Physical Strength Assessment in Ergonomics

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Contents

Chapter 1:

Chapter 2:

Chapter 3:

Chapter 4:

Chapter 5:

Chapter 6:

Appendix

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1. Introduction

Humankind's interest in measurement of human physical strength probably dates to the first humans. At that time, life was truly a struggle in which the fittest survived. To a great extent, fittest meant strongest. Interestingly, current interest in human physical strength in the workplace stems from 1970–1980s vintage research demonstrating that persons with adequate physical strength are less likely to be injured on physically demanding jobs. Survival in many modern workplaces may still be a case of survival of the strongest.

There is, however, a flip side to this issue — that persons with limited strength are more likely to be injured on "hard" jobs. To address this problem, we can apply what we know about physical strength to job design. "Hard" jobs can be redesigned to be within the physical strength capability of most people. Since physical strength is important to these jobs, we must find ways to quantify it through testing.

This publication concerns human physical strength testing. Its purpose is not to recommend any particular type of testing, but rather to describe the types of testing available and their uses. It is up to each individual user of strength testing to decide which testing technique is most appropriate for his or her particular application. This booklet discusses four types of strength testing: isometric, isoinertial, psychophysical, and isokinetic.

Human Strength

Before describing the different types of strength measurement, we must define the term "strength" and explain the concept of strength measurement. *Strength* is defined as the capacity to produce force or torque with voluntary muscle contraction. *Maximum strength* is defined as the capacity to produce force or torque with a maximum voluntary muscle contraction.(1,2) These definitions include some key words that must be explained.

A voluntary muscle contraction is "voluntary." When a person's physical strength is measured, only the effort the person willingly puts forth at the time is measured. Thus, when we test a person's "maximum strength," we are not measuring his or her actual maximum, but some lesser value representing what he or she is comfortable expressing at the time with the existing equipment and environmental conditions. Interestingly, when researchers startled persons being tested (e.g., by setting off a starter's pistol behind them), they have found significant increases in measured strength.(3) It has been hypothesized that the lower strength displayed during normal testing provides a margin of safety against overloading and damaging muscle tissue. The test equipment and the tested person's familiarity with the process also influence the "voluntary" strength output. The interface between the tested person and the test equipment is particularly important. A poorly designed interface induces localized tissue pressures that vary from uncomfortable to painful. In this situation, testers are measuring voluntary discomfort tolerance — not strength. It is important for strength researchers to keep the "voluntary" nature of their data in mind when they are designing their equipment and protocols.

The definition of strength also involves force or torque. Strength researchers and users of strength data must understand this distinction. We commonly use the terms “muscle force” and “muscle strength” to describe the strength phenomenon. Technically, this is incorrect. In most human movements and force exertions, a group of individual muscles (a functional muscle group) actually works together to produce the observable output. In complicated exertions, a number of functional muscle groups work together to produce the measured output. Elbow flexion strength, for example, is the result of the combined efforts of the biceps brachii, brachialis, and brachioradialis; and a squat lift is the result of the combined efforts of the legs, back, and arms. In elbow flexion, each individual muscle’s contribution to the functional muscle group’s output depends on the posture of the arm when being tested. Thus, when we measure elbow flexion strength, we are measuring the strength of the elbow flexor muscle group, not the strength of any individual muscle.

Furthermore, we are measuring (recording) the force created by the functional muscle group(s) against the interface between the person and the equipment (a set of handles, for example). Consider the elbow flexion measurement depicted in Figure 1. The force generated by the elbow flexor muscle group is shown by F_m. This force acts through lever arm “a.” In so doing, it creates a torque about the elbow joint equal to F_m x a. The measured force (*Q, R*, or *S*) depends on how far (*b, c,* or *d*) the interface (force cuff) is from the elbow. Assuming that the exertion is static (nothing moves) in this example, the measured force (on the

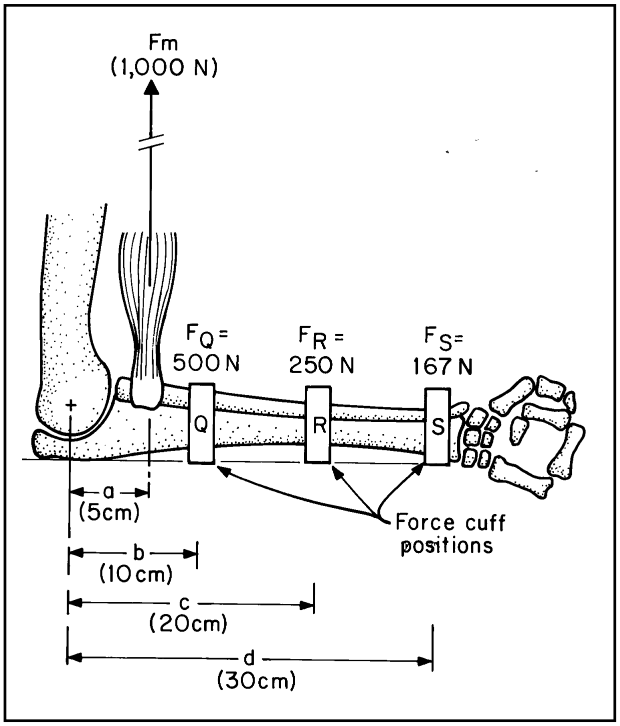

Figure 1*—*
Given a constant muscle force (F_m)*, forces measured at various distances from the elbow will result in different force readings* (F_Q, F_R*, or* F_S)*.*

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,

$$Q = (F_m \text{ x } a)/b \qquad (1)$$

or

$$R = (F_m \text{ x } a)/c \qquad (2)$$

or

$$S = (F_m \text{ x } a)/d \qquad (3)$$

As we move the interface (force cuff) from the elbow to the hand, the measured force will decrease. This example highlights four points. First, as Kroemer et al. wrote in the *International Journal of Industrial Ergonomics,* "muscular strength is what is measured by an instrument."(4) Second, people publishing or using strength data must report or understand in detail how the measurements were done. Third, the differences in published strengths of the various body parts may be due to differences in the measurement methods and locations. Fourth, interface locations selected using anthropometric criteria will result in more consistent results across the population measured.(5)

In summary, a record of a person's strength describes what the instrumentation measured when the person voluntarily produced a muscle contraction under a specific set of circumstances with a specific interface and instrumentation.

Purposes of Strength Measurement in Ergonomics

People may want to collect human strength data for a number of reasons. One common reason is to build an anthropometric database of population strength data that can be used to create design data for products, tasks, equipment, and so forth, as well as for basic research into the strength phenomenon. This publication focuses on two common uses of physical strength assessment in ergonomics: *worker selection and placement* and *job design*.

Worker Selection and Placement

Worker selection and placement programs ensure that jobs involving heavy physical demands are not performed by those who lack the necessary strength capabilities.(6) It should be noted that this method is not the preferred strategy of the ergonomist; it is a provisional measure for controlling work-related musculoskeletal disorders (WMSDs) when job design cannot be used to alleviate task demands. Nonetheless, this method can be effective in reducing the harmful physical effects caused by the mismatch of worker and job, *given adherence to two fundamental principles*: ensuring that (1) the strength measures closely simulate the actual high-strength elements in a job and (2) strength assessment is performed only under circumstances where those who may be at risk of WMSD can be predicted. The following paragraphs describe these issues in more detail.

It has become quite clear over the past several years that strength, in and of itself, is a poor predictor of the risk of future injury to a worker.(7-9) A worker's strength capacity predicts risk of injury only when it is carefully equated with job demands.(10) All too often, collecting data on individual workers' strength is emphasized, while evaluation of actual job demands receives little or no attention. Recent evidence shows that job demands cannot be generalized as “light” versus “heavy”;(11) a careful biomechanical evaluation of strenuous tasks performed by the worker needs to be done.

The following scenario illustrates the need to analyze strength in relation to specific job demands: An employer has an opening for a worker in 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, he selects the applicant with the highest strength score to perform the job. The employer may have hired the strongest job applicant; however, he may not have decreased the risk of injury to his employee if the demands of the job still exceed this individual’s maximum voluntary strength capacity. This example should make it clear that only through knowing both the person’s capabilities *and* the job demands can worker selection protect workers from WMSDs.

The second issue to be considered when implementing worker selection is the test’s *predictive value*. The predictive value is a measure of the test’s ability to determine who is at risk of future WMSD.(6) In the case of job-related strength testing, the predictive value appears to hold *only* when individuals are tested for jobs *where high risk is known* (i.e., for jobs known to possess high strength demands). Strength testing does not appear to predict the risk of injury or disease to an individual when job demands are low or moderate.

It should be clear from the preceding arguments that worker selection procedures are not the preferred method of reducing the risk of WMSDs, and they should not be applied indiscriminantly in the workplace. Instead, care must be exercised to ensure that these strength testing procedures are applied only in select circumstances. This procedure appears to be effective only when jobs are: known to entail high strength demands, and only when the worker’s strength is evaluated in the context of those demands. However, if attention is paid to these limitations, worker selection can be an effective tool to decrease the risk of WMSDs.

Job Design

Physical strength assessment in ergonomics can also be used in *job design*. Job design has been a primary focus of the psychophysical method of determining acceptable weights and forces. Rather than determining *individual* worker strength capabilities and comparing these to job demands, the psychophysical method attempts to determine workloads that are “acceptable” (a submaximal strength assessment) for *populations* of workers. Once the acceptable workloads for a population are determined, the job or task is designed to accommodate the vast majority of that population. For example, a lifting task might be designed by selecting a weight that is acceptable to 75% of females and 90% of males. Strength assessment in job design has been shown to be an effective method of controlling WMSDs. Proper design of manual tasks using psychophysical strength assessment has been estimated to reduce the risk of back injuries by up to 33%.(12)

Purpose of this Publication

Muscular strength is a complicated function that varies greatly depending on the assessment. As a result there is often a great deal of confusion and misunderstanding of the appropriate uses of strength testing in ergonomics. Not uncommonly, these techniques are misapplied by persons who are not thoroughly familiar with the inherent caveats and limitations of various strength assessment procedures. The purposes of this publication are (1) to familiarize the reader with the four most common strength assessment techniques used in ergonomics (isometric, isoinertial, psychophysical, and isokinetic); and (2) to describe the proper applications of these techniques in controlling WMSDs in the workplace.

