Figure 7-19: The Lever Arm of the Spine in Sitting and Standing Three postures—erect standing (*a*), erect sitting (*b*), and slouched sitting (*c*)—are illustrated with schematic diagrams of the corresponding resistance arm of the upper body mass (L_w) below the photographs. The larger the L_w, the more the compressive force on the lumbar discs, and the more potential to aggravate a lower back problem. Backrests that give lumbar support help to push the spine forward to shorten the L_w (see Figure 7-20). *(Adapted from Lindh, 1980).*

The reasoning behind the common recommendation of designing a [illegible] place so the worker can work at or below elbow height, and not have to [illegible] the upper arms, can be illustrated through the use of a simplified biomechanical approach. Shoulder abduction may be difficult to avoid, however, in [illegible] maintenance work when a large piece of equipment is being repaired at a [illegible] bench (Figure 7-21).

Figure 7-22 presents a simplified scheme for calculating the muscle [illegible] needed to maintain the arm in an abducted, or elevated, position.

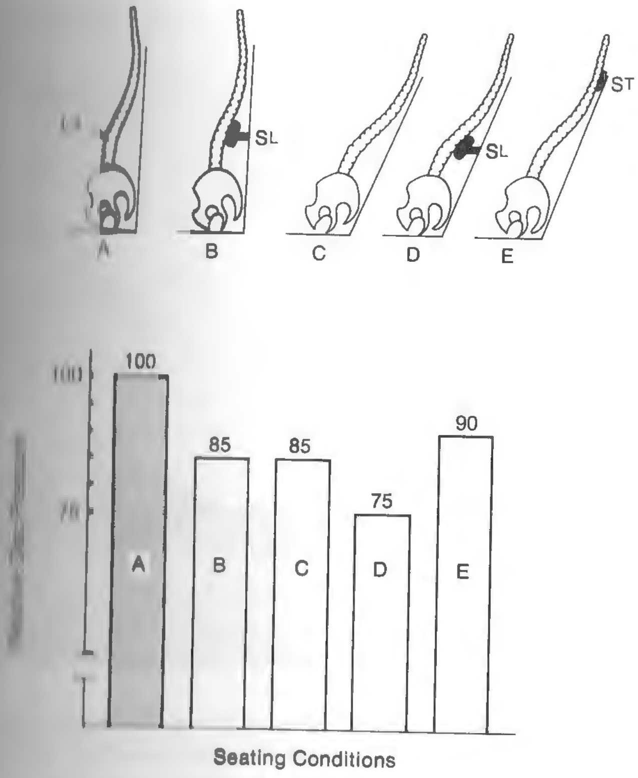

Figure 7-20: Effects of Chair Design on Back Stress The relative compressive forces on the third lumbar disc (L_3) are shown in the lower graph for the five seating conditions illustrated in the upper part of the figure. A and B are upright backrests with and without lumbar support (S_L). C, D, and E are angled backrests (about 110 degrees) with and without lumbar support and with thoracic support (S_T), respectively. An angled backrest with lumbar support (D) is the recommended seating condition for minimal compressive force on the lumbar discs, this being about 75 percent of the force measured at L_3 when the person sits in a chair without lumbar support and with the backrest at 90 degrees (A). *(Adapted from Andersson et al., 1974; Lindh, 1980; Nachemson,* [illegible]

Certain assumptions have been made in this example, as in other biomechanical problems. Although more than one muscle contributes force, the resultant muscle force can be represented by force M (F_M). The moment arm for F_M is assumed to be 0.03 m (1.2 in.). By using the static equilibrium relationship that the sum of all moments equals zero, F_M can be estimated. In this example, the moment due to the mass of the arm acting at a perpendicular distance

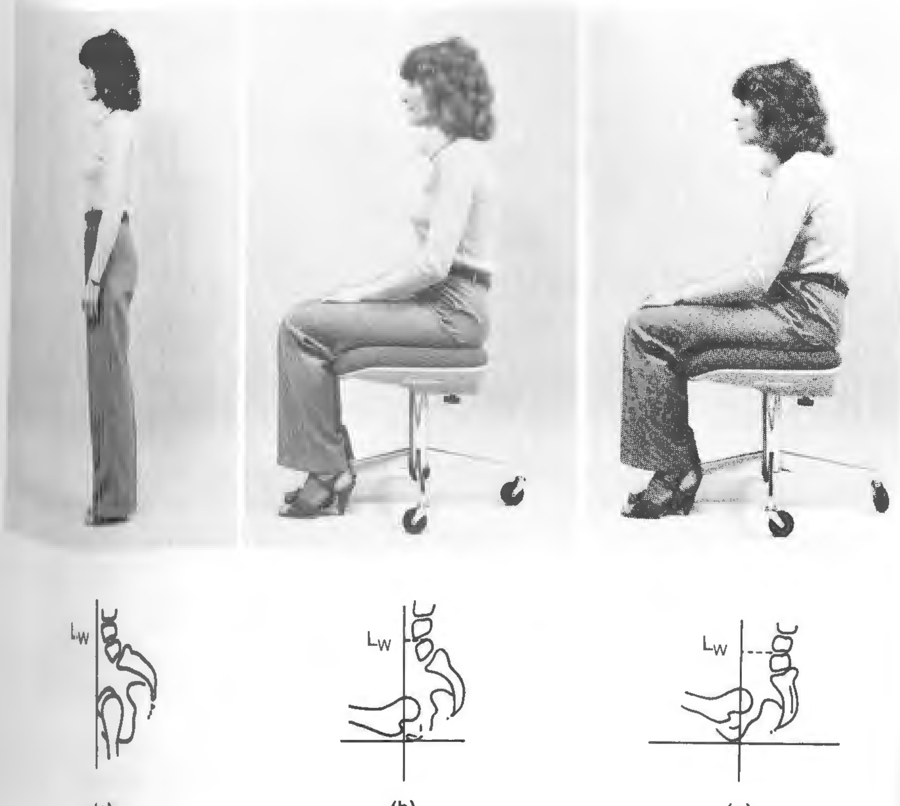

Figure 7-19: The Lever Arm of the Spine in Sitting and Standing Three postures—erect standing (*a*), erect sitting (*b*), and slouched sitting (*c*)—are illustrated with schematic diagrams of the corresponding resistance arm of the upper body mass (L_w) below the photographs. The larger the L_w, the more the compressive force on the lumbar discs, and the more potential to aggravate a lower back problem. Backrests that give lumbar support help to push the spine forward to shorten the L_w (see Figure 7-20). *(Adapted from Lindh, 1980).*

The reasoning behind the common recommendation of designing a work place so the worker can work at or below elbow height, and not have to abduct the upper arms, can be illustrated through the use of a simplified biomechanical approach. Shoulder abduction may be difficult to avoid, however, in some maintenance work when a large piece of equipment is being repaired at a work bench (Figure 7-21).

Figure 7-22 presents a simplified scheme for calculating the muscle force needed to maintain the arm in an abducted, or elevated, position.

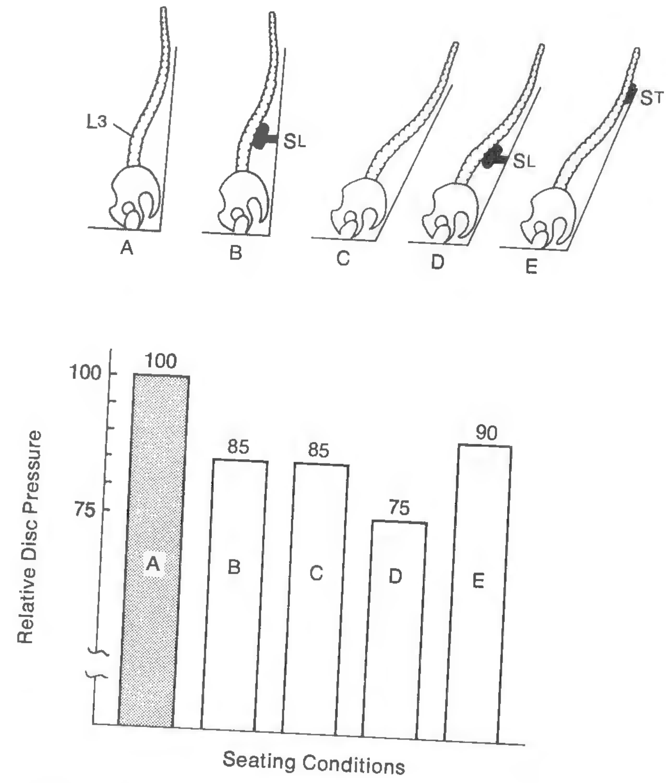

Figure 7-20: Effects of Chair Design on Back Stress The relative compressive forces on the third lumbar disc (L_3) are shown in the lower graph for the five seating conditions illustrated in the upper part of the figure. A and B are upright backrests with and without lumbar support (S_L). C, D, and E are angled backrests (about 110 degrees) with and without lumbar support and with thoracic support (S_T), respectively. An angled backrest with lumbar support (D) is the recommended seating condition for minimal compressive force on the lumbar discs, this being about 75 percent of the force measured at L_3 when the person sits on a chair without lumbar support and with the backrest at 90 degrees (A). *(Adapted from Andersson et al., 1974; Lindh, 1980; Nachemson, 1975).*

