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Worker Strength Evaluation: Job Design and Worker Selection

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21.1 Introduction

Many jobs in industry severely tax the worker's musculoskeletal system and may approach or exceed the worker's maximum voluntary strength capabilities. When this occurs, there is evidence that the worker is at higher risk of experiencing a musculoskeletal disorder (Chaffin, 1978; Keyserling et al., 1980). It is for this reason that efforts have been taken over the last couple of decades to provide a means of evaluating the muscular strength capabilities of workers, so that jobs can be designed to eliminate taxing exertions, and to ensure that workers performing physically demanding jobs have the strength to safely perform required tasks.

The effectiveness of worker strength evaluation in reducing work-related musculoskeletal disorders (WMSDs) depends in large part on the purpose of the evaluation. Assessment of physical strength has been used for two primary purposes in the field of ergonomics: job design and worker selection. Job design has been the focus of the psychophysical method of strength assessment and is the technique most likely to have a positive impact in reducing WMSDs. In this technique, the strength of a population of workers is used to design the job so that the majority of workers find the exertion to be acceptable. Studies have indicated that designing tasks by this approach may reduce back injuries by up to 33% (Snook et al., 1978). Strength testing has also been used for the purpose of worker selection, that is,

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making sure that workers have sufficient strength to perform physically demanding jobs. In a sense, this approach to controlling WMSDs is antithetical to one of the primary tenets of ergonomics: design the job to fit the worker. Instead, worker selection seeks to "fit" a strong worker into a physically demanding job. Predictably, this technique does not result in nearly the same magnitude of reduction in injuries compared to the job design approach. However, some studies have indicated a partial success using this technique. It should be noted that such an effect has only been evident when the procedure is employed in an environment known to place workers at very high risk of injury. Furthermore, it must be noted that most studies that have examined worker selection procedures have been short term (usually a follow-up period of one year or less). There can be no guarantee that this approach will be successful in protecting workers over the long term.

Muscular strength is a very complex function that can vary greatly depending upon the methods of assessment (Gallagher et al., 1998). As a result, there is often a great deal of confusion and misunderstanding with regard to the appropriate uses of strength testing in the context of ergonomics. It is not uncommon to see techniques misapplied by those unfamiliar with the caveats and limitations associated with various strength-testing procedures. The purposes of this chapter will be threefold: to provide the reader with a basic understanding of human strength, to characterize various methods of strength testing, and to describe ways that these techniques have been used in the attempt to control work-related musculoskeletal disorders (WMSDs).

21.2 Definition of Muscular Strength

Before describing the various strength-testing procedures available, one must first understand what is meant by the term *muscular strength*. For the purposes of this paper, muscular strength will be defined as *the capacity to produce a force or torque with a voluntary muscle contraction* (Gallagher et al., 1998). It is important to note that the strength or force output measured is that which the subject is willing to produce, and is probably somewhat lower than what the muscle is capable of producing in absolute terms (Chaffin and Andersson, 1991). It has been estimated that the maximal voluntary strength a subject is willing to put forth may be as much as 30% lower than the physiological tolerance of the muscle–tendon–bone system (Hettinger, 1961).

21.3 Measurement of Human Strength

We do not currently have the ability to directly measure the force or tension developed within the muscle of a living person (Kroemer et al., 1994). If this were possible, it might greatly simplify the analysis of worker strength. Lacking this ability, we must use indirect measurement techniques in which we measure (externally) the forces or torques generated at some interface between the person and a measurement device. This is important to realize because there are a multitude of ways that such an interface can be constructed, each of which can (and will) influence the resulting strength measure.

Consider the isometric elbow flexion measurement depicted in Figure 21.1 (Gallagher et al., 1998). Were we able to measure the muscle force directly, we would find that the muscle was developing a force of 1,000 Newtons (N). Being unable to do so, we must measure the forces external to the body using a force cuff. But where should we place the force cuff, close to the elbow joint or near the wrist? As will be demonstrated, the force reading will be dramatically affected depending on where the cuff is placed.

In this figure, the tension developed by the muscle acts through a lever arm of distance a. In so doing, it creates a torque about the elbow joint equal to $F_m \times a$. Assuming that the exertion is static (nothing moves), measured forces (on the gauge) will equal the elbow flexor torque divided by the distance that the gauge's associated force cuff is from the elbow joint. That is,

$$Q = (F_m \times a)/b \tag{1}$$

or

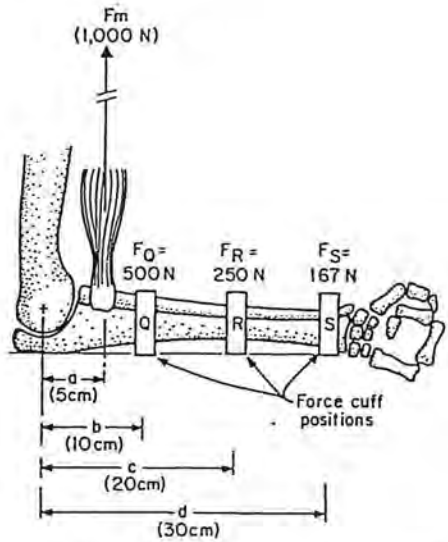

FIGURE 21.1 Given a constant muscle force (F_m), forces measured at various distances from the elbow will result in different force readings (F_Q, F_R or F_S).

$$R = (F_m \times a)/c \tag{2}$$

or

$$S = (F_m \times a)/d \tag{3}$$

As we move the interface (a force cuff) from the elbow to the hand, the measured force will decrease. So, what can we say is the maximal force that can be generated in elbow flexion?