Four chapters cover these four strength measurement techniques. Each chapter describes the strength measurement technique and reviews the relevant published data. Equipment considerations and testing protocols are described, and the utility of the tests in the context of ergonomics is also evaluated. Finally, each chapter concludes with a discussion of the measurement technique with regard to the Criteria for Physical Assessment in Worker Selection.(6) Each measurement technique is subjected to the following set of questions:

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?

This publication is intended as a resource for better understanding and proper application of these strength assessment techniques in the effort to reduce the risk of WMSDs.

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2. Isometric Strength

Definition of Isometric Strength

Isometric strength is defined as the capacity to produce force or torque with a voluntary isometric (muscle[s] maintain[s] a constant length) contraction. The key thing to understand about this type of contraction and strength measurement is that no body movement occurs during the measurement period. The tested person's body angles and posture remain the same throughout the test.

Isometric strength has historically been the type most studied and measured. It is probably the easiest to measure and to understand. Some strength researchers feel that isometric strength data may be difficult to apply to some "real life" situations because in most real circumstances people are moving — they are not static. Other researchers counter that it is equally difficult to determine the speed of movement of a person or group of persons doing a job (each moves in his or her unique manner and speed across the links and joints of the body). Thus, dynamic strength test data collected on persons moving at a different speed and/or in a different posture from the "real world" condition will be just as hard to apply. In truth, neither is better — they are different measurements. Both researchers and users should collect and use data that they understand and that fits their application.

Workplace Assessment

When a worker is called on to perform a physically demanding lifting task, the external load produces moments — tendencies to produce motion, also called torques — about various joints of the body.(1) 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 forearm's center of mass. To perform the task successfully, the muscles responsible for moving the joint must develop a greater moment than the combined moments of the external load and body segment. It should be clear that, at each joint of the body, there is a limit to the strength that the muscle can produce to move ever-increasing external loads. This concept forms the basis of isometric muscle strength prediction modeling.(1)

The following procedures are generally used with this biomechanical analysis technique. First, workers are observed (and usually photographed or videotaped) as they perform physically demanding tasks. For each task the posture of the torso and the extremities are documented at the time of peak exertion. The postures are then re-created using a computerized software package, which calculates the load moments produced at various joints of the body as the task is performed. 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 estimates the proportion of the population capable of performing the exertion, as well as the predicted compression forces acting on the lumbar discs as a result of the task.

Figure 2 shows an example of the workplace analysis necessary for this approach. Direct observations of the worker performing the task provide the necessary data. For example, one must know the load magnitude and direction (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 to perform it. Results of this particular analysis indicate that the muscles at the hip are most stressed; 83% of men but only slightly more than 50% of women would have the necessary strength in this region. These results can then be used as the basis for determining which workers have adequate strength for the job. However, such results can also be used as ammunition for recommending changes in job design.(1)

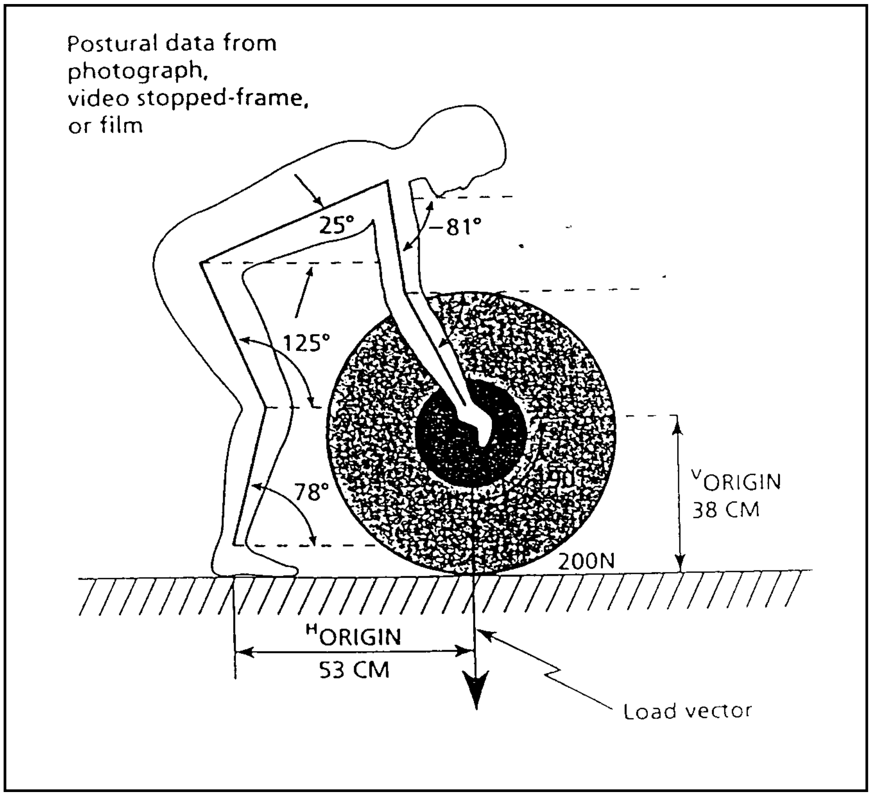

***Figure 2**—Postural data required for analysis of joint moment strengths using the isometric technique.* (From *Occupational Biomechanics,* Chaffin, D.B., and G.B.J. Andersson, ©1991 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

Isometric Testing Protocol

The basic protocol for isometric strength testing was developed by Caldwell et al.(2) and published in an AIHA ergonomics guide by Chaffin.(3) The protocol outlined herein includes additional information determined by researchers since that time. When conducting isometric testing, a number of factors must be considered and controlled (if possible) to avoid biased results. These factors include:

- Equipment used to make the measurements;
- Instructions given to the person tested;
- Duration of the measurement period;
- Person's posture during the test;
- Length of the rest plod between trials;
- Number of trials a person is given for each test;
- Tested person's physical state at the time of testing;
- Type of postural control used during the tests; and
- Environmental conditions during the test.

Test Duration

The length of an isometric strength test impacts the result in two ways. If it is too long, the subject will fatigue and the strength score will decline. If it is too short, the subject will not reach his or her maximum force level before the test is terminated. Chaffin suggests a 4-second test, with the score being the average strength displayed during the second through fourth seconds.(3) The appropriate 3-second period is determined as follows:

If the measuring equipment has the capability, collect strength data by having the person begin contraction with the equipment, monitor the force until some preselected threshold is reached (usually 20%–30% below the expected maximum force for the person and postures, have equipment wait 1 second, and then have the equipment average the displayed force for the next 3 seconds. This is easily done with computerized systems.

If the equipment does not have this capability, have the person tested begin the test and gradually increase his or her force over a 1-second period. The force should be measured and averaged over the next 3 seconds. In complex whole body tests involving multiple functional muscle groups, persons may take a few seconds to reach their maximum. Under these conditions, the data collector must adjust the premeasurement time interval accordingly and carefully monitor the progress of the testing to ensure that the maximal force during the 3-second period is, in fact, being measured.

Instructions

The instructions to the person tested should be factual, include no emotional appeals, and be the same for all persons in a given test group. This is most reliably accomplished with standardized written instructions since the test administrator may reveal feelings about the testee or the desired outcome during verbal instruction.

The following additional factors should also be considered. The purpose of the test, the use of the test results, the test procedures, and the test equipment should be thoroughly explained to the persons tested. Generally, the anonymity of the persons tested is maintained, but if names may be released, the tested person's written permission must be obtained. Any risks inherent to the testing procedure should be explained to the persons tested, and an informed consent document should be provided to and signed by, all participating persons. All test participants should be volunteers.

Rewards, performance goals, encouragement during the test (e.g., "pull, pull, pull, you can do it"), spectators, between-person competition, and unusual noises all affect the outcome of the tests and must be avoided. Feedback to the tested person should be positive and qualitative. Feedback should not be provided during the test exertion but may be provided after a trial or when the test is complete. Quantitative results provided during the testing period may change the person's incentive and thus the test result.

To the tested person, a 4-second maximal exertion seems to take a long time. During the test, tester–testee agreed-on feedback, such as a slow 4 count, should be provided so the tested person knows how much longer a test will last.

Rest Period Length

Persons undergoing isometric strength testing generally perform a series of tests, with a number of trials for each test. Under these conditions, localized muscle fatigue must be avoided since it will result in underestimating strength. Studies by Schanne(4) and Stobbe(5) have shown that a minimum rest period of 2 minutes between trials of a given test or between tests is adequate to prevent localized muscle fatigue. The data collector must be alert for signs of fatigue such as a drop in strength scores as a test progresses. The person tested must be encouraged to report any symptoms of fatigue and the rest periods should be adjusted accordingly. Whenever possible, successive tests should not stress the same muscle groups.

Number of Trials for Each Test

The test–retest variability for this type of testing is about 10%. It is higher for people with limited experience with either isometric testing or forceful physical exertion in general. In addition, these people often require a series of test trials to reach their maximum. The use of a single trial of a test generally underestimates a person's maximum strength, possibly by more than 50%. A 2-trial protocol results in less of an underestimate, but it may still exceed 30%.(6)

For this reason, it is preferable to determine the number of trials for each test based on performance. Begin by having the subject perform two trials of the test. Compare the two scores, and if they are within 10% of each other, use the highest of the two values as the estimate of the person's maximal strength, then proceed to the next test. If the two values differ by more than 10%, perform additional trials of the same test until the two largest values are within 10% of each other. Using this approach, Stobbe and Plummer averaged 2.43 trials per test across 67 subjects performing an average of 30 different strength tests.(6) In any case, a minimum of two trials is needed for each test.