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d on the results of this study, the researchers identified five discrete of effort that emerge from the combinations of intensity and fre- effort. For example, constant light (CL), frequent moderate (FM), and heavy (OH) effort are substantially the same total effort level. The eterminant of the effort level is the oxygen consumption, or the energy of the job studied. Figure 10-1 shows the five total effort level cate-

ppendix C there are tables of effort equivalencies for different occu- nd recreational tasks. These are grouped by five effort categories that l to the ones described in Figure 10-1.

ical effort stress can be assessed by identification of primary and sup- y job requirements. The analyst finds the intensity of a given task, ing or pushing, by choosing the effort level according to the weights rces exerted. Each job task is similarly analyzed and the total time for of effort is calculated. The points for primary effort are determined two factors. Supplementary effort is recognized via additional points job activities not covered under primary effort. The rest of this chap- es this effort estimation technique.

ARY PHYSICAL EFFORT REQUIREMENTS

fort includes manual handling tasks and climbing (see Table 10-1). nt of effort can be described in terms of an intensity (degree of effort) tion (percent of total shift time) for each degree of effort. First, one ach type of effort in a job. The amount of time each degree of effort then be determined. The balance of the shift includes all other types (total residual). Residual time can be calculated according to the of activities in Table 10-2.

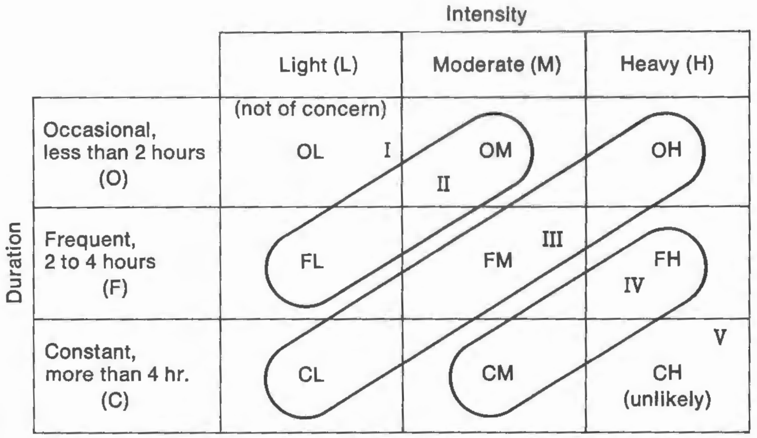


Figure 10-1: Categories of Physical Effort—Intensity and Duration Nine combinations of effort intensity (across the top) and duration (column 1) are shown in columns 2 through 4. The equivalent effort levels are circled, such as FL and OM, for example. These combinations result in five discrete effort levels, which are indicated by I through V. Of these effort levels, jobs with only occasional light effort are not of concern for their physical effort demands. Jobs that require constant heavy effort are rare, and very few people can sustain them for the time required. Most industrial jobs fall in effort categories II, III, and IV. *(Adapted from Rodgers, 1978).*

An example illustrates the use of the primary requirements factor in analyzing a specific job. A chemical bagging job involves the following activities:

- Placing empty bags (1 kg or 2.2 lbm) on loading chutes, 60 times per hour.
- Pulling the filled bags (23 kg or 50 lbm) down the conveyor line, 60 per hour, forces of 90 newtons or 20 lbf.
- Lifting full bags off of the conveyor and onto a pallet, 60 times per hour.
- Procuring supplies (sheaves of empty bags, 25 kg or 55 lbm), eight to ten times per shift.
- Dragging empty pallets to the conveyor area (forces of 180 newtons or 40 lbf), 12 times per shift.

From the primary requirements factor in Table 10-1, you can see that the frequent handling of empty bags, except in a sheaf, is not included since bag weight is less than 1.8 kg (4 lbm). The 25 kg (55 lbm) sheaf of bags is relatively easy to handle, so it falls into the moderate effort category. Dragging the pallet

For a number of environmental conditions, such as heat, cold, and the presence of some chemicals, job designers need to estimate the physical workload of a job in order to assess the appropriateness of the exposure. Data on the oxygen demands of work and recreational tasks (Appendix A) may be used with caution to estimate workload, but oxygen consumption cannot always be measured and does not describe all categories of physical job demands. Over the years, methods have been developed to assess the physical effort for handling tasks and other job tasks (Garg, Chaffin, and Herrin, 1978; Passmore and Durnin, 1955); these are often based on elemental analyses of job tasks. Similarly, the method of workload estimation given in this chapter was developed to help quantify the physical effort levels of jobs for an evaluation of total job demands. When the results from a work physiology study on 21 jobs were compared to estimated effort levels (using the method presented here), the correlation between total points and average oxygen consumption on the job was 0.83 (Rodgers, Caplan, and Nielsen, 1976).

Based on the results of this study, the researchers identified five discrete categories of effort that emerge from the combinations of intensity and frequency of effort. For example, constant light (CL), frequent moderate (FM), and occasional heavy (OH) effort are substantially the same total effort level. The primary determinant of the effort level is the oxygen consumption, or the energy demands of the job studied. Figure 10-1 shows the five total effort level categories.

In Appendix C there are tables of effort equivalencies for different occupational and recreational tasks. These are grouped by five effort categories that are parallel to the ones described in Figure 10-1.

Physical effort stress can be assessed by identification of primary and supplementary job requirements. The analyst finds the intensity of a given task, such as lifting or pushing, by choosing the effort level according to the weights lifted or forces exerted. Each job task is similarly analyzed and the total time for each level of effort is calculated. The points for primary effort are determined from these two factors. Supplementary effort is recognized via additional points for specific job activities not covered under primary effort. The rest of this chapter describes this effort estimation technique.

A. PRIMARY PHYSICAL EFFORT REQUIREMENTS

Primary effort includes manual handling tasks and climbing (see Table 10-1). The amount of effort can be described in terms of an intensity (degree of effort) and a duration (percent of total shift time) for each degree of effort. First, one identifies each type of effort in a job. The amount of time each degree of effort takes can then be determined. The balance of the shift includes all other types of activities (total residual). Residual time can be calculated according to the breakdown of activities in Table 10-2.

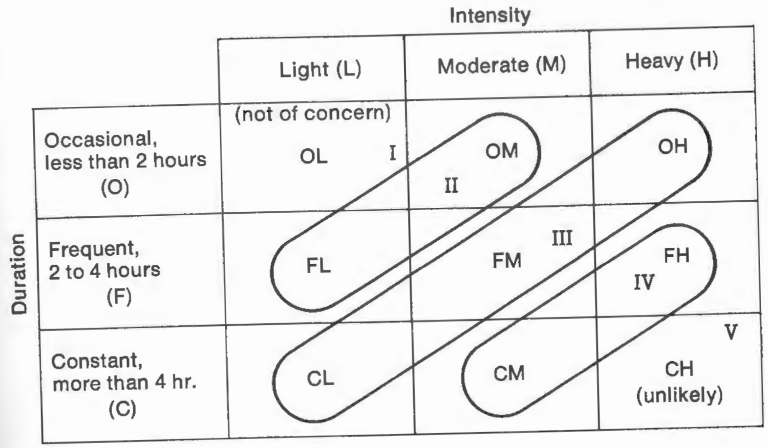


Figure 10-1: Categories of Physical Effort—Intensity and Duration Nine combinations of effort intensity (across the top) and duration (column 1) are shown in columns 2 through 4. The equivalent effort levels are circled, such as FL and OM, for example. These combinations result in five discrete effort levels, which are indicated by I through V. Of these effort levels, jobs with only occasional light effort are not of concern for their physical effort demands. Jobs that require constant heavy effort are rare, and very few people can sustain them for the time required. Most industrial jobs fall in effort categories II, III, and IV. *(Adapted from Rodgers, 1978).*

An example illustrates the use of the primary requirements factor in analyzing a specific job. A chemical bagging job involves the following activities:

- Placing empty bags (1 kg or 2.2 lbm) on loading chutes, 60 times per hour.
- Pulling the filled bags (23 kg or 50 lbm) down the conveyor line, 60 per hour, forces of 90 newtons or 20 lbf.
- Lifting full bags off of the conveyor and onto a pallet, 60 times per hour.
- Procuring supplies (sheaves of empty bags, 25 kg or 55 lbm), eight to ten times per shift.
- Dragging empty pallets to the conveyor area (forces of 180 newtons or 40 lbf), 12 times per shift.