The answer is that it depends on how and where the forces are being measured.

This example highlights several important points. One central idea that should be understood is that "muscular strength is what is measured by an instrument" (Kroemer et al., 1994). One can see from the example given above that it would be entirely possible to have a case where two groups of subjects have (in actuality) identical muscle strength, but where differences in measurement techniques indicate wildly different strength capabilities. People using strength data must understand in detail how the measurements were done. Thus, a record of a person's strength describes what the instrumentation measured when the person voluntarily produced a muscle contraction in a specific set of circumstances with a specific interface and instrumentation (Gallagher et al., 1998).

21.4 Types of Muscular Strength

Muscular exertions can be divided into those which produce motion about a joint (*dynamic* exertions), and those which do not (*isometric* or *static* exertions). The vast majority of occupational tasks involve dynamic exertions. Unfortunately, the complexity of dynamic tasks (where one has to deal with factors such as velocity and acceleration) makes quantification of this type of strength more difficult (Chaffin and Andersson, 1991; Kroemer et al., 1994). For example, there may be great variability in speed of contraction with different people performing a given task. This, in turn, has a large bearing on the forces that can be produced by the muscles (Åstrand and Rodahl, 1977). Static exertions, on the other hand, are easier to quantify, but do not accurately represent muscle forces where the activity is very dynamic in nature (Kroemer et al., 1994). Neither of these types of strength testing is inherently better than the other — the important thing is to make sure that the test that is used is appropriate for the application being studied.

Isometric Strength

Tests of isometric strength involve application of a force against a stationary load-measuring device (Chaffin, 1996). Because of the relative simplicity of isometric strength tests, standardized procedures have been developed (Caldwell et al., 1974). The recommended protocol describes several control measures to standardize the execution and reporting of tests of static strength. For example, the recommended exertion duration is four to six seconds, with 30 seconds' to two minutes' rest provided between tests. Instructions are to be carefully stated to inform subjects of potential risk and use of the test results, and to prevent coercion or undue incentives to the subject during the exertions. The recommendations also detail methods of standardizing test postures, body supports, and restraint systems, as well as the control of environmental factors (temperature, humidity, noise, spectators, etc.). These procedures have been widely accepted, and have helped unify the techniques used to test isometric muscle strength by researchers around the world.

Dynamic Strength

In contrast to isometric strength testing, a number of different techniques exist to examine dynamic strength capabilities. One type of dynamic strength assessment is that involving measurement of *isoinertial* strength. Kroemer (1983) and Kroemer et al. (1990) define the isoinertial technique of strength assessment as one in which *mass properties of an object are held constant*, as in lifting a given weight over a predetermined distance. Several strength assessment procedures possess the attribute in this definition. Most commonly associated with the term is a specific test developed to provide a relatively quick assessment of a subject's maximal lifting capacity using a modified weight-lifting device. Another is a technique where the subject is asked to provide an estimate of an acceptable (submaximal) load, under set conditions (frequency and duration of lift, a specified lifting task, etc.). This technique is called the *psychophysical* methodology (Snook, 1978). Both will be discussed in greater detail later in the chapter.

Dynamic strength can also be evaluated using tests of *isokinetic* strength (Hislop and Perrine, 1969). This procedure evaluates dynamic strength *throughout a range of motion and at a constant velocity*. Such an exercise allows the muscle to contract at its maximum capability at all points throughout the range of motion. At the extremes of the range of motion of a joint, the muscle has the least mechanical advantage, and the resistance offered by the machine is correspondingly lower. Similarly, as the muscle reaches its optimal mechanical advantage, the resistance of the machine increases proportionally.

These are the most common tests of dynamic strength used in ergonomics; however, others are available. For example, there are devices that can measure force exerted during a constant acceleration exertion, those measuring strengths in an eccentric (muscle lengthening) mode, and several others (Kroemer et al., 1990). However, most of these have been used primarily for research purposes and not for worker strength evaluations. These devices are beyond the scope of the present chapter.

21.5 Factors Affecting Muscular Strength

Before discussing the use of physical strength assessment in job design and worker selection, it is important for the reader to understand some of the factors that can influence muscular strength. These may include personal factors, variables related to the task, or environmental factors (Ayoub and Mital, 1989). The following sections describe some of the major factors known to have a significant influence on strength test performance.

Personal Factors

Gender

There is a distinct difference between males and females in terms of muscular strength. On the average, the muscle strength of women is about two thirds that of men; however, the difference is variable according to which muscle group is examined. For example, for certain muscle groups women may have only 35% (on the average) the strength of the same muscle group in men. For other muscle groups, the difference

TABLE 21.1 Psychological Factors Affecting Maximal Muscular Strength and Their Likely Effects

Factor	Likely effect
Feedback of results	Positive
Instructions on how to exert strength	Positive
Arousal of ego involvement, aspiration	Positive
Pharmaceutical agents	Positive
Startling noise, subject's outcry	Positive
Hypnosis	Positive
Setting of goals, incentives	Positive or negative
Competition, contest	Positive or negative
Verbal encouragement	Positive or negative
Spectators	?
Deception by researcher	?
Fear of injury	Negative
Deception by subject	Negative

From Kroemer, K.H.E. and Marras, W.S., 1981. Evaluation of maximal and submaximal static muscle exertions. *Human Factors*, 25: 643-653. With permission.

between genders may be as little as 15% (Chaffin and Andersson, 1991). Women tend to perform relatively better when the task involves lower extremity muscle groups, and relatively poorer when the exertion requires a great deal of upper body strength. Some of the difference in strength between men and women can be accounted for by the difference in body size between the genders. However, it seems that even when one accounts for the difference in size, there remains a 20% difference in strength between males and females (Åstrand and Rodahl, 1977).