When to Give Tests

A person's measured strength is, for a variety of reasons, somewhat variable. It will not be constant over time or over a workday. In the absence of specific muscle strength training, however, it should remain within a relatively narrow range. It is generally higher at the beginning of a workday than at the end. The fatigue-induced strength decrement varies from person to person and depends on the nature of the work done during the day. A person who performs repetitive lifting tasks all day can be expected to have a large lifting strength decrement over a workday, whereas a sedentary worker should have little or no decrement. Based on these results, the fairest evaluation of a person's maximum strength can be done at the beginning of, or at least early in, a workday.

Test Posture

Measured strength is highly posture dependent. Even small changes in the body angles of persons being tested or changes in the direction of force application can result in large changes in measured strength. When collecting strength data, a researcher should first determine what type of data are sought, and then design one or more strength tests to provide that specific type of data. If, for example, the test is to determine whether people are physically fit for a job, the test posture should emulate, to the extent possible, the posture required on the job.

Once the test posture has been determined, the researcher must ensure that the same posture is used on each trial of the test, monitoring the test to ensure that the posture does not change during the test. If these things are not done, the test results will be erratic and may seriously overestimate or underestimate the person's actual maximal strength.

Restraint Systems

Restraint systems are generally used either to confine a person to the desired test posture or to isolate some part of the tested person's body so that a specific muscle group (or groups) can be tested (Figure 3). In addition, restraint systems help ensure that all persons participating in a given study are performing the same test. The type and location of restraint system used can have a major impact on test results. Similarly, the lack of a restraint system can allow the posture to vary or allow the use of the wrong or additional muscle groups, either of which will impact test results.

Any restraint system used should be comfortable and padded in a manner that prevents local tissue stress concentrations during the test; it should be positioned so that the correct muscle group(s) and posture(s) are used and maintained. Achieving the latter condition often requires some experimentation.

For many strength tests, restraint systems are necessary to achieve consistent and meaningful results. Researchers reporting strength testing results should describe in detail the restraints used and their location so that other researchers and persons applying their data can interpret it correctly. The nonuse of restraints should also be reported.

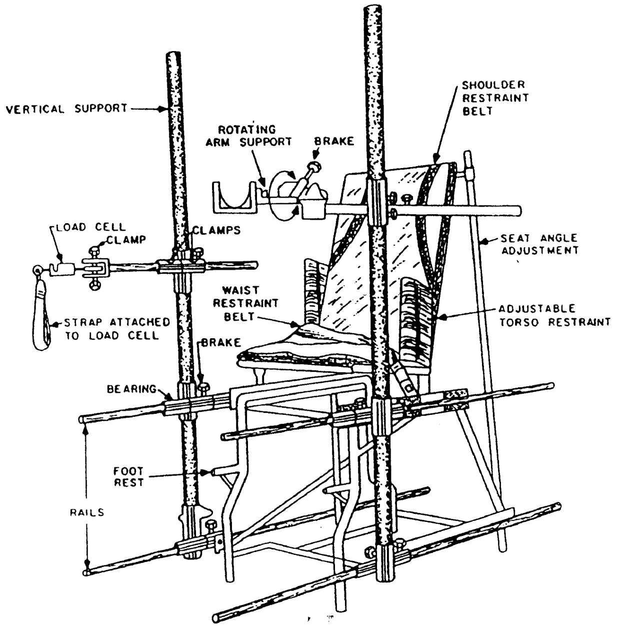

Figure 3*—Example of a test fixture designed to restrain various body segments during isometric strength testing.* (From *Occupational Biomechanics,* Chaffin, D.B, and G.B.J. Andersson, ©1991 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

Environmental Conditions

The environmental conditions selected for the testing periods should be appropriate to the purpose of the test. For most testing, the environmental conditions found in a typical office building or medical department are acceptable. In cases where the effects of the environment on measured strength or physical performance must be determined, appropriate conditions can be established (e.g., work sites requiring exposure to hot or cold temperature extremes).

Equipment

Isometric strength testing equipment has not been standardized. Any equipment capable of performing the necessary timing and averaging described previously under Test Duration is probably acceptable. Today, this varies from dedicated force measurement devices, such as the force monitor developed in the 1970s at University of Michigan, to a force transducer coupled to a PC via an A-D converter and managed by appropriate software or complex multiple-mode strength measuring devices manufactured by companies such as Cybex, Chattex, Loredan, and Isotechnologies. Prices vary from $1000 plus to as high as $50,000 or $100,000.

The issue is not equipment price, rather, it is equipment function. Researchers should select or build equipment suited to their needs. Researchers must also understand what is happening inside the device (and its associated software) in order to properly interpret the data they collect.

The human–equipment interface is another matter that affects the test results. The interface must be appropriate to the task measured, it should be comfortable (unless discomfort effects are being studied), and it should give the person tested a sense of security about the test. Persons generally provide a maximal exertion in a situation in which there is no movement. If they fear that the testing system may fail or move unexpectedly, they will not give a maximal performance. Similarly, the equipment must be strong enough to remain intact under the maximum load placed on it. If it fails unexpectedly, someone is going to be injured — perhaps severely.

Subjects

The subjects selected for strength testing will determine the results obtained. When collecting strength data, the subjects selected must therefore appropriately represent the population the test claims to describe (e.g., design data for retired persons should be collected on retired persons, and design data for entry-level construction workers should be collected on young, healthy adults).

For general research purposes, persons participating in a strength testing project should not have a history of musculoskeletal injuries. Other medical conditions, including hypertension, may pose a threat of harm to a participant. Whenever possible, prospective participants should be medically evaluated and approved before participating in a strength testing project.

The following data should be provided about the subject population when reporting strength testing results:

- Gender;
- Age distribution;
- Relevant anthropometry (height, weight, etc.);
- Sample size;
- Method by which sample was selected and who it is intended to represent;
- Extent of strength training done by participants, and their experience with isometric testing; and
- Health status of participants (medical exam and/or health questionnaire recommended).

Strength Data Reporting

Following are the minimum data that should be reported for strength testing projects:

- Mean, median, and mode of data set;
- Standard deviation of data set;
- Skewness of data set (or histogram describing data set); and
- Minimum and maximum values.

Evaluation According to Physical Assessment Criteria

A set of five criteria has been proposed to evaluate the utility of all forms of strength testing. isometric strength testing is evaluated with respect to these criteria in the following sections.

Is Isometric Strength Testing Safe to Administer?

Any form of physical exertion carries some risk. The directions for the person undergoing an isometric test specifically state that the person is to slowly increase the force until he or she reaches what feels like a maximum, and to stop any time during the exertion if discomfort or pain is experienced. The directions also expressly forbid jerking on the equipment. Isometric testing performed in this manner is quite safe to administer because the tested person decides how much force to apply, over what time interval, and how long to apply it. The only known complaints relating to participation in isometric testing are rare reports of some residual soreness in the muscles that were active in the test(s).

Does Isometric Strength Testing Provide Reliable Quantitative Values?

The test–retest variability for isometric testing is 5%–10%. In the absence of a specific strength training program individual isometric strength remains relatively stable over time. When the number of trials is based on the 10% criterion discussed earlier, the recorded strength is near or at the tested person’s maximum voluntary strength. Assuming these factors, and that test postures are properly controlled, isometric strength testing is highly reliable and quantitative.

Is Isometric Strength Testing Method Practical?

Isometric strength testing has already been used successfully in industry for employee placement, in laboratories for collecting design data, and in rehabilitation facilities for patient progress assessment.

Is Isometric Strength Testing Related to Specific Job Requirements (Content Validity)?

Isometric strength testing can be performed in any posture. When it is conducted for employee placement purposes the test postures should be as similar as possible to the postures that will be used on the job. The force vector applied by the tested person should also be similar to the force vector that will be applied on the job. When these two criteria are met, isometric strength testing is closely related to job requirements. However, it should be noted that results obtained using isometric strength testing lose both content- and criterion-related validity as job demands become more dynamic.

Does Isometric Strength Testing Predict the Risk of Future Injury or Illness?

A number of researchers have demonstrated that isometric strength testing does predict risk of future injury or illness for people on physically stressful jobs.(7,8) The accuracy of this prediction depends on the quality of the job evaluation on which the strength tests are based and the care with which the tests are administered.

Summary

Isometric strength is defined as the capacity to produce force or torque with a voluntary isometric (muscles maintain a constant length) contraction. A characteristic of this type of strength measurement is the absence of body movement during the measurement period. Isometric strength testing has a long history, and it may be the easiest to measure and understand. The basic procedures for testing isometric strength are well-established. Risk of injury appears to be small, and of relatively minor nature. Residual soreness of muscle groups tested is occasionally reported. Tests of isometric strength appear reliable, with test–retest variability on the order of 5%–10%. The approach appears quite practical and has been applied in many industrial situations. The major limitation of isometric strength testing is in its inability to accurately model materials handling tasks that have a significant dynamic component. It is therefore recommended that tests of isometric strength be applied when there is little or no dynamic movement involved. In spite of this limitation, it should be duly noted that of all the procedures reviewed in this chapter, tests of isometric strength are the only strength tests that have shown the ability to predict individuals with a high risk of future injury or illness on physically stressful jobs.(1) The accuracy of this prediction appears to depend on careful biomechanical evaluations of the jobs on which strength tests are based, and proper administration of the isometric strength testing procedures.

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3. Maximal Isoinertial Strength Testing

Definition of Isoinertial Strength

Kroemer(1-3) and Kroemer et al.(4) 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 this characteristic. 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.(1,5) The classic psychophysical methodology of assessing maximum acceptable weights of lift is also considered an isoinertial technique under this definition.(6)

While the definition provided by Kroemer(1) and Kroemer et al.(4) has been most widely accepted in the literature, some have applied the term "isoinertial" to techniques that differ somewhat from the preceding definition, such as in a description of the Isotechnologies B-200 strength testing device.(7) Rather than lifting a constant mass the B-200 applies a constant force against which the subject performs an exertion. The isoinertial tests described here apply to situations in which the mass to be moved by a musculoskeletal effort is set to a constant.