From the primary requirements factor in Table 10-1, you can see that the frequent handling of empty bags, except in a sheaf, is not included since bag weight is less than 1.8 kg (4 lbm). The 25 kg (55 lbm) sheaf of bags is relatively easy to handle, so it falls into the moderate effort category. Dragging the pallet

Table 10-1: Primary Physical Effort Requirements Three types of effort (lifting/carrying, application of forces, and climbing) are shown in column 1. Three degrees of effort (light, moderate, and heavy) are shown across the top of the table. Under each degree of effort, two parameters are given: the range of weight handled or force exerted in kilograms (kg) or newtons (N), with the pounds equivalent, and the ease of handling or exerting force, defined as easy or difficult. Examples of difficult handling are lifting or carrying a container of liquid, applying force or supporting a weight on a thin edge instead of on a broad surface, or carrying a bulky object when climbing up a ladder. Easy handling usually suggests that there are well-designed handholds on the object and that it is compact and balanced.

	Degree of Effort					
	Light		Moderate		Heavy	
Type of Effort	Weight or Force	Ease of Handling	Weight or Force	Ease of Handling	Weight or Force	Ease of Handling
Lift/carry (weight)	1.8–4.5 kg (4–10 lbm)	Easy/Difficult	5–34 kg (11–75 lbm)	Easy	>34 kg (75 lbm)	Easy
			5–18 kg (11–40 lbm)	Difficult	>18 kg (>40 lbm)	Difficult
Application of Forces (force)	18–180 N (4–40 lbf)	Easy	181–335 N (>40–75 lbf)	Easy	>335 N (>75 lbf)	Easy
	18–110 N (4–25 lbf)	Difficult	111–180 N (>25–40 lbf)	Difficult	>180 N (>40 lbf)	Difficult
Climbing (weight)	0–4.5 kg (0–10 lbm)	Easy/Difficult	5–18 kg (11–40 lbm)	Easy	>18 kg (>40 lbm)	Easy
			5–11 kg (11–25 lbm)	Difficult	>11 kg (>25 lbm)	Difficult

Table 10-2: Time Analyses—Percent of Time at Different Effort Levels per Shift. The calculation to account for 100 percent of shift time is shown in (a). The job analyst identifies what percent of total shift time is spent in light, moderate, or heavy activities (see Table 10-1). Any balance will be residual activity, which can be further broken into specific activities, as shown in (b). Heavy effort is counted in the primary requirements points (see Table 10-3) only if it occurs for 5 percent or more of shift time. If it occurs for less than 5 percent of the time, the effort is recognized through the supplementary requirements points (see Table 10-5). The percent of shift time spent on a specific activity is determined by dividing the total time per shift (often 480 minutes) into the total time spent on each degree of effort category.

(a) Total Light % ______ + Total Moderate % ______
+ Total Heavy %* ______ + Total Residual % ______ = 100% of Shift Time

*If less than 5 percent, use Table 10-4.

(b) Residual Time

Other physical activities	______ %
Base/nonphysical activities	______ %
Standby	______ %
Paid lunch	______ %
Breaks	______ %
Total Residual	______ %

is a moderate effort. Pulling the bag along the conveyor is a light effort. Liftin the bag onto the pallet is a heavy effort because the bag's contents will shif making them difficult to handle, and they have to be turned from vertical horizontal.

The percent of time in each effort category has to be determined from a activity analysis. In this instance, the large majority of the shift was spent loading, pulling, and handling the bags; about two hours were spent on eac activity each shift, on the average. The auxiliary-supplies handling tasks (palle and bags) each took about 20 minutes per shift. In summary, then:

- Light: pulling bags for two hours.
- Moderate: dragging pallets for 20 minutes; carrying sheaves of bags 20 minutes.
- Heavy: lifting bags for two hours.
- No effort category: loading empty bags for two hours.

The first part of this chapter includes information about body size, segment weights, ranges of joint motion, and cross-sectional areas of muscles. This information can be used to estimate lever arms and counteractive forces in static and dynamic work postures and manual handling tasks.

The second part gives data on the strengths of several muscle groups that are actively involved in many industrial tasks, especially manual handling jobs. Torques are indicated for arm muscles involved in rotating the hand at the wrist. This information can be used to evaluate the percent of maximum voluntary strength that a particular task requires.

The third part summarizes data on the maximum aerobic work capacities of an industrial population. Values are given for whole-body work (treadmill) as well as for upper body work (a lifting task). Comparisons to data from nonindustrial populations are given for bicycle ergometer and other lifting and arm cranking tasks.

The fourth part provides information on the energy expenditure demands of common industrial tasks. These tables show equivalent metabolic demands for a variety of tasks and can be used to estimate workload in situations where measurements cannot be made easily.

A. ANTHROPOMETRIC INFORMATION FOR BIOMECHANICAL ANALYSES

An introduction to the biomechanical analysis of work can be found in Part III. The techniques presented there are useful in evaluating many manual materials handling problems. Task variables that are difficult to measure directly must be estimated in order to calculate biomechanical stresses. Fortunately, these estimates can be obtained from basic anthropometric measurements, body-segment mass values, and the locations of body-segment centers of gravity. The range of motion of the major joints of the body and the cross-sectional area of several muscle groups are also included in this section.

1. BODY SIZE AND SEGMENT LENGTH

Some anthropometric data on body size are shown in Tables 26-1 and 26-2. (Volume 1 of this series contains a more thorough discussion of anthropometric data and should be consulted for additional information.) These data can be used to evaluate the muscles available for lifting at different heights above the floor. Below waist level, for example, most people use leg and back muscles to assist in lifting an object. Above shoulder height, most of the lifting is done with the arm and shoulder muscles.

Another way to use anthropometric information is in determining the length of lever arms in a biomechanical analysis of lifting tasks or work postures. Figures 26-1 and 26-2 show the lengths of various body segments as a proportion of height for males and females. It is important to recognize that these proportions are usually based on average-value percentages of the populations of interest. There is a large variation in individual proportions, so any calculations made can only be considered estimates. Designs based on these estimates should be simulated prior to implementation to test their appropriateness.