Age

Muscle strength generally reaches a peak in an individual's late 20s or early 30s, and begins a gradual decline thereafter. In general, the strength of the 40-year-old is approximately 5% less than that achieved at its peak. By the time the individual is 65, strength is 20% below its peak. However, it should be duly noted that a regimen of strength training can significantly influence the rate of decline (Åstrand and Rodahl, 1977).

Anthropometry

Anthropometry is the study of the physical dimensions and composition of the human body (Stramler, 1993). Certain anthropometric measures appear to be related to the amount of strength of which a subject is capable. The measures that most highly relate to strength are lean body mass (body mass corrected for fat), and limb cross-sectional data (obtained from measurements of circumference) (Chaffin and Andersson, 1991). Stature (a subject's height) does not appear to be highly related to strength.

Motivation

Many psychological factors, especially subject motivation, can have a marked influence on measured strength. These factors can have both positive and negative effects. Table 21.1 illustrates certain factors that may influence subject motivation, and the expected effect (Kroemer and Marras, 1981).

Task Influences

Posture

The posture adopted by the body can have a major impact on the expression of human strength. For example, the angle of a joint during an exertion can profoundly affect measured muscle strength. As illustrated in Figure 21.2, elbow flexion strength is highest when the joint is at 90 degrees. As the joint deviates from that angle, less force can be developed. Whole-body posture has also been shown to have a large effect on strength. For example, lifting strength is much lower when a subject is kneeling or seated as compared with standing (Gallagher et al., 1988; Yates and Karwowski, 1987).

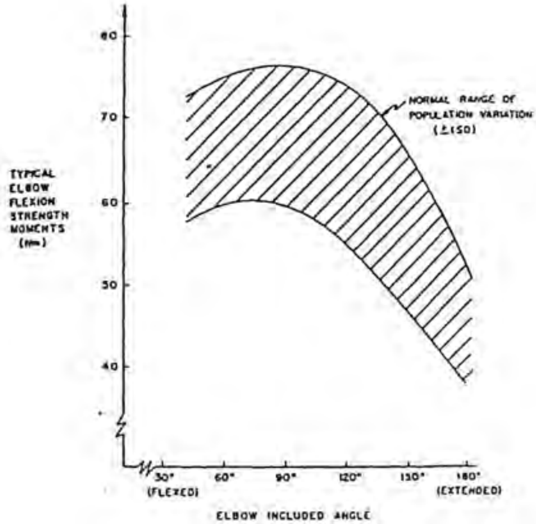

FIGURE 21.2 Change in elbow flexion strength as a result of changes in the angle of the elbow. (From *Occupational Biomechanics*, Chaffin, D.B. and G.B.J. Andersson, © 1991 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

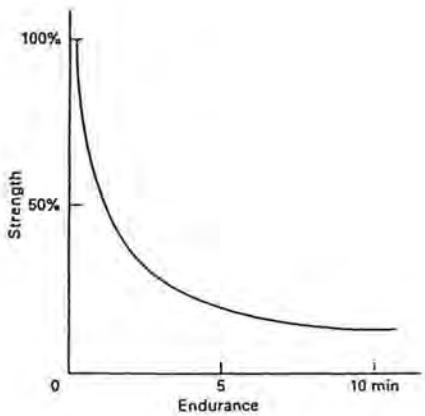

FIGURE 21.3 Endurance time as a function or required strength. (From Rohmert, W., 1966. *Maximal Forces of Men Within the Reach Envelope of the Arms and Legs* (in German), Research Report No. 1616, State of Northrhine — Westfalia, Westdeuscher Verlag Koeln-Opladen. With permission.)

Duration of Exertion

The amount of force that can be sustained during an exertion depends on the length of time of that exertion. Figure 21.3 illustrates this point. An exertion requiring 100% of a subject's maximal voluntary strength can only be sustained for a short period of time. However, as strength requirements are reduced, the exertion can be maintained for longer periods (Rohmert, 1966).

Velocity of Contraction

In work activities, muscular forces are usually applied through a range of motion and may be performed at a wide range of velocity of movement. As illustrated in Figure 21.4, the peak force (or torque) generated by a muscle decreases with increasing velocity of movement. In other words, higher forces can be produced at slow movement speeds. Muscles cannot generate as much force during high-velocity movements (Fox and Mathews, 1981).

