; 3 = least preferred.
† Estimated, no experiments known.
Source: Modified from K. H. E. Kroemer, "Ergonometrics," chap. 13 in B. A. Plog (ed.), *Fundamentals of Industrial Hygiene,* 3d ed., 1988, pp. 521–539, with permission of the publisher, National Safety Council, Chicago.

TABLE 9.6 Guide for Selection of Controls

Small operating force	
2 discrete positions	Keylock, hand-operated Toggle switch, hand-operated Pushbutton, hand-operated Rocker switch, hand-operated Legend switch, hand-operated Bar knob, hand-operated Slide, hand-operated Push-pull switch, hand-operated
3 discrete positions	Toggle switch, hand-operated Bar knob, hand-operated Legend switch, hand-operated Slide, hand-operated
4 to 24 discrete positions, or continuous operation	Bar knob, hand-operated Round knob, hand-operated Joystick, hand-operated Continuous thumbwheel, hand-operated Crank, hand-operated Lever, hand-operated Slide, hand-operated Track ball, hand-operated Mouse, hand-operated Light pen, hand-operated
Continuous slewing, fine adjustments	Crank, hand-operated Round knob, hand-operated Track ball, hand-operated
Large operating force	
2 discrete positions	Pushbutton, foot-operated Pushbutton, hand-operated Detent lever, hand-operated
3 to 24 discrete positions	Detent lever, hand-operated Bar knob, hand-operated
Continuous operation	Hand wheel, hand-operated Lever, hand-operated Joystick, hand-operated Crank, hand-operated Pedal, foot-operated

Source: Modified from K. H. E. Kroemer, "Ergonomics," chap. 13 in *Fundamentals of Industrial Hygiene,* 3d ed., 1988, pp. 521–539, with permission of the publisher, National Safety Council, Chicago.

- Provide extra resistance (viscous or coulomb friction, by spring loading or inertia) so that an unusual effort is required for activation.
- Provide a delaying means so that the control must pass through a critical position with an unusual movement, such as in manual gear shifting in automobiles.
- Provide interlocking between controls so that prior operation of a related control is required before the critical control can be activated.

Some of these measures may be combined. Note, however, that such design features usually slow the operation, which may be detrimental in an emergency.

9.6 DESIGNING LABELS AND WARNINGS

Ideally, it should not be necessary to explain the use of a control or piece of equipment or to warn about possible hazards. However, in many cases an ideal design solution is impossible, and it is therefore necessary to use labels, symbols, and warnings so that one may locate, identify, activate and correctly manipulate the equipment [9.8].

9.6.1 Labels

Labeling must be done in such a way that the information is accurately provided and rapidly understood. The guidelines in Table 9.7 apply.

The font (typeface) should be simple, bold, and vertical, as is the case with Futura, Helvetica, Namel, Tempo, and Vega. Most electronically generated fonts are, unfortunately, inferior to printed fonts, but special effort and attention help to make these as legible as possible.

- The recommended *height of characters* depends on the viewing distance; for example,

TABLE 9.7 Guidelines for Labeling

- *Orientation.* A label and the information printed on it shall be oriented horizontally so that it can be read quickly and easily. (Note that this applies if the operator is used to reading horizontally, as in western countries.)
- *Location.* A label shall be placed on or very near the item that it identifies.
- *Standardization.* Placement of all labels shall be consistent throughout the equipment and system.
- *Equipment Functions.* A label shall primarily describe the function ("what does it do?") of the labeled item.
- *Abbreviations.* Common abbreviations may be used. If a new abbreviation is necessary, its meaning shall be obvious to the reader. The same abbreviation shall be used for all tenses and for the singular and plural forms of a word. Capital letters shall be used, with periods normally omitted.
- *Brevity.* The label inscription shall be as concise as possible without distorting the intended meaning or information. The texts shall be unambiguous, with redundancy minimized.
- *Familiarity.* Words that are familiar to the operator shall be chosen, if possible.
- *Visibility* and *Legibility.* The operator shall be able to read easily and accurately at the anticipated actual reading distances, at the anticipated worst illumination level, and within the anticipated vibration and motion environment. Important are the contrast between the lettering and its background; the height, width, stroke width, spacing, and style of letters; and the specular reflection of the background, cover, or other components.
- *Font* and *Size.* Typography determines the legibility of written information; it refers to style, font, arrangement, and appearance.