Table 26-1: Anthropometric Size Data—Centimeters. Fifteen anthropometric measurements that are useful in the design of manual handling tasks and workplaces are shown in column 1. The average (50th percentile) values plus or minus one standard deviation (SD) are given for men (column 2) and women (column 3). The 5th, 50th, and 95th percentile values are given for a statistically combined population of men and women (50-50 mix) in columns 4 through 6. See also Table VIA-2, Appendix A, Volume 1. *(Adapted from NASA, 1978).*

Measurements	Males 50th ± 1 SD	Females 50th ± 1 SD	50-50 Mix		
			5th	50th	95th
Forward functional reach, acromial process to functional pinch	68.3 ± 4.3	62.5 ± 3.4	57.5	65.0	74.5
Eye height, standing	164.4 ± 6.1	151.4 ± 5.6	144.2	157.7	172.3
Shoulder height, standing	143.7 ± 6.2	132.9 ± 5.5	124.8	137.4	151.7
Elbow height, standing	110.5 ± 4.5	102.6 ± 4.8	96.4	106.7	116.3
Waist height, standing	106.3 ± 5.4	101.7 ± 5.0	94.9	103.9	113.5
Tibial height, standing	45.6 ± 2.8	42.0 ± 2.4	38.8	43.6	49.2
Functional overhead reach, standing	209.6 ± 8.5	199.2 ± 8.6	188.0	204.5	220.8
Upper leg length, seated	59.4 ± 2.8	57.4 ± 2.6	53.7	58.4	63.3
Elbow to fist length	38.5 ± 2.1	34.8 ± 2.3	31.9	36.7	41.1
Upper arm length	36.9 ± 1.9	34.1 ± 2.5	31.0	35.7	39.4
Popliteal height, seated	44.6 ± 2.5	41.0 ± 1.9	38.6	42.6	47.8
Hand length	19.0 ± 1.0	18.4 ± 1.0	17.0	18.7	20.4
Hand spread, digit one to digit two, second phalangeal joint	10.5 ± 1.7	8.1 ± 1.7	5.9	9.3	12.7
Grip breadth, inside diameter	4.9 ± 0.6	4.3 ± 0.3	3.8	4.5	5.7
Height	174.5 ± 6.6	162.1 ± 6.0	154.4	168.0	183.0

2. THE MASSES AND CENTERS OF GRAVITY OF BODY SEGMENTS

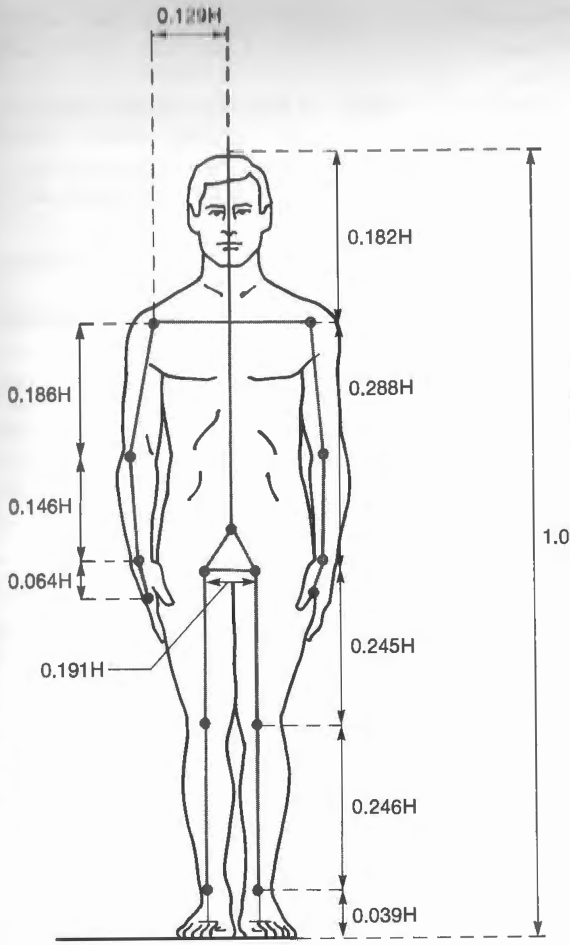
The masses of different body segments are also needed to estimate postural torques and lifting stresses on the body. Table 26-3 presents the slopes and constants for a series of regression equations that can be used to predict body-seg-

Table 26-2: Anthropometric Size Data—Inches. The information found in Table 26-1 is given in inches. See also Table VIA-3, Appendix A, Volume 1 of this series. *(Adapted from NASA, 1978).*

Measurements	Males 50th ± 1 SD	Females 50th ± 1 SD	50-50 Mi		
			5th	50th	[illegible]
Forward functional reach, acromial process to functional pinch	26.9 ± 1.7	24.6 ± 1.3	22.6	25.6	[illegible]
Eye height, standing	64.7 ± 2.4	59.6 ± 2.2	56.8	62.1	[illegible]
Shoulder height, standing	56.6 ± 2.4	51.9 ± 2.7	48.4	54.4	[illegible]
Elbow height, standing	43.5 ± 1.8	40.4 ± 1.4	38.0	42.0	[illegible]
Waist height, standing	41.9 ± 2.1	40.0 ± 2.0	37.4	40.9	[illegible]
Tibial height, standing	17.9 ± 1.1	16.5 ± 0.9	15.3	17.2	[illegible]
Functional overhead reach, standing	82.5 ± 3.3	78.4 ± 3.4	74.0	80.5	[illegible]
Upper leg length, seated	23.4 ± 1.1	22.6 ± 1.0	21.1	23.0	[illegible]
Elbow to fist length	14.2 ± 0.9	12.7 ± 1.1	12.6	14.5	[illegible]
Upper arm length	14.5 ± 0.7	13.4 ± 0.4	12.9	13.8	[illegible]
Popliteal height, seated	17.2 ± 1.0	16.2 ± 0.7	15.1	16.6	[illegible]
Hand length	7.5 ± 0.4	7.2 ± 0.4	6.7	7.4	[illegible]
Hand spread, digit one to digit two, second phalangeal joint	4.1 ± 0.7	3.2 ± 0.7	2.3	3.6	[illegible]
Grip breadth, inside diameter	1.9 ± 0.2	1.7 ± 0.1	1.5	1.8	[illegible]
Height	68.7 ± 2.6	63.8 ± 2.4	60.8	66.2	[illegible]

ment mass from total body mass. Since muscle force and energy are required to move body segments, reasonably accurate biomechanical calculations require inclusion of segmental mass in the torque calculations. An estimate of the center of gravity is also required for torque calculations since the distance between the center of gravity of the segment and the joint where movement occurs defines the length of the moment arm for segmental torque calculations (see Part III).

The approximate locations of body-segment centers of gravity are shown in Figure 26-3 as a percentage of segment length from each joint. These values can be used to calculate the torque required to move the segment. They are especially important for calculating the load on the muscles during lifting tasks performed in different working postures. In general, the center of gravity of a segment is located slightly less than halfway (approximately 4/9) from the joint that is closer to the trunk.



Height Distribution

	in.	cm
5%	64.4	164
10%	65.7	167
50%	68.7	174
90%	71.7	182
95%	73.0	185

Figure 26-1: Body-Segment Length in Proportion to Stature—Males. This illustrates the major body segments for males. The equations to predict the length of arm and leg segments from height (H) for American males appear next to each segment. The height distribution for a mixed population of males is shown in the upper right corner. An estimate of body-segment lengths is required for calculations of torque. Measured values should be used in workplace design instead of estimates whenever possible. *(Adapted from NASA, 1978).*

. THE RANGES OF JOINT MOTION

Table 26-4 summarizes the motions of the major joints of the body and shows the ranges of motion around these joints. The motions are illustrated in Figures 26-4 through 26-8. Muscle strength may be considerably less near the extreme

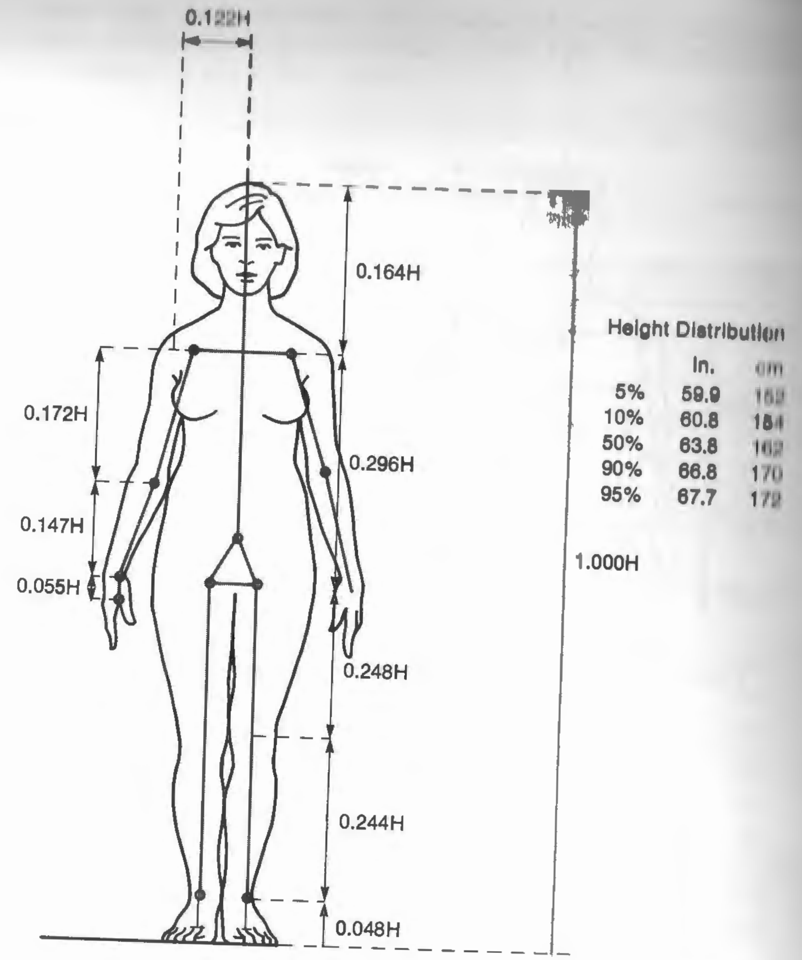


Figure 26-2: Body-Segment Length in Proportion to Stature—Females. This illustrates the major body segments for females. The equations to predict the length of arm and leg segments from height (H) for American females appear next to each segment. The height distribution for a mixed population of females is shown in the upper right corner. *(Adapted from NASA, 1978).*

of the range because of both physiological and biomechanical factors (see Parts II and III).