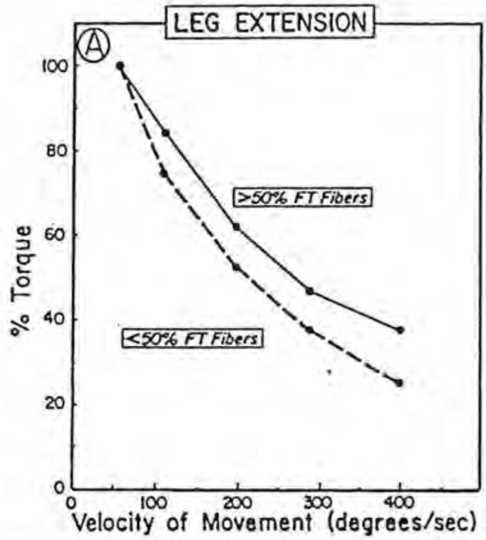

FIGURE 21.4 An example of the force–velocity relationship of muscle: forces generated by a muscle decrease with increasing velocity of movement. (From *The Physiological Basis of Physical Education and Athletics*, Fox, E.L. and D.K. Mathews, © 1981 By CBS College Publishing. With permission.)

Muscle Fatigue

Muscles that are highly stressed become fatigued, which correspondingly reduces the amount of strength that can be produced. Muscular fatigue appears to be dependent on the blood flow through the muscle. When a muscle is tightly contracted, blood flow is impeded, and the delivery of oxygen to the muscle is thereby reduced. Very low levels of exertion (less that 15% of maximal contraction) can be performed for long periods of time without excessive muscular fatigue (Åstrand and Rodahl, 1977).

Environmental Influences on Strength

Temperature and Humidity

Changes in temperature and humidity can affect strength capabilities, particularly at higher levels. Snook and Ciriello (1974) reported that an increase in Wet Bulb Globe Temperature (an index of heat stress) from 20 degrees C to 27 degrees C resulted in a 20% decrease in lifting capacity, a 16% reduction in pushing strength and an 11% reduction in carrying capacity. The effect of cold environments of strength capacity has not been well studied.

21.6 Purposes of Strength Measurement in Ergonomics

There are a number of reasons people may want to collect human strength data. Among the most common is collecting population strength data which can be used to build an anthropometric database; create design data for products, tasks, equipment, etc.; and for basic research into the strength phenomenon. This chapter will discuss two common uses of physical strength assessment in ergonomics: job design and worker selection and placement.

Strength Assessment for Job Design

Perhaps the most effective use of worker strength evaluations is in the area of job design (Snook, 1978). Job design has been a primary focus of the psychophysical method of determining acceptable weights and forces. In this technique, subjects are typically asked to adjust the weight or force associated with a

TABLE 21.2 Excerpt from the Liberty Mutual Tables for Maximum Acceptable Weight of Lift (kg) for Males and Females

				Floor Level to Knuckle Height One Lift Every							
Gender	Box Width (cm)	Distance of Lift (cm)	Percent Capable	5 sec	9 sec	14 sec	1 min	2 min	5 min	30 min	8 hr
			90	7	9	10	14	16	17	18	20
			75	10	13	15	20	23	25	25	30
Males	49	51	50	*14*	17	20	27	30	33	34	40
			25	*18*	*21*	25	34	38	42	43	50
			10	*21*	*25*	*29*	40	45	49	50	59
			90	*6*	7	8	9	10	10	11	15
			75	*7*	9	9	11	12	12	14	18
Females	49	51	50	*9*	10	11	13	15	15	16	22
			25	*10*	*12*	13	16	17	17	19	26
			10	*11*	*14*	15	18	19	20	22	30

Italicized values exceed 8-hour physiological criteria (energy expenditure).

Source: Snook, S.H. and Ciriello, V.M., 1991. The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics* 34(9):1197-1213. With permission.

task in accordance with their own perception of what is an *acceptable workload* under specified test conditions (Snook, 1985). It can be seen from this description that this technique does not attempt to evaluate the maximum forces a subject is capable of producing. Instead, it evaluates a type of "submaximal," endurance-based estimate of acceptable weights or forces.

In the context of lifting tasks, the following procedure is usually used in psychophysical strength assessments. The subject is given control of one variable, typically the amount of weight contained in a lifting box. There will usually be two 20-minute periods of lifting for each specified task: one starting with a light box (to which the subject will add weight), the other starting with a heavy box (from which the subject will extract weight). The box will have a hidden compartment containing an unknown (to the subject) amount of weight, varied before each test, to prevent visual cues to the subject regarding how much weight is being lifted. The amount of weight selected during these two sessions is averaged and is taken as the maximum acceptable weight of lift for the specified conditions. In psychophysical assessments, the subject is instructed to work consistently according to the concept of "a fair day's pay for a fair day's work": working as hard as he or she can without straining or becoming unusually tired, weakened, overheated, or out of breath (Snook and Ciriello, 1974).

As psychophysical strength data are collected on large numbers of subjects, it becomes possible to design jobs so that they are well within the strength capabilities of the vast majority of workers. One criterion that is often used is to design the job so that 75% of workers rate the load as acceptable (Snook et al., 1978). Studies have indicated that if workers lift more than this amount, they may be three times more likely to experience a low back injury. On the other hand, designing jobs in accordance with this criterion has the potential to reduce the occurrence of low back injuries by up to 33% (Snook et al., 1978).