Source: Adapted with permission from K. H. E. Kroemer, H. B. Kroemer, and K. E. Kroemer-Elbert, *Ergonomics: How to Design for Ease and Efficiency,* 1994 (Ref. [9.8]).

Viewing distance 35 cm, suggested height 22 mm
Viewing distance 70 cm, suggested height 50 mm
Viewing distance 1 m, suggested height 70 mm
Viewing distance 1.5 m, suggested height at least 1 cm

- The *ratio of stroke width to character height* should be between 1:8 and 1:6 for black letters on a white background, and between 1:10 and 1:8 for white letters on a black background.
- The *ratio of character width to character height* should be about 3:5.
- The *space between letters* should be at least one stroke width.
- The *space between words* should be at least one character width.
- For continuous text, mix upper- and lowercase letters. For labels, use uppercase letters only.
- Text should be horizontal.

9.6.2 Warnings

All devices should be safe to use, but realistically this cannot always be achieved through design. If it cannot be, one must warn users of dangers associated with the product and provide instructions for safe use to prevent injury or damage.

It is preferable to have an active warning, consisting of a sensor that notices inappropriate use and an alerting device that warns the human of an impending danger. Yet, in most cases, the warnings are passive, often simply a label attached to the product and instructions written in the user manual. Such passive warnings rely completely on the human to recognize an existing or potential dangerous situation, to remember the warning, and to behave prudently, and so passive warnings are often ineffectual. Thus, passive warnings must be carefully designed, in conformance with the most recent government laws and regulations, national and international standards, and the best applicable human engineering information.

Warning labels and placards usually contain text and/or graphics. Pictures, pictograms, and icons can communicate information to persons from various cultures who speak different languages; however, users may have rather different perceptions depending on their ages, experiences, and ethnic and educational backgrounds. Therefore, designing a "safe" product is much preferable to applying warnings to an inferior product.

9.7 DESIGNING FOR VISION

For an erect operator, the preferred direction of the line of sight to distant targets is about horizontal. However, if one must focus on a close target, the preferred line of sight is distinctly lower. The best way of describing the angle of gaze is against a reference line that moves with the skull, because the head may be held at different pitch angles. An easy way to establish such a reference is to run a straight line through the earhole and the juncture of the upper and lower eyelids, in the side view from the right. This *ear-eye line* is shown in Fig. 9.12. An approximately upright head has an angle (P in Fig. 9.12) between the ear-eye line and the horizon of about 15 degrees. The angle of the line of sight is easily described in relation to the ear-eye line. For close targets, such as at reading distance, most people prefer the line-of-

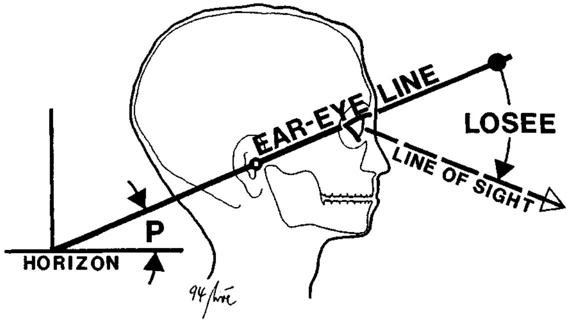


FIGURE 9.12 The Ear–Eye Line runs, in the side view, through the ear hole and the junction of the eyelids. The head is held "erect" (or "upright") when the angle between the ear–eye line and the horizon is approximately 15°. Distant targets can be easily viewed when "straight ahead," i.e., with a LOSEE angle of about 15° below the ear–eye line. Close targets, however, are best located distinctly below, that is at an average LOSEE of 45°, plus or minus 20° to accommodate individual preferences.

sight angle below the ear-eye line (LOSEE in Fig. 9.12) to be between 25 and 65 degrees (the average is 45). Note that this differs from some erroneous statements in the older literature, which indicate a flatter LOSEE angle. Optometrists always knew better and habitually ground the reading section of bifocal lenses into their lower part. They knew: "the closer, the lower."