4. MUSCLE CROSS-SECTIONAL AREAS

The amount of strength that can be generated by a muscle is directly related to its cross-sectional area. Table 26-5 shows the approximate cross-sectional areas of six muscles. The cross-sectional area is estimated by measuring the girth of the muscle at its widest part (the "belly" of the muscle) and calculating the area by assuming that the muscle is cylindrical at that point. The deltoid muscle is not longitudinal and does not fit these assumptions; its cross-sectional area has been estimated from a computerized axial tomography (CAT) scan.

Table 26-3: Regression Equations for Estimating the Mass of Body Segments. Column 1 shows the body segments of interest in biomechanical analyses. The slope (a), which is common to both kg and lbm calculations, is shown in column 2. Columns 3 and 4 give the constants for the equation in kg and lbm, respectively; columns 5 and 6 give the standard errors of estimate. Example: To estimate the mass of both upper extremities, in kg, the equation to use is 0.13 times the total body weight in kg minus 1.4 kg, with a standard error of ± 1.0 kg. *(Adapted from Barter, 1957).*

		Constant (b)		Standard Error of Estimate	
Body Segment	**Slope (a)**	**kg**	**lbm**	**kg**	**lbm**
Head, neck, and trunk	0.47	+5.4	+12.0	±2.9	±6.4
Total upper extremities	0.13	−1.4	−3.0	±1.0	±2.1
Both upper arms	0.08	−1.3	−2.9	±0.5	±1.0
Forearms plus hands	0.06	−0.6	−1.4	±0.5	±1.2
Both forearms	0.04	−0.2	−0.5	±0.5	±1.0
Both hands	0.01	+0.3	+0.7	±0.2	±0.4
Total lower extremities	0.31	+1.2	+2.7	±2.2	±4.9
Both upper legs	0.18	+1.5	+3.2	±1.6	±3.6
Both lower legs plus feet	0.13	−0.2	−0.5	±0.9	±2.0
Both lower legs	0.11	−0.9	−1.9	±0.7	±1.6
Both feet	0.02	+0.7	+1.5	±0.3	±0.6

Segment Mass = (a) × (Total Body Weight in kg or lbm) + (b)

B. MUSCLE STRENGTH DATA

The voluntary muscle system is made up of approximately 434 muscles of which about 75 pairs are involved in movement and postural control of the body (Rasch and Burke, 1978). This explains the complexity of analyzing muscular work and the difficulty of identifying the muscles that contribute to movement and of evaluating their capacities to develop force. As we will discuss in Appendix B under strength testing, the muscle strengths specific to a particular task should be measured. If this is not possible, one must rely on the measurements that have been published in the scientific literature. When using data from these studies, the same precautions should be applied as when designing a strength-

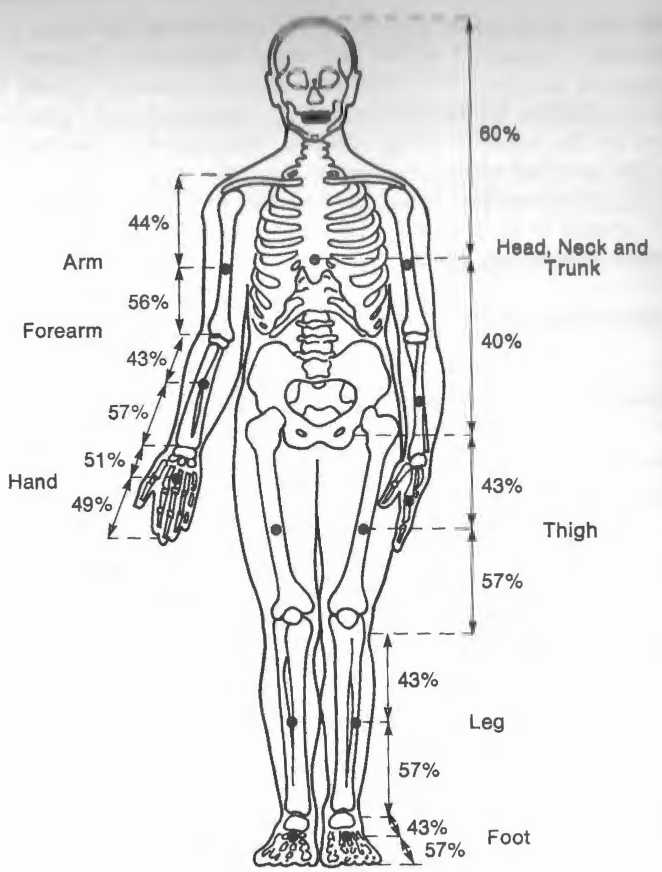


Figure 26-3: Estimated Body-Segment Centers of Gravity Expressed as a Percent of Segment Length The locations of body-segment centers of gravity are presented as percentages of segment length. These centers of gravity must be estimated for torque calculations since the mass of a segment results in a force acting through the segment's center of gravity. The distance from the proximal joint to the center of gravity defines the moment arm. For example, the center of gravity of the upper arm is 44 percent of the way towards the elbow from the shoulder. One can use this to define the moment arm for the upper arm and, thus, estimate the torque in handling tasks or other arm activities. *(Adapted from Dempster, 1955; Williams and Lissner, 1962).*

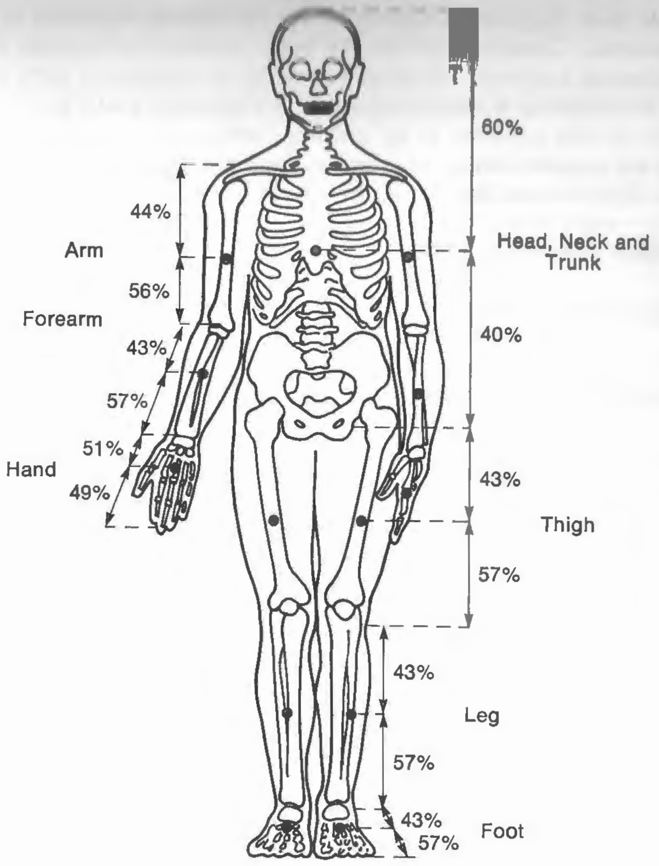
testing study. The following questions should be asked before using the data to solve an ergonomics problem:

- What subject population was tested?
- What was the subject's position during the measurements—that is, what were the locations of the limbs? Was the person standing or seated?
- Were maximum measurements made?
- Was the measurement static or dynamic?
- If dynamic, what type? Isotonic (concentric or eccentric) or isokinetic?
- If dynamic, what was the velocity?
- How long was the effort sustained, and was the reading a peak or a average value?