Several authors have published comprehensive tables on loads deemed acceptable by workers over a wide variety of industrial tasks. Of these, the most comprehensive are those developed by Snook and colleagues (Snook et al., 1978; Snook and Ciriello, 1991), which detail maximum acceptable loads for lifting, lowering, pushing, pulling, and carrying for both male and female workers. Table 21.2 presents an excerpt from one such tabulation, dealing with acceptable weights of lift for male and female workers for a floor level to knuckle height lift (Snook and Ciriello, 1991). If one wanted to design a lifting task requiring 4.1 lifts/min (one lift every 14 seconds) so that it was acceptable to 75% of females and 90% of males for the given box dimensions, one could go to these tables and determine that the acceptable weights of lift are 9 kg and 10 kg, respectively. Such a job should be designed so that the weight lifted is no more than 9 kg, or approximately 20 pounds

As with all strength evaluation techniques, there are both advantages and disadvantages to the psychophysical approach. The major advantages of the psychophysical approach include the fact that it allows a realistic simulation of industrial tasks, and is capable of simulating intermittent as well as continuous types of lifting tasks. Furthermore, psychophysical results appear to be very reproducible, and are related to the occurrence of low back pain (Snook, 1985). However, disadvantages can also be identified. Perhaps the most important of these is that psychophysical results sometimes exceed what experts feel are safe according to other criteria, such as biomechanical stress or physiological cost (Snook, 1985). Furthermore, the technique is subjective. That is to say, it relies on self-reporting by the subject. Given the large number of overexertion injuries that occur every year, it is not clear that workers can always tell how much weight is safe for them to lift.

Despite the disadvantages that may be present with this technique, it is the only strength evaluation procedure that focuses on using the acquired data to develop a permanent engineering (job design) solution to the control of low back pain. It would be expected that this approach would afford a greater level of protection to workers than the worker selection techniques that follow.

Worker Selection and Placement

The purpose of worker selection and placement programs is to ensure that jobs which involve heavy physical demands are not performed by those lacking the necessary strength capabilities (Chaffin, 1996). It should be noted that this method is not the preferred strategy of the ergonomist, and there continues to be some controversy regarding the effectiveness of the approach, but there is some support for worker selection procedures in the literature (Chaffin et al., 1978; Keyserling et al., 1980). However, it is clear that specific conditions need to be met for this procedure to have a chance of success.

The process of strength evaluation for worker selection should be approached with caution on many fronts. In the first place, issues of unfair discrimination may be raised if appropriate testing procedures are not used (Chaffin and Andersson, 1991). If strength is to be used as a screening criterion, it is critical that the strength test employed is directly related to specific work requirements. Accurate representations of working postures are also important, as strength in one posture cannot accurately predict strength in another posture. Chaffin and Andersson (1991) suggested that the following criteria be used for methods of worker selection:

1. Is it safe to administer?
2. Does it give reliable, quantitative values?
3. Is it related to specific job requirements?
4. Is it practical?
5. Does it predict risk of future injury or illness?

Prior to testing, a history should be taken to ensure the worker does not have any cardiovascular or musculoskeletal problems that would increase the risk of taking the test.

Research has shown that worker selection cannot consist of general tests of strength (Battié et al., 1989; Troup et al., 1981; Mostardi et al., 1992). Such tests do not appear to be helpful in identifying those at risk of overexertion injury (strong workers seem to experience injury rates similar to those less strong). Instead, worker strength measures must be tied to a biomechanical analysis of workplace demands in order to predict those having increased risk of injury (Chaffin et al., 1978; Keyserling et al., 1980). There are two key principles that must be considered regarding the use of strength assessment for purposes of worker selection. These principles deal with the job relatedness of the test employed, and use of strength tests only under conditions where they have shown the ability to identify workers at high risk of injury.

The literature has shown that worker selection is only effective when a worker's strength capacity is equated with the demands of the job. All too often, emphasis is placed on collecting data on the former attribute, while the latter receives little or no attention (Chaffin, 1996). As will be illustrated, strength data in the absence of information regarding job demands is insufficient for purposes of worker selection. Consider the following scenario: an employer has an opening for a physically demanding job and wishes to hire an individual with strength sufficient for the task. This employer decides to base his employment decision on a strength test given to a group of applicants. Naturally, the employer selects the applicant with the highest strength score to perform the job. The employer may have hired the strongest job applicant; however, what this employer must understand is that he may not have decreased the risk of injury to his employee if, for example, the demands of the job still exceed this individual's capacity. This illustration should make it clear that only through knowing about the person's capabilities *and* the job demands might worker selection protect workers from WMSDs.

A second issue that must be considered when worker selection is to be implemented is that of the test's predictive value. The predictive value of a test is a measure of its ability to determine who is at risk of future WMSD. In the case of job-related strength testing, the predictive value appears to hold only when testing individuals for jobs where high risk is known (Chaffin, 1996). Strength testing does not appear to predict the risk of injury or disease to an individual when job demands are low or moderate. Furthermore, as noted previously, the effectiveness of worker selection techniques has not been demonstrated in long-term studies, only in relatively short-term investigations. It is unclear whether such tests will predict workers at risk of injury over the long term.

Finally, it should be noted that muscular strength is only one factor in a complicated and poorly understood mechanism of injury. A host of other tissues (such as the tendons, ligaments, and joint surfaces) may be deformed or injured by the stresses they experience, whether or not the muscles are able to develop sufficient strength for the job. Thus, it can be said that adequate muscular strength is necessary for safe performance of physical work but is not in itself sufficient for protection against injury.