Is Isoinertial Testing Psychophysical or Is Psychophysical Testing Isoinertial?

As various types of strength tests have evolved over the past few decades, some unfortunate developments in terminology have arisen to describe and classify different strength assessment procedures. This is particularly evident in sorting out various tests that have been labeled "isoinertial." One example was cited earlier. Another problem that has evolved is that the term "isoinertial strength" has two connotations. The first is the conceptual definition: isoinertial strength tests include any strength test in which a constant mass is handled. In practice, however, the term is often used to denote a *specific* strength test in which subjects' maximal lifting capacity is determined using a machine and a constant mass is lifted.(1,5) Partially as a result of this dual connotation, the literature contains references to both "isoinertial strength test" as a psychophysical variant(8) and the psychophysical method as an "isoinertial strength test."(4,9) To lay the framework for the next two chapters, the authors will briefly discuss some operational definitions of tests of isoinertial and psychophysical strength.

In stating that the isoinertial strength test is a variant of the psychophysical method, Ayoub and Mital(8) refer to the specific strength test developed by Kroemer(1) and McDaniel et al.(5) Clearly, this isoinertial protocol has many similarities to the psychophysical method: both are dynamic; weight is adjusted in both; and both measure the load a subject is willing to endure under specified circumstances. However, while both deal with lifting and adjusting loads, there are significant differences between the psychophysical (isoinertial) technique and the Kroemer–McDaniel (isoinertial) protocol in their procedures and the use of the data collected in these tests. For our purposes, we designate the

Kroemer–McDaniel protocol Maximal Isoinertial Strength Tests (MIST). This chapter deals with the latter isoinertial technique, which differs from the psychophysical technique on the following counts:

1. In maximal isoinertial strength tests, the amount of weight lifted by the subject is *systematically adjusted by the experimenter, primarily by increasing the load to the subject's maximum*. In contrast, in psychophysical tests, *weight adjustment is freely controlled by the subject, and may be upwards or downwards.*
2. The maximal isoinertial strength tests discussed in this chapter are designed to quickly establish an individual's *maximal strength* using a *limited number of lifting repetitions,* whereas psychophysical strength assessments are typically performed over a *longer duration of time* (usually at least 20 minutes), and the subject is instructed to select an *acceptable (submaximal) weight of lift,* not a maximal one. Because of the typically longer duration of psychophysical assessments, greater aerobic and cardiovascular components are usually involved in the acceptable workload chosen.
3. Isoinertial strength tests have traditionally been used as a *worker selection tool* (a method of matching physically capable individuals to demanding tasks). A primary focus of psychophysical methods has been to establish data that can be used for the purpose of *ergonomic job design.*(6)

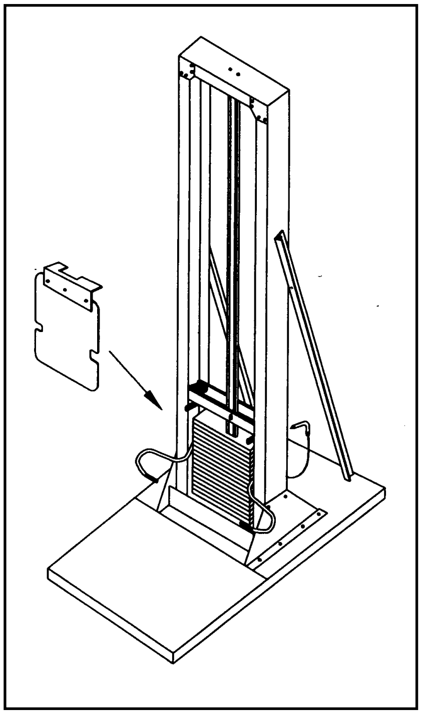


Figure 4—Incremental Weight Lift Machine. The barrier has been removed to expose the stack of weights. (Reprinted from **McDaniel, J.W., R.J. Shandis, and S.W. Madole:** *Weight Lifting Capabilities of Air Force Basic Trainees* (AFAMRL–TR–83–0001). Dayton, Ohio: Wright–Patterson AFBDH, Air Force Aerospace Medical Research Laboratory, 1983.)

Published Data

We describe two primary maximal isoinertial strength test procedures in this section. One involves the use of a modified weight-lifting machine with which the subject lifts a rack of hidden weights to prescribed heights, as depicted in Figure 4.(5) Kroemer(1) refers to his technique as LIFTEST, and the Air Force protocol has been named the Strength Aptitude Test (SAT). The other test uses a lifting box, into which weights are placed incrementally at specified times until the lifting limit is reached.(10) The bulk of the isoinertial testing literature deals with the former procedure.

The LIFTEST/Strength Aptitude Test (SAT) Techniques

The LIFTEST and SAT procedures are isoinertial techniques of strength testing that attempt to establish the maximal amount of weight a person can safely lift.(1) 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 overhead reach height). The amount of weight to be lifted is at first relatively light, but the mass is continually increased in succeeding tests until it reaches the maximal amount that the subject voluntarily indicates he or she can handle. This technique has been used extensively by the U.S. Air Force(5) and is applicable to dynamic lifting tasks in industry as well.(1,11)

Since a constant mass is lifted in LIFTEST, the acceleration of the load during a test depends on the force applied to the load during the test (in accordance with Newton's second law: $F = ma$). The dynamic nature of this procedure, the fact that a constant mass is being lifted, and the subject's freedom to choose the preferred lifting technique, all make the LIFTEST generally similar to certain types of industrial lifting tasks. A unique aspect of the LIFTEST technique is that it is the only strength measurement procedure discussed in this document in which results are based on the success or failure to perform a prescribed criterion task. The criterion tasks studied have typically included lifting to shoulder height,(3,5,11,12) elbow height,(5,11) or knuckle height.(3,11) The USAF also developed a muscular endurance test using an incremental lift machine (ILM).(5)

The LIFTEST shoulder height maximal strength test has demonstrated the highest correlation with manual materials-handling activities.(11) It has been subjected to a biomechanical analysis by Stevenson et al.,(13) who demonstrated that this criterion task could be divided into three distinct phases: (1) a powerful upward pulling phase, during which maximal acceleration, velocity, and power values are observed; (2) a wrist changeover maneuver (at approximately elbow height), which requires momentum to compensate for low force and acceleration; and (3) a pushing phase (at or above chest height), characterized by a secondary (lower) maximal force and acceleration profile.

The analysis by Stevenson(13) suggests that successful performance of the criterion shoulder height lift requires a technique quite different from the slow, smooth lifting usually recommended for submaximal lifting tasks. On the contrary, lifting a maximal load requires a rapid and powerful lifting motion. This is largely because of the need to develop sufficient momentum to complete the wrist changeover portion of the lift successfully. Most lift failures occur during the wrist changeover procedure, probably because of poor mechanical advantage of the upper limb to apply force to the load at this point in the lift.(13)

Stevenson et al.(13) found that certain anatomical landmarks were associated with maximal force, velocity, and power readings (Figure 5). Maximal force readings were found to occur at mid-thigh and maximal velocity at chest height, minimum force was recorded at head height, and the second maximal acceleration (pushing phase) was observed at 113% of the subject's stature.

The Strength Aptitude Test(5)

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.(14) The SAT is given to all Air Force recruits as part of their preinduction examinations. Results of the SAT are used to determine whether the individual tested possesses the minimum strength criterion 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 percentage 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. Before the

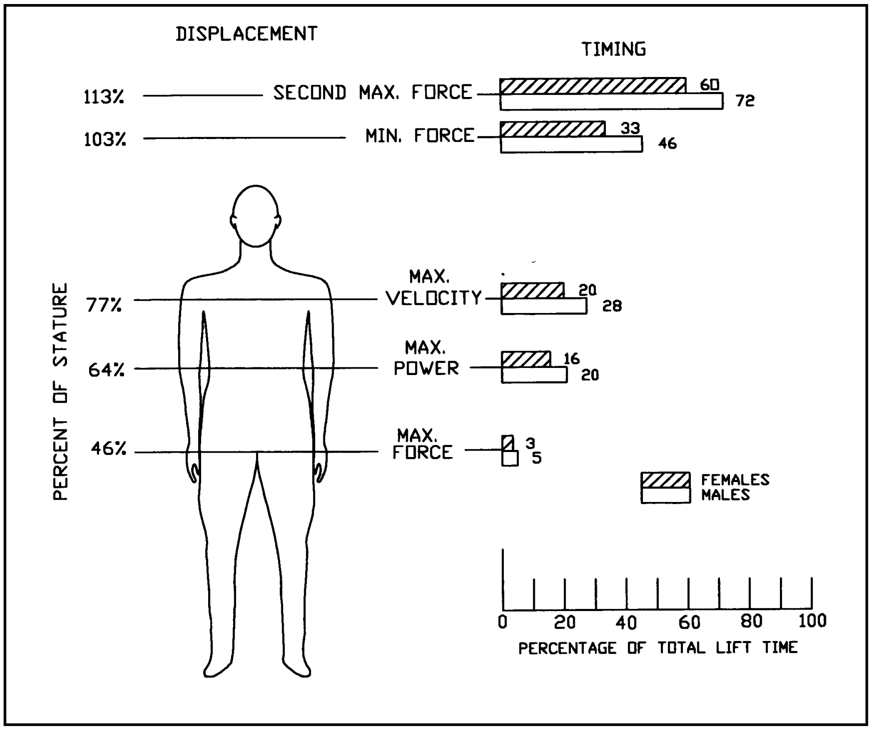
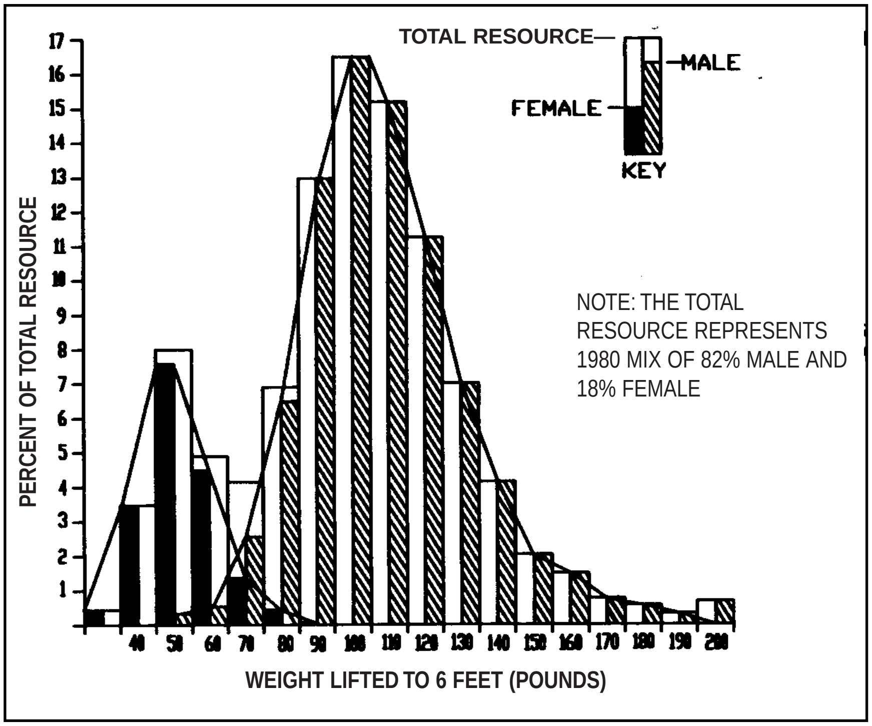