Table 26-4: Normal Ranges of Joint Motion. The average ranges of motion (columns 3 and 4, in degrees and radians) of eight joints (column 1) are shown for several types of motion (column 2). The motions are illustrated in Figures 26-4 through 26-8. *(Adapted from American Academy of Orthopedic Surgeons, 1965).*

Joint	Motion	Range of Motion*, degrees (radians)	
Elbow	Flexion to extension	150	(2.62)
	Hyperextension	10	(0.17)
Forearm	Pronation	80	(1.48)
	Supination	80	(1.48)
Wrist	Flexion	80	(1.40)
	Extension	70	(1.22)
	Radial deviation	25	(0.44)
	Ulnar deviation	40	(0.70)
Shoulder	Abduction	180	(3.14)
	Adduction	75	(1.31)
	Forward flexion	180	(3.14)
	Backward extension	60	(1.05)
	Horizontal flexion	130	(2.27)
	Horizontal extension	50	(0.87)
Cervical spine	Flexion	45	(0.78)
	Extension	45	(0.78)
	Lateral bending	45	(0.78)
	Rotation	60	(1.05)
Lumbar spine	Flexion	80	(1.40)
	Extension	20–30	(0.35–0.52)
	Lateral bending	35	(0.61)
	Rotation	45	(0.78)
Knee	Flexion	135	(2.36)
	Hyperextension	10	(0.17)
Ankle	Flexion (plantar flexion)	50	(0.87)
	Extension (dorsiflexion)	20	(0.35)

*The values represent averages; individual values may vary.



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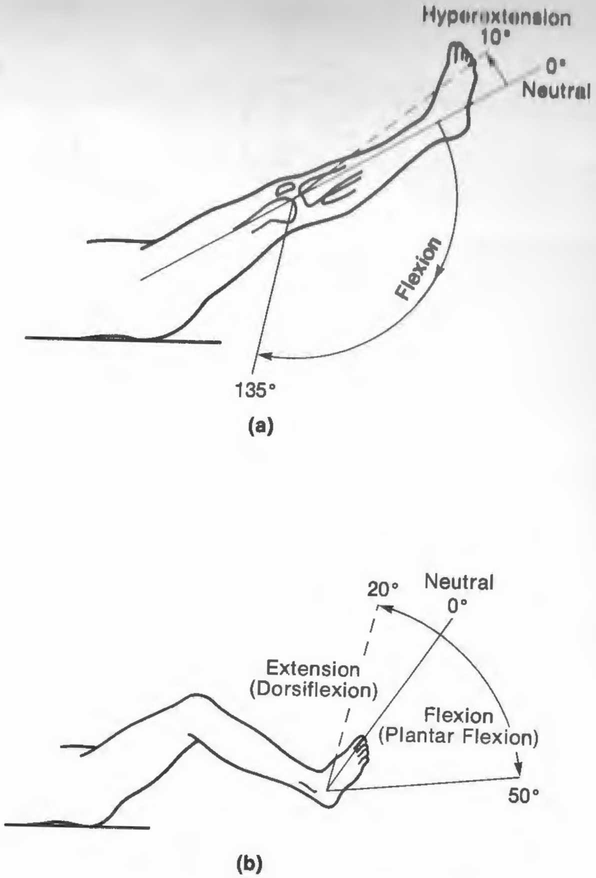


Figure 26-8: Ranges of Motion of the Knee and Ankle. The range of motion of the knee in flexion and hyperextension is illustrated in *a*. Using a neutral point of full leg extension, there are 135 degrees of flexion and 10 degrees of hyperextension ("locked knee") available. The ankle joint's extension and flexion range is illustrated in *b*; the neutral point is taken with the knee at about 90 degrees and the foot at 90 degrees from the lower leg. Flexion is towards the sole of the foot (plantar flexion), and extension (dorsiflexion) is towards the knee. *(Adapted from American Academy of Orthopaedic Surgeons, 1965).*

In many cases, a close evaluation will show that the published studies do not adequately describe the task conditions during data collection. However, by applying the physiological and biomechanical principles developed in Parts II and III, one can make adjustments to the literature values to make them more applicable to specific tasks in industry. This section includes summaries of se- ected muscle strength data both from the literature and from some industrial

Table 26-5: The Approximate Cross-Sectional Areas of Selected Muscle Groups. The estimated cross-sectional areas of three muscles of the arm and shoulder and three leg muscles (column 1) are shown in column 2. Average values plus or minus one standard deviation are given in square centimeters (cm^2). The populations tested and the number in each group, where known, are given in column 3. The source of the information is cited in column 4. Note: The force per cross-sectional area has been reported to be between 20 N/cm^2 and 100 N/cm^2. Values of 30 to 40 N/cm^2 are most common. *(Brunnstrom, 1972; Haxton, 1944; Schantz, et al, 1983; Winter, 1979).*

Muscle	Cross-Sectional Area (cm^2)	Population (n)	Reference
Upper Body			
Triceps brachii	31.1 ± 1.6	Male phys. ed. students (8)	Schantz et al., 1983
	19.0 ± 0.7	Female phys. ed. students (6)	Schantz et al., 1983
Biceps	23.5 ± 1.2	Male phys. ed. students (8)	Schantz et al., 1983
	14.4 ± 0.6	Female phys. ed. students (6)	Schantz et al., 1983
Deltoid (lateral)	25.3	Not given	Brunnstrom, 1972
Lower Body			
Quadriceps femoris	88.3	Male phys. ed. students (8)	Adapted from Schantz et al., 1983
	66.5	Female phys. ed. students (6)	Adapted from Schantz et al., 1983
Soleus	67	Not given	Winter, 1979
Gastrocnemius	35	Not given	Winter, 1979

studies not yet published. The intent is not to make a comprehensive review of the strength-testing literature but to provide information that will be useful in solving problems and improving the workplace. Where appropriate, attempts are made to suggest relationships that can be used to adjust the published strength values so they can better approximate industrial task requirements.

The muscle groups included are those that flex and extend the forearm, rotate the forearm and move the hand at the wrist, provide grip strength, and flex the arm at the shoulder, thereby raising the arms out in front of the body. Information about whole-body and upper body lifting strength, which involves large numbers of muscle groups, is also included. The chapter concludes with

Table 26-16: Comparisons of Whole-Body Maximum Aerobic Work Capacities for Industrial and Civilian Populations. The mean maximum aerobic capacities for whole-body work are shown in column 5 in milliliters of oxygen per kilogram of body weight per minute. The number of subjects is shown in column 2, and their sex and average ages (plus or minus one standard deviation) in columns 3 and 4, respectively. The type of test is given in column 1. In submaximal tests, a predicted maximum heart rate is calculated, not measured, as it is in a maximal test, and the tests may therefore over- or underestimate the work capacity. The maximum aerobic capacities for industrial men are about 15 percent lower than the values reported for nonindustrial men; the industrial women are similar to a sedentary adult population studied by Profant et al. (1972), prior to an exercise program.

Test	n	Sex	Age (years)*	(mL $O_2 \cdot$ kg $BW^{-1} \cdot$ min^{-1})*	Reference
Treadmill, submaximal	84 37	M F	37 ± 12 33 ± 12	38 ± 7 31 ± 6	Rodgers, Eastman Kodak Company, 1975
Treadmill, maximal	28	M	20.7 ± 2.5	44.6 ± 8.0	Sloan, Koeslag, and Bredell, 1973
Treadmill, maximal	11 10 9 7 8	M M M M M	24.5 35.1 44.3 51.0 63.1	48.7 43.1 39.5 38.4 34.5	Robinson, 1938
Treadmill, submaximal	35	M	37.1 ± 8.9	43.7 ± 10.2	Coleman and Burford, 1971
Treadmill, maximal	39 47 33	F F F	29 to 39 40 to 49 50 to 59	29.1 ± 3.5 26.9 ± 4.0 25.7 ± 3.0	Profant et al., 1972
Bicycle ergometer, submaximal	13 9 66 8	M M M M	34.8 42.6 53.3 62.9	39.8 ± 7.3 39.2 ± 5.5 33.1 ± 4.9 31.4 ± 5.3	Astrand, 1960
	8 12 8 16	F F F F	25.0 34.7 43.9 55.6	39.9 ± 4.7 37.3 ± 5.2 32.5 ± 2.7 28.4 ± 2.7	
Bicycle ergometer, submaximal and maximal	31 35	M F	46.9 42.9	45.3 ± 4.0 38.4 ± 4.0	Astrand et al., 1973

*Mean values ± 1 SD (where available).