Especially in the design of computer work stations, but also in many other circumstances, one must consider all equipment components as parts of an interactive system in which the visual targets (for example, the display), the manipulation areas (for example, controls or the keyboard), and the body support (the chair) interact with one another in determining the postures and habits of the worker. Of course, the work task and the environment (illumination, sound, climate) also strongly affect the worker; if just one element is badly placed, the resulting system condition may be unacceptable. Recommendations for the design of ergonomically acceptable computer work stations are provided in recent publications—see especially Refs. [9.6], [9.8], and [9.19].

9.8 DESIGNING FOR MATERIAL HANDLING

Handling objects is a common task; examples are loading and unloading machines, manipulating objects in assembly and inspection, or using hand tools. Design for such tasks will be discussed in this section; the more general topic of manual material handling (lifting, lowering, carrying, etc.) is treated in other publications, especially by Ayoub and Mital [9.20] and in special 1992 issues of the journal *Ergonomics* [9.21]. The 1981 and 1991 NIOSH recommendations for safe lifting [9.22] and the 1991 guidelines by Snook and Ciriello [9.23] were compared by Kroemer, Kroemer, and Kroemer-Elbert [9.8].

In focusing on material handling at the workplace, especially the design of machines for proper manual feeding and unloading, one can distinguish between two cases. In one, raw material such as pipe or solid stock is cut and worked (milled, turned, etc.) by the equipment; the human activity mostly involves bringing the raw material to the machine and inserting it. The operator does this by hand and body motion; if the material is bulky or heavy, two operators may be needed to manipulate and move the material (see Fig. 9.13). Storage facilities, paths between there and the machine, and proper loading provisions must be planned. In some cases, it may be possible to use jigs, rollers, or conveyors. It is important that the work height for the material handler is appropriate: Keep storage and the loading station at about hip height for heavy objects, and at waist or even chest height for light material. If, in the other case, single pieces of material are provided and must be loaded, one by one, into a feeder magazine or directly into the machine, the loading fixtures of the

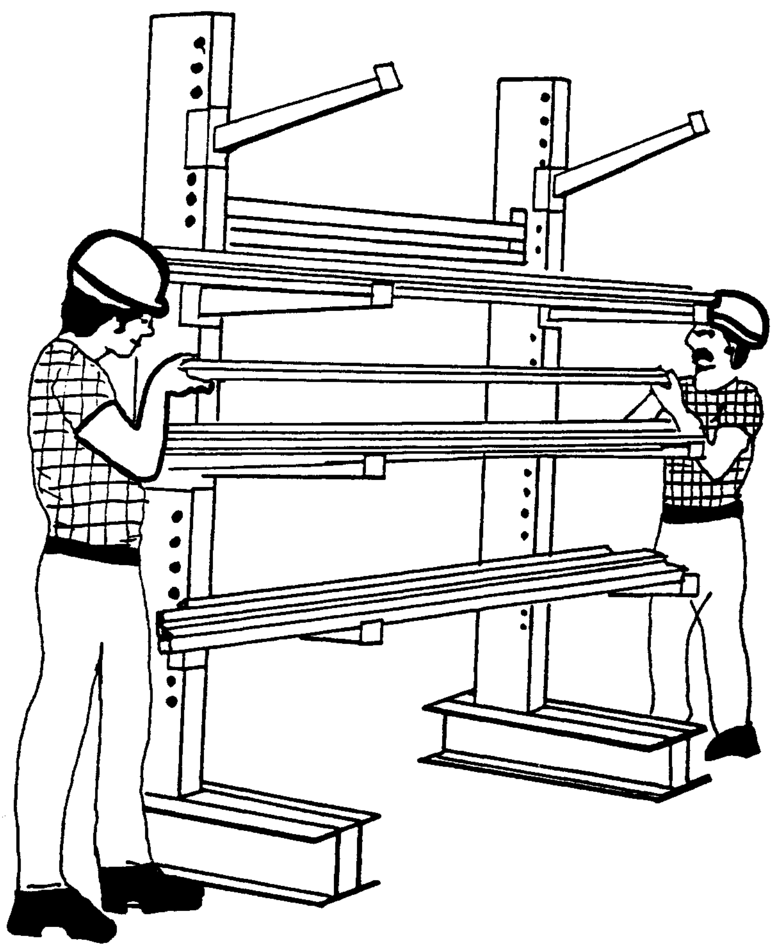


FIGURE 9.13 Bulky and heavy material should be so stored that it can be moved easily by two operators without bending and twisting. (Adapted, with permission, from [9.22].)

equipment itself must be so designed that the operator does not have to bend or twist the body. The manipulation area should be close to the body, in front of the trunk, as discussed before.