21.7 Isometric Analysis

When a worker is called upon to perform a physically demanding lifting task, moments (or torques) are produced about various joints of the body by the external load (Chaffin and Andersson, 1991). Often these moments are augmented by the force of gravity acting on the mass of various body segments. For example, in a biceps curl exercise, the moment produced by the forearm flexors must counteract the moment of the weight held in the hands, as well as the moment caused by gravity acting on the center of mass of the forearm. In order to successfully perform the task, the muscles responsible for moving the joint must develop a greater moment than that imposed by the combined moment of the external load and body segment. It should be clear that for each joint of the body, there exists a limit to the strength that can be produced by the muscle to move ever-increasing external loads. This concept has formed the basis of isometric muscle strength prediction modeling (Chaffin and Andersson, 1991).

The following procedures are generally used in this biomechanical analysis technique. First, workers are observed (and usually photographed or videotaped) during the performance of physically demanding tasks. For each task, the posture of the torso and the extremities is documented at the time of peak exertion. The postures are then recreated using a computerized software package, which calculates the load moments produced at various joints of the body during the performance of the task (Chaffin and Andersson, 1991). The values obtained during this analysis are then compared to population norms for isometric strength obtained from a population of industrial workers. In this manner, the model can estimate the proportion of the population capable of performing the exertion, as well as the predicted compression forces acting on the lumbar discs resulting from the task.

Figure 21.5 shows an example of the workplace analysis necessary for this type of approach. Direct observations of the worker performing the task provide the necessary data. For example, the load magnitude and direction must be known (in this case a 200 N load acting downward), the size of the worker, the postural angles of the body (obtained from photographs or videotape), and whether the task requires one or two hands. Furthermore, the analysis requires accurate measurement of the load center relative to the ankles and the low back. A computer analysis program can be used to calculate the strength requirements for the task, and the percentage of workers who would be likely to have sufficient strength capabilities to perform it. Results of this particular analysis indicate that the muscles at the hip are most

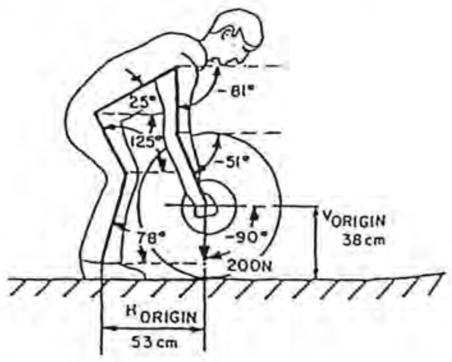

FIGURE 21.5 Postural data required for analysis of joint moment strengths using the isometric technique. (From *Occupational Biomechanics*, Chaffin, D.B. and G.B.J. Andersson, © 1991 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

stressed, with 83% of men having the necessary capabilities but only slightly more than half of women would have the necessary strength in this region. These results can then be used as the basis for determining those workers who have adequate strength for the job. However, such results can also serve as ammunition for recommending changes in job design (Chaffin and Andersson, 1991).

21.8 Isoinertial Testing

The Strength Aptitude Test

The Strength Aptitude Test (SAT) is a classification tool for matching the physical strength abilities of individuals with the physical strength requirements of jobs in the Air Force (McDaniel et al., 1983). The SAT is given to all Air Force recruits as part of their preinduction examinations. Results of the SAT are used to determine whether an individual has the minimum strength criterion which is a prerequisite for admission to various Air Force Specialties (AFSs). The physical demands of each AFS are objectively computed from an average physical demand weighted by the frequency of performance and the percent of the AFS members performing the task. Objects weighing less than 10 pounds are not considered. physically demanding and are not considered in the job analysis. Prior to averaging the physical demands of the AFS, the actual weights of objects handled are converted into equivalent performance on the incremental weight lift test using statistical procedures developed over years of testing. These relationships consider the type of task (lifting, carrying, pushing, etc.), the size and weight of the object handled, and the type and height of the lift. Thus, the physical job demands are related to, but are not identical to, the ability to lift an object to a certain height. Job demands for various AFSs are reanalyzed periodically for purposes of updating the SAT (McDaniel, 1994).

In this technique, a preselected mass, constant in each test, is lifted by the subject (typically from knee height to knuckle height, elbow height, or to overhead reach height). The amount of weight to be lifted is relatively light at first, but the amount of mass is continually increased in succeeding tests until it reaches the maximal amount that the subject voluntarily indicates he/she can handle. Figure 21.6 shows an example of an isoinertial strength testing device. At the time of this writing, over 2 million Air Force personnel have been tested using this procedure.

A unique aspect of this technique is that it is the only strength measurement procedure discussed in this document where results are based on the success or failure to perform a prescribed criterion task (Kroemer, 1983). The criterion tasks studied have typically included lifting to shoulder height, elbow height, or knuckle height.