***Figure 5**—Displacement and timing parameters for a 1.83 m maximal isoinertial lift. Figure illustrates anatomical landmarks for the location of key events, found to be consistent for both genders.* (From **Stevenson, J.M., et al.:** Dynamic Analysis of Isoinertial Lifting Technique, *Ergonomics 33(2):*161–172 (1990). Reprinted with permission of Taylor and Francis Ltd.)

physical demands of the AFS are averaged, the actual weights of objects handled are converted into equivalent performance measures on the incremental weight lift test using regression equations developed over years of testing. These relationships consider the type of task (lifting, carrying, pushing, etc.), the size and weight of the object handled, as well as 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 to update the SAT.

The first major report describing this classification tool was a study of 1671 basic trainees (1066 males and 605 females).(5) The incremental weight lift tests started with an 18.1 kg weight, which was to be raised to 1.83 m or more above the floor. This initial weight was increased in 4.5-kg increments until subjects were unable to raise the weight to 1.83 m. Maximal weight lift to elbow height was then tested as a continuation of the incremental weight lift test. In the test of lifting the weight to 1.83 m, males averaged 51.8 kg (±10.5 SD), while females averaged 25.8 kg (±5.3). The respective weights lifted to elbow height were 58.6 kg (±11.2) and 30.7 kg (±6.3). Figure 6 shows the distributions of weight-lifting capabilities for both male and female basic trainees in lifts to 6 feet. Results of the elbow height lift are presented in Table I.



NOTE: THE TOTAL RESOURCE REPRESENTS 1980 MIX OF 82% MALE AND 18% FEMALE

Figure 6*—Distribution of weight lifted in a 1.83 m maximal isoinertial lift for male and female United States Air Force recruits.* (Reprinted from **McDaniel, J.W., R.J. Shandis, and S.W. Madole:** *Weight Lifting Capabilities of Air Force Basic Trainees* (AFAMRL–TR–83–0001). Dayton, Ohio: Wright–Patterson AFBDH, Air Force Aerospace Medical Research Laboratory, 1983.)

Table I

Weight Lifted by Male and Female U.S. Air Force Recruits Using Maximal Isoinertial Lift to Elbow Height.(5)

	Males		Females	
Percentile	Pounds	Kilograms	Pounds	Kilograms
1	80	36.3	40	18.1
5	93	42.2	48	21.8
10	100	45.4	52	23.6
20	109	49.5	58	26.3
30	116	52.6	61	27.7
40	122	55.4	65	29.5
50	127	57.6	68	30.9
60	133	60.3	71	32.2
70	140	63.5	75	34.0
80	150	68.1	78	35.4
90	160	72.6	85	38.6
95	171	77.6	90	40.8
99	197	89.4	100	45.4
Mean	129	58.6	68	30.7
S.D.	25	11.2	14	6.3
Minimum	50	22.7	<40	<18.1
Maximum	>200	>90.7	100	49.9
Number	1066		605	

McDaniel et al.(5) also performed a test of isoinertial endurance. This involved holding a 31.8-kg weight at elbow height for the duration the subject could perform the task. Male basic trainees were able to hold the weight for an average of 53.3 seconds (±22.11), while female basic trainees managed to hold the weight an average of 10.3 seconds (±10.5).

When developing the SAT, the Air Force examined more than 60 candidate tests in an extensive, 4-year research program and found the incremental weight lift to 1.83 m to be the single best test of overall dynamic strength capability that was both safe and reliable.(14) This finding was confirmed by an independent study funded by the U.S. Army.(15) This study compared the SAT to a battery of tests developed by the Army (including isometric and dynamic tests), and then compared these with representative heavy-demand tasks performed within the Army. Results showed the SAT to be superior to all other tests in predicting performance on the criterion tasks.

Virginia Tech Data

Kroemer(1,3) described results of a study using an apparatus similar to the one used by the U.S. Air Force. The sample consisted of 39 subjects (25 male) recruited from a university student population. The procedures were similar to those of McDaniel et al.,(5) except that the minimum starting weight was 11.4 kg and maximal lifting limits were established to prevent overexertion. These were 77.1 kg for floor to knuckle height tests, and 45.4 kg for floor to overhead reach tests. The following procedure was used to establish the maximal load: if the initial 11.4 kg weight was successfully lifted, the weight was doubled to 22.7 kg. Additional 11.4-kg increments were added until an attempt failed or the maximal lifting limit was reached. If an attempt failed, the load was reduced by 6.8 kg. If this test weight was lifted, 4.5 kg was added; if not, 2.3 kg was subtracted. This scheme allowed quick determination of the maximal load the subject could lift.

In Kroemer's study, 6 of 25 male subjects exceeded the cut-off load of 100 pounds in overhead reach lifts.(1,3) All 14 females stayed below this limit. The 19 remaining male subjects lifted an average of 27 kg. The female subjects lifted an average of 16 kg. In lifts to knuckle height, 17 of the 25 male (but none of the female) subjects exceeded the 77.1 kg cut-off limit. The remaining subjects lifted an average of about 54 kg, with males averaging 62 kg and females 49 kg. The coefficients of variation for all tests were less than 8%. Summary data for this study are given in Table II.

Table II

Results of Maximal Isoinertial Strength Tests for 25 Male and 14 Female University Students.(2)

	All				Male				Female			
	Mean	SD	CV	N	Mean	SD	CV	N	Mean	SD	CV	N
Overhead Liftest (kg)	27.0	10.3	3.5%	33	34.8	5.2	3.2%	19	16.3	3.7	3.9%	14
Lift >45.5 kg	—	—	—	6	—	—	—	6	—	—	—	0
Knuckle Liftest (kg)	53.9	13.4	6.9%	22	62.2	7.8	5.2%	8	49.1	13.7	7.8%	14
Lift > 77 kg	—	—	—	17	—	—	—	17	—	—	—	0

The Progressive Isoinertial Lifting Evaluation (PILE)

Another variety of MIST has been described by Mayer et al.(10,16) Instead of using a weight rack, as shown in Figure 4, the Progressive Isoinertial Lifting Evaluation (PILE) is performed using a lifting box with handles; weight is increased in the box as it is lifted and lowered. Subjects perform two isoinertial lifting/lowering tests: one from floor to 30 in. (lumbar) and one from 30 to 54 in. (cervical). Unlike the isoinertial procedures described earlier, this test has three possible criteria for termination: (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%–60% of his or her body weight. Thus, in contrast with the previous tests, the PILE test is terminated as a result of cardiovascular factors rather than when an acceptable load limit is reached.

Since the PILE was developed as a means of evaluating the degree to which functional capacity has been restored in individuals complaining of chronic low back pain (LBP), the initial weight lifted by subjects using this procedure is somewhat lower than in the previous tests. The initial starting weight is 3.6 kg for women and 5.9 kg for men. Weight is increased upwards 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 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.

Mayer et al.(10) developed a normative database for the PILE, consisting of 61 males and 31 females. Both total work (TW) and force in pounds (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 as the ideal weight in overweight individuals. This was done to prevent skewing the normalization in overweight individuals. Table III presents the normative database for the PILE.

Table III

Normative Database for the Progressive Isoinertial Lifting Evaluation.(10)

	Males (n = 61)				
	AW	LW/AW	LTW/AW	CERF/AW	CERTW/AW
Means	161.3	.50	22.8	.40	12.3
Standard Deviations	19.6	.10	7.8	.10	5.1
Standard Error of the Mean	2.51	.01	1.0	.01	.81
	Females (n = 31)				
Means	121.6	.35	17.04	.25	7.32
Standard Deviations	10.65	.07	7.0	.04	2.4
Standard Error of the Mean	1.98	.01	1.3	.01	.56

L = lumbar; CER = cervical; TW = total work in feet–pounds; AW = adjusted weight in pounds; F = final force in pounds.

Evaluation According to Physical Assessment Criteria

Is Isoinertial Strength Testing Safe to Administer?

The MIST procedures described here appear to have been remarkably free of injury. Isoinertial procedures have now been performed many thousands of times without report of verifiable injury. However, reports of transitory muscle soreness have been noted.(10) The temporary muscle soreness associated with isoinertial testing has been similar to that experienced in isokinetic tests but has been reported less frequently than in isometric strength tests.