The location of containers for raw materials or for machined items is of great concern if overexertion injuries of the material handler are to be avoided. Containers should not be put on the floor if this requires the worker to bend or "dive" into them in order to retrieve or deposit material (see Fig. 9.14). Instead, the bins, trays,

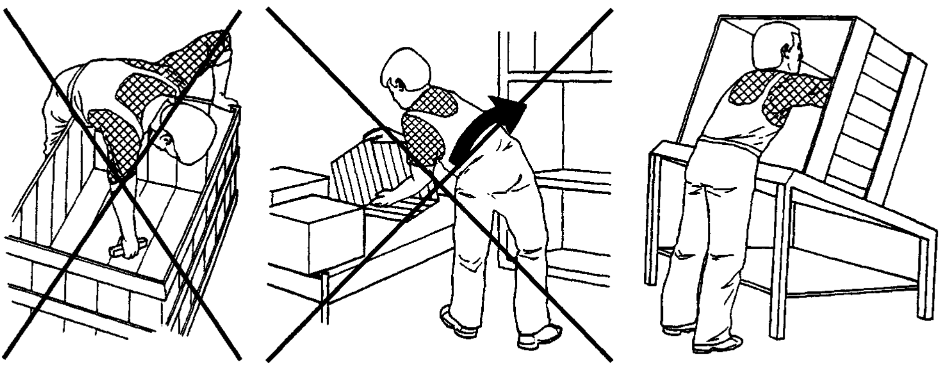


FIGURE 9.14 Avoid twisting and bending the trunk by storing containers at proper height and angle. (With permission from K. H. E. Kroemer, H. B. Kroemer, and K. E. Kroemer-Elbert, (1994), *Ergonomics: How to Design for Ease and Efficiency*. All rights retained by the publisher, Prentice Hall, Englewood Cliffs, NJ.)

or containers should be placed in such a way (raised, tilted) and be of such a size that the operator can work with an upright posture, grasping and moving the objects in front of the trunk and close to the body. The axiom is, "Keep the body upright; avoid body bending and twisting."

Methods commonly used in industrial engineering are suitable for the evaluation of planned or existing material handling. Employ flowcharts and flow diagrams as well as motion analyses and other work study techniques familiar to the industrial engineer (see Ref. [9.8]). These techniques allow a motion-by-motion determination of the activities involved, and of their ease or difficulty for the operator, which in turn facilitates determination of the best work method and equipment design.

Various types of equipment and machines provide assistance to the material handler. There are lift tables, hoists, cranes, turntables, dollies, walkies, trolleys, trucks, stackers, and even forklift trucks (Refs. [9.8], [9.24]). Not only should such equipment be able to move the material, but it should also fit the human operator, and must be easy and safe to operate. In the past, some material movement machinery, such as cranes, conveyors, and hand and power trucks, has been produced that showed an alarming lack of consideration for human factors and safety principles. The worst example was a forklift which obstructed the operator's view and also transmitted shocks and impacts to the operator, who was forced into contorted body postures. The following excerpt from a letter published in the *Human Factors Society Bulletin* of January 1984 on page 7 described this condition:

I was shocked, dismayed, and perturbed. Recently, I attended a regional industrial exhibition that had an emphasis on materials-handling equipment. I intentionally went around looking for bad or lacking human engineering. I found plenty . . . inadequate labels; wrong-size controls; lack of shape, position, color coding; controls that could be inadvertently actuated; absence of guard rails; unintelligible instructions; slippery surfaces; impossible reach requirements; sharp edges; unguarded pinch-points; extreme strength requirements; lack of guards; spaces needed for maintenance too small for the human hand; poorly located emergency switches; and so on, and so on! . . . Spacecraft and supersonic aircraft and missile monitoring equipment need human engineering; so, too, do hydraulic hoists and forklift trucks and conveyor systems and ladders.

9.9 CONCLUSION

Usability is an important aspect in machine design; if the "human factor" is neglected, clumsy, difficult, and unsafe conditions result. There is now ergonomic information available for engineers that enables them to design equipment, work stations, and tools for safe, efficient, and easy working. The references provide extensive and quantitative data for designing machinery and equipment ergonomically, to assure its usability.

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