60 to 80 percent of the maximum aerobic capacities of their colleagues in their 20s. A follow-up study of people in their 40s, whose maximum aerobic capacities had been measured in their 20s, showed about a 20 percent decline in capacity over the 20-year period (Astrand et al., 1973).

In general, the industrial population has lower maximum aerobic capacities than the other populations tested. This is probably explained by the differences in fitness of the populations since many of the civilian groups were tested at gymnasiums where they exercised once or twice a week.

For the workload guidelines given in Part IV, a maximum whole-body aerobic work capacity of 27 mL $O_2 \cdot$ kg $BW^{-1} \cdot min^{-1}$ was used, as 75 percent of the 50-50 male-female population mix would have that capacity or more. Jobs that require higher capacities can be done safely by some people, but there are fewer people suited for them.

2. UPPER BODY MAXIMUM AEROBIC CAPACITY

For jobs done while standing at a counter or next to a machine where the lower body is relatively stationary and all of the work is with the arms and shoulders, a measure of upper body maximum aerobic work capacity is needed. Table 26-17 summarizes data from one industrial lifting task and three studies of stan-

Table 26-17: Upper Body Maximum Aerobic Work Capacity as a Percent of Whole-Body Aerobic Work Capacity. Four reports of tests of upper body work capacity are shown in column 1; the tray lift was a three- or four-stage task using weights up to 12 kg (26 lbm) and is described in Appendix B. The upper body aerobic capacity is expressed as a percentage of the whole-body capacity (column 2). The number and sex of the people studied are in parentheses, and the source of the study is given in column 3. According to these studies, upper body aerobic capacity is about 64 to 78 percent of whole-body aerobic capacity.

Type of Upper Body Work	Average Upper Body As a Percentage of Whole-Body Capacity	Reference
Lifting tray at 24 lifts per minute, all lifts above 76 cm 30 in.	64% (10 F) 75% (11 M)	Rodgers, Eastman Kodak Company, 1973
Arm cranking	70% (13 M)	Astrand et al., 1965
Arm cranking	68% (3 M)	Reybrouck, Heigenhauser, and Faulkner, 1975
Arm cranking	78% (7 M)	Vokac et al., 1975

considered, not just the energy requirements that have been established using a person in good health.

Another important consideration is that the metabolic demands are often not the limiting factor in determining job or task difficulty. A specific strength, reach, decision-making, or visual requirement may make a task too difficult for people even though it is within their aerobic capacities.

With these limitations in mind, Tables 26-19 through 26-23 show tasks and jobs for which oxygen consumption measurements have been made using healthy volunteers. The studies from which these tables are compiled include those by Aberg et al., 1968; Asmussen and Poulsen, 1963; Astrand and Rodahl, 1977; Belding, 1971; Brown and Crowden, 1963; Consolazio, Johnson, and Pecora, 1963; Davies et al., 1976; Davis, Faulkner, and Miller, 1969; Fordham et al., 1978; Garg and Saxena, 1979; Godin and Shephard, 1973; Goldman and Iampietro, 1962; Goldsmith et al., 1978; Hamilton and Chase, 1969; Hettinger, 1970; Kamon, 1973; Lehmann, 1962; McDonald, 1961; Moores, 1970; Nielsen, Eastman Kodak Company, 1962-1973; Oja, Louhevarra, and Korhonen, 1977; Passmore and Durnin, 1955; Raven et al., 1973; Rodgers, 1978; Snook and Ciriello, 1974; and Spitzer and Hettinger, 1958.

1. LIGHT EFFORT

There should be no aerobic capacity limitations for light work for at least 95 percent of the industrial population. These tasks require from 3 to 7 mL $O_2 \cdot kg\ BW^{-1} \cdot min^{-1}$. This is equivalent to 1 to 2.5 kcal per minute or 70 to 175 watts for whole-body work. For upper body work, the upper limits are 5 mL $O_2 \cdot kg\ BW^{-1} \cdot min^{-1}$, 1.8 kcal/min, or 125 watts. Both of these guidelines assume continuous work periods of two hours. Table 26-19 gives examples of whole-body and upper body tasks that are classified as light effort.

2. MODERATE EFFORT

Moderately demanding tasks are not very difficult for 95 percent of the potential work force to sustain for two hours. However, longer continuous periods of work can be difficult for up to 45 percent of the work force. These tasks require from 7.1 to 10.7 mL $O_2 \cdot kg\ BW^{-1} \cdot min^{-1}$, which is equivalent to 2.6 to 3.75 kcal/min or 180 to 260 watts for whole-body work. For upper body work, moderate effort tasks have upper limits of 7.5 mL $O_2 \cdot kg\ BW^{-1} \cdot min^{-1}$, 2.6 kcal/min, or 185 watts. Table 26-20 shows moderate effort tasks.

3. HEAVY EFFORT

Heavy effort tasks include activities that 95 percent of the people can sustain for less than an hour continuously. Only about 55 percent of the potential work force will be able to sustain the work for two hours continuously. These tasks require from 10.8 to 17.1 mL $O_2 \cdot kg\ BW^{-1} \cdot min^{-1}$, which is equivalent to 3.8 to 6.0 kcal/min or 265 to 420 watts for whole-body work. For upper body work, heavy effort has an upper limit of 12 mL $O_2 \cdot kg\ BW^{-1} \cdot min^{-1}$, 4.2 kcal/min, or 295 watts. Table 26-21 gives examples of heavy effort occupational tasks.

Table 26-19: Light Effort Tasks. Several occupational tasks or postures for whole-body and upper body effort are shown in column 1. Column 2 gives the usual continuous duration of each task in discrete categories of less than (<) 15 minutes, less than one hour, one to two hours, or greater than (>) two hours. These tasks are light, as defined in the text and in Table 26-24. *(See text for sources).*

Task	Usual Continuous Duration
Whole-Body Effort:	
Crouching	<15 minutes
Kneeling	<15 minutes
Lecturing, public speaking	1 - 2 hours
Nursing activities: patient care (except lifting), measurement	>2 hours
Sitting, feet and hands active	>2 hours
Sitting in a truck or car	up to 1 hour, >2 hours
Standing, light manual work	>2 hours
Stooping when standing	<15 minutes
Upper Body Effort:	
Canning paint	>2 hours
Coil winding	>2 hours
Drafting	>2 hours
Drilling machine trainees	>2 hours
Inspection of wooden separators	>2 hours
Hand sewing, fur industry	>2 hours
Light assembly work	>2 hours
Sitting, monitoring	>2 hours
Tailoring clothes, seated	>2 hours
Watch and clock repair	>2 hours

4. VERY HEAVY EFFORT

Tasks that require very heavy effort are difficult for more than 50 percent of th potential work force to sustain for a full hour. They are often done for 15 to 2 minutes continuously and followed by light work or rest. They require from 17.

Table 27-6: Aerobic Demands of Bicycle Ergometer Work Levels. The energy requirements (in METs) and the oxygen requirements, ($\dot{V}_{O_2}$ liters per minute), of pedaling on a stationary bicycle at seven different workloads, expressed in watts, are shown across the top of columns 2 through 8. People of six different body weights (column 1) are included to show how the METs are affected at each workload. Local muscle fatigue can be a problem for people untrained to bicycle riding. A recommended bicycle ergometer test protocol is shown in Figure 27-7. *(Adapted from American College of Sports Medicine, 1980).*

Body Weight kg (lbm)	Energy Requirements, in METs						
	Exercise Rate, $\dot{V}_{O_2}$						
	50 (0.90)	75 (1.20)	100 (1.50)	125 (1.80)	150 (2.10)	175 (2.40)	200 watts (2.70) $\dot{V}_{O_2}$, L/min
50 (110)	5.1	6.9	8.6	10.3	12.0	13.7	15.4
60 (132)	4.3	5.7	7.1	8.6	10.0	11.4	12.9
70 (154)	3.7	4.9	6.1	7.3	8.6	9.8	11.0
80 (176)	3.2	4.3	5.4	6.4	7.5	8.6	9.6
90 (198)	2.9	3.8	4.8	5.7	6.7	7.6	8.6
100 (220)	2.6	3.4	4.3	5.1	6.0	6.9	7.7

erated from two types of upper body capacity tests: arm cranking on a modified bicycle ergometer known as an arm ergometer, and an upper body lifting test, wherein the weight of a tray is increased in four stages while it is lifted at 24 times per minute around a series of shelves. The protocols for each of these tests of upper body capacity are diagrammed in Figure 27-8.