The following list summarizes the recommendations made by McDaniel et al.(5) for designing safe isoinertial weight lift testing procedures:

1. Weight-lifting equipment should be designed so that the weights and handle move only in a vertical direction.
2. Sturdy shoes should be worn, or the subject may be tested barefoot. Encumbering clothing should not be worn during the test.
3. The initial weight lifted should be low — 20 to 40 pounds. Weights in this range are within the capability of almost everyone. Weight increments should be small.
4. The upper limit should not exceed the largest job-related requirement or 160 pounds, whichever is less.
5. The starting handle position should be 1 to 2 feet above the standing surface. If the handle is lower, the knees may cause obstruction. If the handle is too high, the subject will squat to get his or her shoulders under it before lifting. A gap between the handles allows them to pass outside the subject's knees during lifting, allowing a more erect back and encouraging the use of leg strength.
6. The recommended body orientation before lifting should be (a) arms straight at the elbow, (b) knees bent to keep the trunk as erect as possible, and (c) head aligned with the trunk. The lift should be performed smoothly, without jerk.
7. A medical history of the subject should be obtained. If suspicious physical conditions are identified, a full physical examination should be performed prior to testing. Subjects over 50 years of age or pregnant should always have a physical before testing.
8. All sources of overmotivation should be minimized. Testing should be done in private and results kept confidential. Even the test subject should not be informed until the testing is completed.
9. If the subject pauses during a lift, the strength limit has been reached, and the test should be terminated. Multiple attempts at any single weight level should not be allowed.
10. The testing should always be voluntary. The subject should be allowed to stop the test at any time. The subject should not be informed of the criteria prior to or during the test.

It is noteworthy that, as of 1994, more than 2 million subjects have been tested on the SAT without any back injury or overexertion injury. (14)

Does Isoinertial Strength Testing Give Reliable, Quantitative Values?

Kroemer et al.(3) reported LIFTEST coefficients of variation (measures of intra-individual variability in repeated exertions) of 3.5 for all subjects in overhead lifts, and 6.9 in lifts to knuckle height. The same study showed somewhat higher variability in tests of isometric strength (coefficient of variations ranging from 11.6 to 15.4). Test-retest reliability was not reported by McDaniel et al.(5) Mayer et al.(10) reported correlation coefficients of a reproducibility study of the PILE that demonstrated good test-retest reliability for both floor to 30 in. lifts ($r = .87$, $p < .001$) and 30 to 54 in. lifts ($r = .93$, $p < .001$). Thus, the reliability of isoinertial procedures appears to compare favorably with that demonstrated by other strength assessment techniques.

Is Isoinertial Strength Testing Practical?

Isoinertial techniques generally appear practical in terms of providing a test procedure that requires minimal administration time and minimal time for instruction and learning. Even in a worst case scenario, the isoinertial procedures used by Kroemer(2) would take only a few minutes to determine the maximal weight-lifting capability of the subject for a particular condition. The McDaniel et al. (5,14) procedure can be performed in approximately three to five minutes. The PILE test administration time is reported to last on the order of five minutes. (10)

Practicality is determined in part by cost of the equipment required — and the cost of isoinertial techniques is quite modest. In fact, the PILE test requires no more hardware than a lifting box, some sturdy shelves, and some weight. The equipment needed to develop the LIFTEST devices used by McDaniel et al.(5) and Kroemer (1-3) are slightly more expensive, but are not prohibitive for most applications. In fact, Kroemer (2) states that the device is easily dismantled and transported to different sites in a small truck or station wagon, or perhaps in a mobile laboratory vehicle.

Is Isoinertial Strength Testing Related to Specific Job Requirements?

Since industrial lifting tasks are performed dynamically, isoinertial strength tests do appear to provide some useful information related to an individual's ability to cope with the dynamic demands of industrial lifting. McDaniel (14) has reported that these tests are predictive of performance on a wide range of dynamic tasks, including asymmetric tasks, carrying, and pushing tasks. Furthermore, Jiang et al.(11) demonstrated that the isoinertial lifting test to six feet was more highly correlated with psychophysical tests of lifting capacity than isometric techniques. The PILE test possesses good content validity for industrial lifting tasks, as subjects are able to use a more "natural" lifting technique when handling the lifting box.

Does Isoinertial Strength Testing Predict Risk of Future Injury or Illness?

The ability of a strength test to predict risk of future injury or illness depends on performance of prospective epidemiological studies. As of this writing, no such studies have been conducted on the isoinertial techniques described here.

Summary

Isoinertial strength tests are defined as those in which *mass properties of an object are held constant*, as in lifting a given weight over a predetermined distance. Several types of strength tests fit this rather broad definition, including the classic psychophysical technique. However, several distinctions can be made between psychophysical strength assessments and other isoinertial procedures. Maximal Isoinertial Strength Tests (MIST) are typically characterized as techniques designed to quickly establish an individual's maximal strength through a systematic adjustment of weight by the experimenter. Psychophysical strength assessments typically are designed to establish an acceptable (not maximal) workload over a relatively longer duration, with the subject being allowed to freely adjust the weight. Isoinertial techniques have typically been used as a worker selection tool, whereas psychophysical tests are most often used for ergonomic job design.

Two primary MIST assessment techniques have been established. One involves use of a modified weight lifting device with which the subject lifts a rack of weights to a prescribed height (the LIFTEST technique). The other test uses a lifting box, into which weights are placed at specified times until the lifting limit is achieved (the Progressive Isoinertial Lifting Evaluation or PILE). Both types of MIST have been shown to be safe, reliable, and practical methods of strength assessment. None of the MIST techniques discussed in this section have demonstrated the ability to predict risk of future injury or illness.

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4. Psychophysical Strength

Theory and Description of the Psychophysical Methodology

According to contemporary psychophysical theory, the relationship between the strength of a perceived sensation (S) and the intensity of a physical stimulus (I) is best expressed by a power relationship.(1)

$$S = kI^{n} \tag{1}$$

This psychophysical principle has been applied to many practical problems, including the development of scales or guidelines for effective temperature, loudness, brightness, and ratings of perceived exertion. Based on the results of a number of experiments using a variety of scaling methods and a number of different muscle groups, the pooled estimate of the exponent for muscular effort and force is 1.7.(2)

When applying this principle to work situations, it is assumed that individuals are capable and willing to consistently identify a specified level of perceived sensation (S). For manual materials handling tasks, this specified level is usually the *maximum acceptable weight* or *maximum acceptable force.* These phrases are defined by the instructions given to the test subject:(3)

> *You are to work on an incentive basis, working as hard as you can without straining yourself, or becoming unusually tired, weakened, overheated, or out of breath.*

If the task involves *lifting,* the experiment measures the maximum acceptable weight of lift. Similarly, there are maximum acceptable weights for *lowering* and *carrying.* Such tests are isoinertial in nature; however, in contrast to the tests described in Chapter 3, they are typically used to test submaximal, repetitive handling capabilities. Data are also available for *pushing* and *pulling.* These are reported as maximum acceptable forces and include data for initial as well as sustained pulling or pushing.

Why Use Psychophysical Methods?

Snook identified several advantages and disadvantages to using psychophysical methods for determining maximum acceptable weights.(4) The advantages include:

- Realistic simulation of industrial work (face validity);
- Ability to study intermittent tasks (physiological steady state not required);
- Results are consistent with the industrial engineering concept of “a fair day’s work for a fair day’s pay”;
- Results are reproducible; and
- Results appear to be related to low-back pain (content validity).

Disadvantages include:

- Tests are performed in a laboratory;
- It is a subjective method that relies on self-reporting by the subject;
- Results for very high frequency tasks may exceed recommendations for energy expenditure; and
- Results are insensitive to bending and twisting.

Liberty Mutual preferred to use the data derived from these studies to design a job to fit the worker since this application represented a more permanent, engineering solution to the problem of low-back pain in industry.(5) This approach not only reduces the worker's exposure to potential low-back pain risk factors, but also reduces liability associated with worker selection.(5)

Published Data

Liberty Mutual

Snook and Ciriello at the Liberty Mutual Insurance Company have published the most comprehensive tables for this type of strength assessment.(6) The most recent data are summarized in nine tables, organized as follows:(6)

1. Maximum acceptable weight of lifting for males.
2. Maximum acceptable weight of lifting for females.
3. Maximum acceptable weight of lowering for males.
4. Maximum acceptable weight of lowering for females.
5. Maximum acceptable forces of pushing for males (initial and sustained).
6. Maximum acceptable forces of pushing for females (initial and sustained).
7. Maximum acceptable forces of pulling for males (initial and sustained).
8. Maximum acceptable forces of pulling for females (initial and sustained).
9. Maximum acceptable weight of carrying (males and females).

Other Sources

Ayoub et al.(7) and Mital(8) have also published tables for maximum acceptable weights of lift. Even though their tables are similar in format and generally in agreement with those from Liberty Mutual, there are some differences. Possible sources for these differences may be differences in test protocol, differences in task variables, and differences in subject populations and their characteristics.

Experimental Procedures and Methods

For the sake of simplicity and convenience, the Liberty Mutual protocol for lifting or lowering and an excerpt from the lifting table will be used as examples for this section. The protocols used by Ayoub et al.(7) and Mital(8) were similar, but not exactly the same. The reader should refer to the original publications for details.

The Liberty Mutual experimental procedures and methods were succinctly reviewed in their most recent revision of the tables.(6) The data reported in these revised tables reflect results from 119 second-shift workers from local industry (68 males, 51 females). All were prescreened to ensure good health prior to participation. These subjects were employed by Liberty Mutual for the duration of the project (usually 10 weeks). All received 4 to 5 days of conditioning and training prior to participation in actual test sessions.