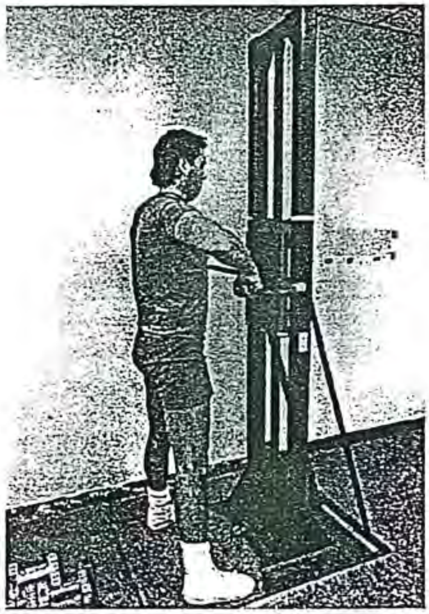

FIGURE 21.6 An isoinertial weight-lifting device. (From Kroemer, K.H.E., 1983. An isoinertial technique to assess individual lifting capacity. *Human Factors*, 25: 493–506. With permission.)

When developing the SAT, the Air Force examined more than 60 candidate tests in an extensive, four-year research program and found the incremental weight lift to 1.83 m to be the single best test of overall dynamic strength capability, which was both safe and reliable (McDaniel, 1994). This finding was confirmed by an independent study funded by the U.S. Army (Myers et al., 1984). This study compared the SAT to a battery of tests developed by the Army (including isometric and dynamic tests) and compared these with representative heavy demand tasks performed within the Army. Results showed the SAT to be superior to all others in predicting performance on the criterion tasks.

The Progressive Inertial Lifting Evaluation (PILE)

Another variety of isoinertial strength test is the Progressive Isoinertial Lifting Evaluation (PILE) (Mayer et al., 1988a, b). Instead of using a weight rack as shown in Figure 21.6, the Progressive Isoinertial Lifting Evaluation (PILE) is performed using a lifting box with handles and increasing weight in the box as it is lifted and lowered. Subjects perform two isoinertial lifting/lowering tests: one from floor to 30" (LUMBAR) and one from 30" to 54" (CERVICAL). Unlike the isoinertial procedures described above, there are three possible criteria for termination of the test: (1) voluntary termination due to fatigue, excessive discomfort, or inability to complete the specified lifting task; (2) achievement of a target heart rate (usually 85% of age predicted maximal heart rate); or (3) when the subject lifts a "safe limit" of 55 to 60% of his/her body weight. Thus, contrary to the tests described above, the PILE test may be terminated due to cardiovascular factors, rather than when an acceptable load limit is reached.

Since the PILE was developed as a means of evaluating the degree of restoration of functional capacity of individuals complaining of chronic low back pain (LBP), the initial weight lifted by subjects using this procedure is somewhat lower than the tests described above. The initial starting weight is 3.6 kg for women and 5.9 kg for men. Weight is incremented upward at a rate of 2.3 kg every 20 seconds for women, and 4.6 kg every 20 seconds for men. During each 20-second period, four lifting movements (box lift or box lower) are performed. The lifting sequence is repeated until one of the three endpoints is reached. The vast majority of subjects are stopped by the "psychophysical" endpoint, indicating the subject has a perception of fatigue or overexertion. The target heart rate endpoint is typically reached in older or large individuals. The "safe limit" endpoint is typically encountered only by very thin or small individuals.

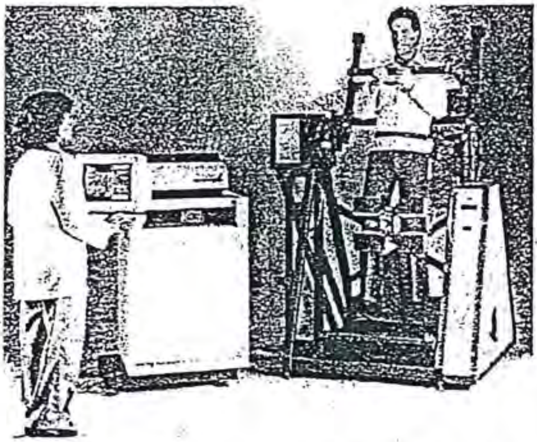

FIGURE 21.7 An isokinetic trunk flexion and extension device used to evaluate lumbar muscle strength. (Cybex Medical, Division of Henley Healthcare, Sugarland, TX.) (Photo courtesy of Henley Healthcare.)

Mayer et al. (1988b) developed a normative database for the PILE, consisting of 61 males and 31 females. Both total work (TW) and force in lbs. (F) were normalized according to age, gender, and a body weight variable. The body weight variable, the adjusted weight (AW), was taken as actual body weight in slim individuals, but was taken as the ideal weight in overweight individuals. This was done to prevent skewing the normalization in overweight individuals.

21.9 Isokinetic Tests

A technique of dynamic testing that has been growing in popularity is that dealing with the measurement of isokinetic strength (Hislop and Perrine, 1969). As defined previously, this technique evaluates muscular strength throughout a range of motion and at a constant velocity. It is important to realize that people do not normally move at a constant velocity (Kroemer et al., 1990). Instead, human movement is usually associated with significant acceleration and deceleration of body segments. Thus, there is a perceptible difference between isokinetic strength and free dynamic lifting. In the latter instance, subjects may use rapid acceleration to gain a weight lifting advantage, as in the Strength Aptitude Test described above. Acceleration is not permitted in isokinetic tests of strength.