The lifting task test of upper body capacity appears to be limited by the discomfort felt at the wrists when the tray is lifted to 127 cm (50 in.) above the floor. The heavier the tray, the more discomfort was felt, so some people were unable to handle the 11.5 kg (25 lbm) tray for the three to four minutes required for the test. The arm cranking test is more standardized, but there are not many industrial tasks that use the muscles of the trunk and arms in the way that they are used in a cranking task. Therefore, the test may predict a higher aerobic capacity than is actually available in materials handling, packing, or assembly tasks done primarily with the upper body.

As was discussed in Appendix A under aerobic work capacities, the aero-

gram of body weight per minute (mL O_2/kg BW · min), required to walk, run, pedal, or step up at a given speed or grade can be calculated using these six sets of prediction formulas. The equations yield estimates only and should not be used to determine individual suitability for a given job. They are useful in predicting the appropriate staging of a whole-body aerobic capacity test protocol for an individual. *(American College of Sports Medicine, 1980).*

A. Horizontal Walking

$\dot{V}_{O_2}$ (mL/kg·min) = speed (m/min) × 0.1 mL O_2/kg·min + 3.5 mL O_2/kg·min

B. Grade Walking (50 to 100 m/min)

1. Horizontal Component: Calculate as above.
2. Vertical Component:
   $\dot{V}_{O_2}$ (mL/kg·min) = % grade* × speed (m/min) × 1.8 mL O_2/kg·min
3. Total for Grade Walking: Horizontal Component + Vertical Component

C. Horizontal Jogging and Running (greater than 134 m/min)

$\dot{V}_{O_2}$ (mL/kg·min) = speed (m/min) × 0.2 mL O_2/kg·min + 3.5 mL O_2/kg·min

D. Grade Running (Treadmill)

1. Horizontal Component: Calculate as above.
2. Vertical Component:
   $\dot{V}_{O_2}$ (mL/kg·min) = % grade* × speed (m/min) × 1.8 mL O_2/kg·min × 0.5
3. Total for Grade Running: Horizontal Component + Vertical Component

E. Bicycle Ergometer

$\dot{V}_{O_2}$ (mL/min) = work rate (kpm/min) × 2 mL/kpm + 300 mL/min

F. Bench Stepping

1. Stepping Up and Down:
   $\dot{V}_{O_2}$ (mL/min) = height (m/lift) × rate per minute × 1.33 × 1.8 mL(m/lift)kgm × body mass (kg)
2. Stepping Back and Forth on Level:
   $\dot{V}_{O_2}$ (mL/min) = (rate per minute/10)** × 3.5 mL O_2/kg·MET × body mass (kg)
3. Total for Bench Stepping:
   Stepping Up and Down + Stepping Back and Forth

1 mph = 26.8 m/min = 1.6 km/hr.

*% grade = fraction of vertical distance climbed per minute divided by the belt speed.

**Approximate energy cost in METs.

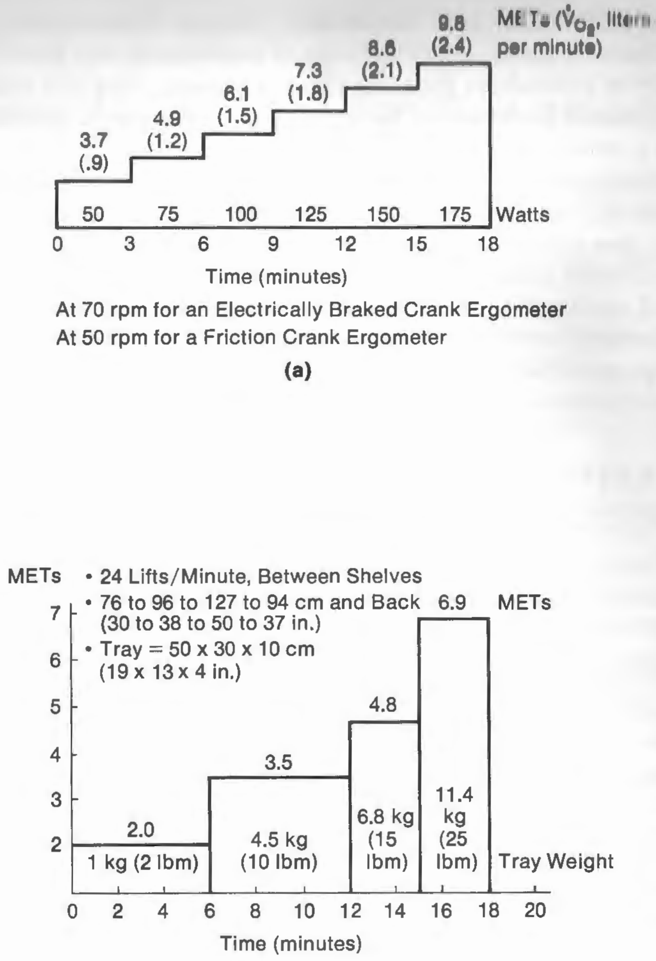
Table 27-8: Equivalents for Standard Units in Capacity Testing. Several constants that demonstrate the relationship between power and work and energy units of measurement are given. Although the SI system uses the watt as the unit of power, the MET is a standard unit in exercise physiology capacity testing. The kilocalorie has been used traditionally by nutritionists, ergonomists, and industrial engineers as a measure of energy; milliliters of oxygen per kg body weight per minute is used by physiologists. The kilopond-meter (kpm) is only used in bicycle ergometry where watts are more commonly used to describe workload. The 5 kcal equivalent for one liter of oxygen is approximate and depends heavily on the metabolic pattern of the subject and the type and duration of the muscular work being done. *(Astrand and Rodahl, 1977).*

Power		
1 watt	=	0.01433 kcal/min
1 watt	=	1 joule/sec
1 watt	=	6.12 kpm/min
1 kcal/min	=	69.767 watts
1 kcal/hr	=	1.163 watts
1 MET	=	3.5 mL O_2/kg·min
1 MET	=	1.0 kcal/kg·hr
Work and Energy		
1 kcal	=	4,186 joules
1 kcal	=	426.85 kpm
1 kg-m	=	2.34×10^{-3} kcal
1 L O_2	≅	5 kcal

bic capacity for a manual handling task will vary with the weight, location, and frequency of lifting. Therefore, the preferred approach for measuring lifting capacity is to simulate the workplace conditions and to vary load and frequency of lifting to produce a staged workload similar to the treadmill and ergometer tests discussed earlier in this chapter.

C. CARDIOVASCULAR AND METABOLIC MEASUREMENTS

Most industrial evaluations of job demands measure the worker's performance but not the physiological cost of performing. Measures of heart rate, blood pres-



At 70 rpm for an Electrically Braked Crank Ergometer
At 50 rpm for a Friction Crank Ergometer

(a)

(b)

Figure 27-8: Upper Body Aerobic Capacity Test Protocols Two examples of graded tests to evaluate upper body aerobic capacity are shown. In *a,* an arm crank ergometer is used to increase the load sequentially on the upper body musculature; each stage lasts three minutes. The work required is shown in watts above the time axis. The aerobic demands are shown above the line as liters of oxygen per minute ($\dot{V}_{O_2}$) and METs. In *b,* a protocol for a submaximal capacity lifting test used in an industrial setting is indicated at the top of the graph. Tray weight was varied from 1 to 11.4 kg (2 to 25 lbm) as shown in each time period. The work in METs is indicated above each block of time. The longer work periods at lower workloads reflect the need to "warm up" and settle into a steady work pattern. Oxygen consumption was measured during the last two minutes of each time block. *(Rodgers, Eastman Kodak Company, 1974; Sawka, Foley, and Timental, 1983).*