Test subjects wore standardized clothing and shoes. The experiments were performed in an environmental chamber maintained at 21°C (dry bulb) and 45% relative humidity. Forty-one anthropometric variables were recorded for each subject, including several isometric strengths and aerobic capacity.

A single test session lasted approximately 4 hours and consisted of five tasks. Each task session lasted 40 minutes, followed by 10 minutes rest. Most subjects participated in at least two test sessions per week for 10 weeks. In general, a subject's heart rate and oxygen consumption were monitored during the sessions.

Lifting or Lowering Tasks

In a lifting or lowering task session, the subject was given control of one variable, usually the weight of the box. The other task variables would be specified by the experimental protocol. These variables include:

1. *Lifting zone* — whether the lift occurs between floor level to knuckle height (low), knuckle height to shoulder height (center), or shoulder height to arm reach (high).
2. *Vertical distance of lift* — the vertical height of the lift within one of these lifting zones. The specified values for distance of lift in the tables are 25 cm. (10 in.), 51 cm. (20 in.), and 76 cm. (30 in.). It is possible to use linear extrapolation for lift distances not exactly equal to one of these values.
3. *Box width* — the dimension of the box away from the body. The three values of box width are 34 cm. (13.4 in.), 49 cm. (19.3 in.), and 75 cm. (29.5 in.). It is possible to use linear extrapolation between these values.
4. *Frequency of lift* — expressed as one lift per time interval, including intervals of 5 seconds, 9 seconds, 14 seconds, 1 minute, 2 minutes, 5 minutes, and 8 hours.

These definitions apply to a lowering task, except the word "lower" is substituted for "lift." The test protocol for lowering was essentially identical to that for lifting, and the results are reported in a similar format. It should be noted, however, that the test protocols for lifting and lowering involved using a special apparatus that returned the box to its original specified location, so that the subject *only* lifted or lowered, not both.

The subject was instructed to adjust the weight of the box, according to his or her own perceptions of effort or fatigue, by adding or removing steel shot or welding rods from a box. The box had handles and a false bottom to eliminate visual cues. Each task experiment was broken into two segments so that the initial weight of the box could be randomly varied between high versus low so that the subject approached his or her maximum acceptable weight from above as well as below. If the results met a 15% test–retest criterion, the reported result was the average of these two values. If the results did not meet this criterion, they were discarded and the test repeated at a later time.

In reporting the results, it was assumed that the gender-specific maximum acceptable weights for a particular task were normally distributed. As a consequence, the results were reported as percentages of population, stratified by gender. The Liberty Mutual tables are organized around the following percentages: 90%, 75%, 50%, 25%, and 10%.(6) The 90th percentile refers to a value of weight that 90% of individuals of that gender would consider a maximum acceptable weight (90% "acceptable"), while the 10th percentile refers to a value of weight that only 10% of individuals of that gender would find acceptable (10% "acceptable").

Important Caveats

Snook and Ciriello have identified several important caveats that should be remembered when using the Liberty Mutual tables.(6)

1. The data for each experimental situation were assumed to be normally distributed when the maximum acceptable weights and forces acceptable to 10%, 25%, 50%, 75%, and 90% of the industrial population were determined.
2. Not all values in the tables are based on experimental data. Some values were derived by assuming that the variation noted for a particular variable for one type of task would be similar to that observed for another task, e.g., the effects on lowering would be similar to that on lifting.
3. The tables for lifting, lowering, and carrying are based on boxes with handles that were handled close to the body. They recommend that the values in the tables be reduced by approximately 15% when handling boxes without handles. When handling smaller boxes with extended reaches between knee and shoulder heights, they recommend reducing the values by approximately 50%.
4. Some of the reported weights and forces exceed recommended levels of energy expenditure if performed for 8 or more hours per day. These data are italicized in the tables.
5. The data in the tables give results for individual manual materials handling tasks. When a job involves a combination of these tasks, each component should be analyzed separately, and the component with the lowest percent of capable population represents the maximum acceptable weight or force for the combined task. It should be recognized, however, that the energy expenditure for the combined task will be greater than that for the individual components.

Some recent data suggest that persons performing lifting tasks are relatively insensitive to the perception of high disc compression forces on the spine.(9) As a result, there may be some tasks in the tables that exceed recommended levels of disc compression.

Related Research

Task and Subject Variables

A variety of researchers have examined the effects of other task and subject variables using the psychophysical protocol. Most of these studies involve a small number (<10) of college students as test subjects. Some experiments used the Liberty Mutual protocol; others used the protocol described by Ayoub et al.(7) and Mital.(8) These "refinements" are summarized in Table IV.

Table IV

Miscellaneous Task Variables Evaluated Using the Psychophysical Methodology.

Task Variable(s)	Reference(s)
Zone of lift	5–8, 21–23
Distance of lift	5–8, 21–23
Frequency of lift	5–8, 21–23
Box width	5–8, 21–24
Extended work shifts	8
Combinations of lift, carry, and lower	11, 12
Angle of twist	23
Box length	23, 24
Material density	25
Location of center of gravity	25
Center of gravity relative to preferred hand	25
Sleep deprivation	26
Bag versus box	26
Fullness of bag (same weight)	26
Bag ± handles	26
Day 1 to day 5 of work week	19
Asymmetrical loads	28–30
Asymmetrical lifting	28–31
Emergency scenario	32
Handle position	33
Handle angle	33
Duration of lifting	34, 35
Overreach heights	36
Restricted vs. unrestricted shelf opening clearances	37
Experienced vs. inexperienced workers	38
Nonstandard or restricted postures	20, 39–41

Recommended Applications

Job Evaluation

The Liberty Mutual tables were developed for the purpose of evaluating work, not workers.(10) In particular, the tables are intended to help industry in the evaluation and design of manual materials handling tasks that are consistent with worker limitations and abilities.(6) The explicit goal is the control of low-back pain through reductions in initial episodes, length of disability, and recurrences.(10)

To apply the tables in the context of job evaluation, it is first necessary to specify the task variables of the job. For a lifting task, this includes the lift zone, distance of lift, box width, frequency of lift, and the presence or absence of box handles. In addition, it is necessary to measure the weight of the object to be handled, perhaps using a scale or dynamometer. Once these variables are specified, the measured weight can be compared to the data in the table to determine the percent of capable population for males and females. The procedure is similar for pulling or pushing. The required force can be measured with a dynamometer.

Consider the following example. The task is to lift a 49-cm wide box that weighs 20 kg once every minute between floor level to knuckle height for a distance of 51 cm. In Table V, excerpted from the Liberty Mutual tables, the weight of the box, 20 kg, is exactly equal to the maximum acceptable weight of lift for 75% of males, that is, 75% of males would consider this task "acceptable." By contrast, the highest maximum acceptable weight of lift reported for females is 18 kg. As a result, this task is "not acceptable" to more than 90% of females.

Table V

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).

Job Design

To apply the tables in the context of job design, the process is essentially identical. All task-specific parameters must be identified, except the required weight or force (that is what you are determining). You select a desired percent of capable of population, noting gender effects, then identify the maximum acceptable weight or force that corresponds to that desired percent. This is the value recommended for job design.

As an example, suppose you wish to design a lifting task that requires a 49-cm wide box that must be lifted 51 cm once per minute within the floor-to-knuckle zone. You desire to design this job to accommodate 75% of females. According to the data in Table V, you would recommend that the box weigh no more than 11 kg. This weight would be acceptable to 75% of females and over 90% of males.

Multiple task analysis, consisting of lifting, carrying, and lowering, has also been investigated for the Liberty Mutual data.(11) In this circumstance, it was observed that the maximum acceptable weight for the multiple task was less than that for only the carrying task when performed separately, but not significantly different from the lifting or lowering maximum acceptable weights when performed separately. For this type of a multiple task, the maximum acceptable weight for the task should be the lowest maximum acceptable weight of the lifting or lowering task as if it were performed separately. One should be careful, however, because the energy expenditure for the multiple task is probably underestimated when compared to performing the tasks separately. Similar results were reported by Jiang et al.(12)

Validation

Content Validity

The concept of content validity, also called face validity, addresses whether the content of the test is identical or highly similar to the content of the job. This is one of the major advantages of the psychophysical methodology, but it is important for the user to realize the limitations of the data, especially the caveats noted earlier.

It is noted that a 40-minute test protocol is used to predict an 8-hour maximum acceptable weight or force. The researchers at Liberty Mutual examined this assumption by having subjects select their maximum acceptable weight according to the usual protocol, then having them continue to work, adjusting the weight or force as desired, for a total of 4 hours.(10) No statistically significant difference was found between the values selected after 40 minutes and those selected after 4 hours. Karwowski and Yates reported similar results.(13)

Mital also examined this issue relative to the Ayoub et al. data.(14) Mital found that the test subjects' estimates of their 8-hour maximum acceptable weights of lift were significantly greater than that selected at the end of an actual 8-hour period of work (an average 35% reduction). He "corrected" for this effect in his tables for 8-hour maximum acceptable weights of lift.(8)

Criterion-Related Validity

Criterion-related validity, also called predictive validity, deals with the question of whether the results of the this type of job analysis predict risk of future injury or illness. This is generally demonstrated by the presence of a statistically significant correlation between a test "score" and a particular outcome in an appropriately conducted epidemiological study.

There are two such studies relevant to the criterion-related validity of the psychophysical methodology.

Liberty Mutual Data. In 1978, Snook, Campanelli, and Hart published an investigation of three preventive approaches to low-back injuries in industry.(15) They distributed 200 questionnaires to Liberty Mutual Loss Prevention representatives throughout the United States. These representatives were asked to complete the questionnaire for the most recent compensable back injury. If the specific act or movement associated with the injury were some form of manual handling task, a task evaluation was completed to estimate the percent of capable working population that could perform the task without overexertion, e.g., what percent of the population could perform the task without exceeding their maximum acceptable weight or force.