The majority of isokinetic devices available on the market focus on quantifying strength about isolated joints or body segments, for example, trunk extension and flexion (see Figure 21.7). This may be useful for rehabilitation or clinical use, but isolated joint testing is generally not appropriate for evaluating an individual's ability to perform occupational lifting tasks. One should not make the mistake of assuming, for instance, that isolated trunk extension strength is representative of an individual's ability to perform a lift. In fact, lifting strength for a task may be almost entirely unrelated to trunk muscle strength (Himmelstein and Andersson, 1988). Strength of the arms or legs (and not the trunk) may be the limiting factor in an individual's lifting strength. For this reason, machines that measure isokinetic strengths of isolated joints or body segments should not be used as a method of evaluating worker capabilities related to job demands in most instances.

Many investigators have used dynamic isokinetic lifting devices specifically designed to measure whole-body lifting strength (Pytel and Kamon, 1981; Kishino et al., 1985) (see Figure 21.8). These devices typically have a handle connected by a rope to a winch which rotates at a specified isokinetic velocity when the handle is pulled. Studies using this type of device have demonstrated good correlations between isokinetic Dynamic Lift Strength (i.e., a lift from floor to chest height) and the maximum weights individuals were willing to lift for infrequent tasks using the psychophysical approach (Pytel and Kamon, 1981). Thus, under certain circumstances, this device appears to have some validity for assessment of job-related dynamic lifting strength capabilities of individuals. Some investigators have attempted to

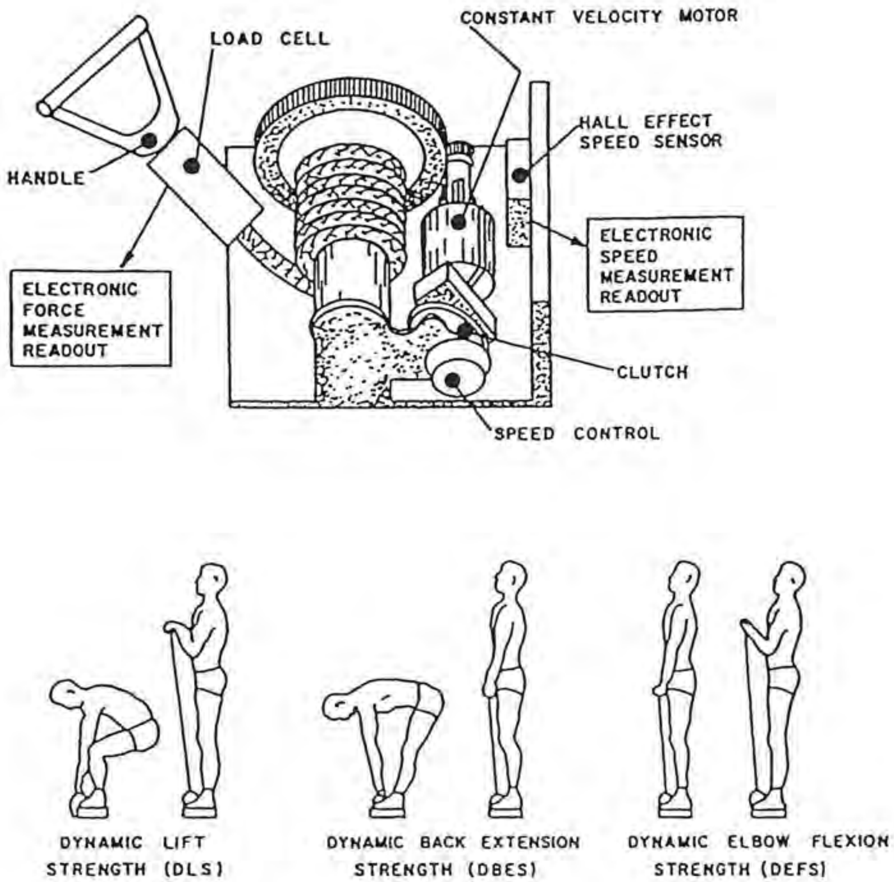

FIGURE 21.8 An isokinetic device used to evaluate whole-body lifting strengths. (From Pytel, J.L. and Kamon, E. Dynamic strength test as a predictor for maximal and acceptable lift, *Ergonomics*, 24: 663–672. With permission.)

modify this type of instrument by providing a means to mount it so that isokinetic strength can be measured in vertical, horizontal, and transverse planes (Mital and Vingararámoothy, 1984). However, while advances have been made in the use of isokinetic devices for worker strength evaluation, this procedure cannot be considered fully developed in the context of worker selection procedures.

21.10 Conclusions

In spite of advances in measurement techniques and an explosive increase in the volume of research, our understanding of human strength remains in its preliminary stages. It is clear that muscle strength is a highly complex and variable function dependent on a large number of factors. It is not surprising, therefore, that there are not only substantial differences in strength between individuals, or that strength measurements for a single individual can vary a great deal even during the course of a single day. Strength is not a fixed attribute — strength training regimens can increase an individual's capability by 30 to 40% or more. Disuse can lead to muscle atrophy (Åstrand and Rodahl, 1977).

The use of physical strength assessment in ergonomics has focused on both job design and worker selection techniques. Of these, the former has a much greater potential to significantly reduce WMSDs. Worker selection techniques must be considered a method of last resort — where engineering changes or administrative controls cannot be used to reduce worker exposure to WMSD risk factors. This technique has only shown a moderate effect in truly high risk environments, and only in short-term studies. It is not known whether worker selection procedures have a protective effect over the long term.

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