The investigators received 192 questionnaires, one with incomplete data. They observed that 70% of these 191 low-back injuries were associated with manual materials handling tasks. They also compared the observed number of injuries to an expected number of injuries according to whether the percent capable population was greater than or less than 75%. This analysis is summarized as follows:

	≥ 75% capable	< 75% capable
Observed	98	93
Expected*	145.9	45.1

* The expected values were derived from control data that revealed that 23.6% of jobs involve handling tasks that less than 75% of the population could perform without overexertion.

$$X^2 = 66.6; p < .01$$

Based on these results, the authors concluded:

1. A worker is three times more susceptible to low-back injury if he or she performs a job that less than 75% of the working population can perform without overexertion.
2. At best, the ergonomic approach could reduce low-back injuries associated with manual material handling tasks by 67% by designing the jobs so that percent capable population were 75% or greater. The remaining 33% of back injuries will occur regardless of the job demands.
3. Since only 50% of the industrial back injuries are related to manual materials-handling tasks where the percent capable population is less than 75%, the overall reduction in in low-back injuries would be 33%. This reduction would be higher if the percent capable population were raised to 90%.

Ayoub et al. Data. Ayoub and co-workers proposed the use of a severity index, called the Job Severity Index (JSI), for purposes of validation.(16) The JSI is a ratio of job demands to worker capability. Since a job may consist of multiple tasks, they defined the JSI as a time- and frequency-weighted average of the maximum weight required by each task divided by the task-specific worker capacity. Their validation studies included 101 jobs, performed by 385 males and 68 females, and involved four steps:

1. Selection of candidate jobs.
2. Analysis of candidate jobs in terms of lifting requirements and morbidity data.
3. Determination of the JSI for jobs and operators.
4. Determination of the relationship between JSI and observed morbidity.

Individual JSIs were calculated for each worker that were subsequently grouped in to four categories: $.00 \leq \text{JSI} < .75$; $.75 \leq \text{JSI} < 1.5$; $1.5 \leq \text{JSI} < 2.25$; and $\text{JSI} \geq 2.25$.

The morbidity data were classified into five groups: musculoskeletal injuries to the back; musculoskeletal injuries to other parts of the body; surface-tissue injuries due to impact; other surface-tissue injuries; and miscellaneous injuries. These data were reported as incidence rates per 100 workers per year. Data for severity (days lost) and cost were also collected.

The results revealed that the incidence of back injuries and the incidence of disabling back injuries increased substantially if the JSI was greater than or equal to 1.5. The relationships were nonlinear. The severity for disabling back injuries was increased if the JSI was greater than 2.25. The authors did not report any statistical analyses.

Another aspect of their validation involved classifying jobs according to the percent of capable population. Each job was categorized according to the percentage of the population "overstressed," that is, JSI greater than 1.5. The ranges were: $\% > 75$; $5 < \% \leq 75$, and $\% \leq 5$. They observed that the incidence of back injuries, incidence of disabling injuries, days lost per injury, and total cost increased as the percent of population "overstressed" increased. The authors did not report any statistical analyses.

Both Sets of Data. Another study that examined the predictive validity of the psychophysical methodology was published by Herrin, Jaraiedi, and Anderson.(17) These investigators performed detailed biomechanical and psychophysical evaluations on 55 industrial jobs from five major industries. The psychophysical analyses involved determining the minimum percent of capable population from the Liberty Mutual tables for each individual task (PSY.MIN) as well as an average percent of capable population when the job involved multiple tasks (PSY.AVG). Additional comparison variables included the Job Severity Index (JSI) and Lifting Strength Ratio (LSR). These investigators modified the definition of JSI to represent a frequency- and time-weighted ratio of weights lifted compared to the average task-specific lifting strength of males and females, averaged across all tasks. By contrast, the LSR represented the worst case scenario in that it was the largest single ratio identified among all the tasks.

After the jobs were characterized as described above, injury and illness data for 6912 incumbent workers were monitored for 2 years retrospectively and 1 year prospectively (> 12.6 million man-hours). Morbidity was categorized as contact incidents, musculoskeletal disorders (excluding the back), and back incidents, and expressed as incidence rates (number of incidents per 100 workers per year). Severity data were also examined (lost-time vs. no-lost-time).

The results revealed a significant negative correlation between the minimum percent capable population (PSY.MIN) and all three incidence rates, that is, the incidence rates increased as the percentage capable population decreased. A similar correlation was noted between PSY.MIN and severity. There was no correlation between the average percentage capable population (PSY.AVG) with any incidence rate or severity. The incidence rates for musculoskeletal disorders and back disorders were positively and significantly correlated with the LSR. LSR was also correlated with severity. The JSI only correlated with severity, not incidence.

The authors offered the following conclusions:

1. Overexertion injuries can be related to physical job stresses.
2. Indices representing the extremes of the job requirements (PSY.MIN and LSR) are generally more predictive of risk than indices representing averages (PSY.AVG and JSI).
3. The percentage of capable population for the most stressful aspect of the job, either isometric or psychophysical, is the simplest index of this type.

Evaluation According to Physical Assessment Criteria

Is Psychophysical Strength Testing Safe to Administer?

According to Snook, there was one compensable injury among the 119 industrial worker test subjects.(18) This single episode involved a chest wall strain associated with a high lift. It was also associated with 4 days restricted activity, but no permanent disability.

Does Psychophysical Strength Testing Give Reliable Quantitative Values?

The Liberty Mutual protocol incorporates a criterion for test–retest reliability (maximum difference of 15%). Legg and Myles reported that 34% of their data did not meet this criterion.(19) In contrast, Gallagher and coworkers reported that only 3% of tests in their study had to be repeated because the 15% test–retest criterion was violated.(20) Clearly, the maximum acceptable weights and forces are quantitative.

Is Psychophysical Strength Testing Practical?

There are two major sources of impracticality associated with this type of strength assessment: 1) it is conducted in a laboratory, and 2) the duration of testing is somewhat prolonged compared to other strength assessment methods. It is possible, however, to have the subjects use objects that are actually handled in the workplace. Equipment is not very costly.

Is Psychophysical Strength Testing Related to Specific Job Requirements (Content Validity)?

The content validity of this method of strength assessment is one of its greatest assets. One potential weakness, however, is its insensitivity to bending and twisting.

Does Psychophysical Strength Testing Predict Risk of Future Injury or Illness (Predictive Validity)?

The results of two epidemiological studies suggest that selected indices derived from the psychophysical data are predictive of risk for contact injury, musculoskeletal disorders (excluding the back), and back disorders.(15,16) These indices are correlated to the severity of these injuries. A third study demonstrated predictive value.(17) It should be noted, however, that at high frequencies, test subjects selected weights and forces that often exceeded consensus criteria for acceptable levels of energy expenditure. In addition, test subjects may also select weights and forces that exceed consensus levels of acceptable disc compression.

Summary

The psychophysical methodology, as applied to strength, has been used to determine the maximum acceptable weights and forces associated with manual materials-handling tasks for healthy adult male and female industrial workers. The results of these studies have been published in a series of tables for lifting, lowering, pushing, pulling, and carrying. The data were primarily developed for the assessment of the strength requirements of such tasks relative to the abilities of a population of healthy adult workers. As a result, a job is analyzed by comparing the required weight or force to the percent of capable population. Applied in this manner, the job analysis results correlate with observations of morbidity, especially related to the low back.

This technique was neither developed nor standardized for the purpose of worker selection. At this time, the use of psychophysical methods of strength assessment for predicting capability or future risk of injury, illness, impairment, or disability for an individual has not been validated. In the context of a preemployment evaluation, job-specific psychophysical testing might be considered for testing ability to perform critical job tasks; however, the motivation of the test subject may affect the results. For example, an individual who is highly motivated to demonstrate capability may select a “maximum acceptable weight or force” greater than what would be selected in a different context. In terms of a preplacement evaluation, the issue may be direct threat. At this time, no evidence indicates that this testing can predict risk of future injury for an individual. The assessment of human strength by psychophysical methods therefore has limited application to the assessment of individuals. As Snook and associates state, the available data should rather be used to analyze jobs.(10)

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5. Isokinetic Strength

Theory and Description of Isokinetic Strength Measurement

The concept of isokinetic measurement of strength was originally related by Hislop and Perrine.(1) Characteristics of an isokinetic exertion are constant velocity throughout a predetermined range of motion. Strictly speaking, a means of speed control, and not a load in the usual sense, is applied in isokinetic exertions.(1) However, load and resistance are definitely present in this technique. In this case, the load is a result of the energy absorption process performed by the device to keep the exertion speed constant. The device prevents energy from being dissipated through acceleration in isokinetic exercise. The energy is instead converted into a resistive force, which varies in relation to the efficiency of the skeletal muscle.

Since the speed of motion is held constant in isokinetic exercise, the resistance experienced during a contraction is equivalent to the force applied throughout the range of motion. For this reason, the technique of isokinetic exercise has sometimes been referred to as *accommodating resistance exercise*. This type of 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. It must be understood, however, that while isokinetic devices control the speed of the exertion, this does not assure a constant speed of muscle contraction.

The speed of isokinetic contractions is constant during individual exertions; however, it is also possible to compare muscular performance over a wide range of isokinetic velocities. Increasing the isokinetic speed of contraction will place increasing demands on Type II muscle fibers (fast twitch and fast oxidative glycolytic).

Workplace Assessment

It is clear that isometric strength testing cannot substitute for dynamic strength assessment when examining highly dynamic occupational job demands. As most industrial work tasks contain a significant dynamic component, analysis of isokinetic strength capabilities appears to offer some advantage to isometric testing in this regard. However, it must be recognized that isokinetic devices are not entirely realistic compared with free dynamic lifting in which subjects may use rapid acceleration to gain a weight-lifting advantage.

Most isokinetic devices available on the market focus on quantifying strength about isolated joints or body segments, for example, trunk extension and flexion (see Figure 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 assume, for instance, that isolated trunk extension strength is representative of an individual's ability to perform a lift. In fact, lifting strength may be almost entirely unrelated to trunk muscle strength. 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.

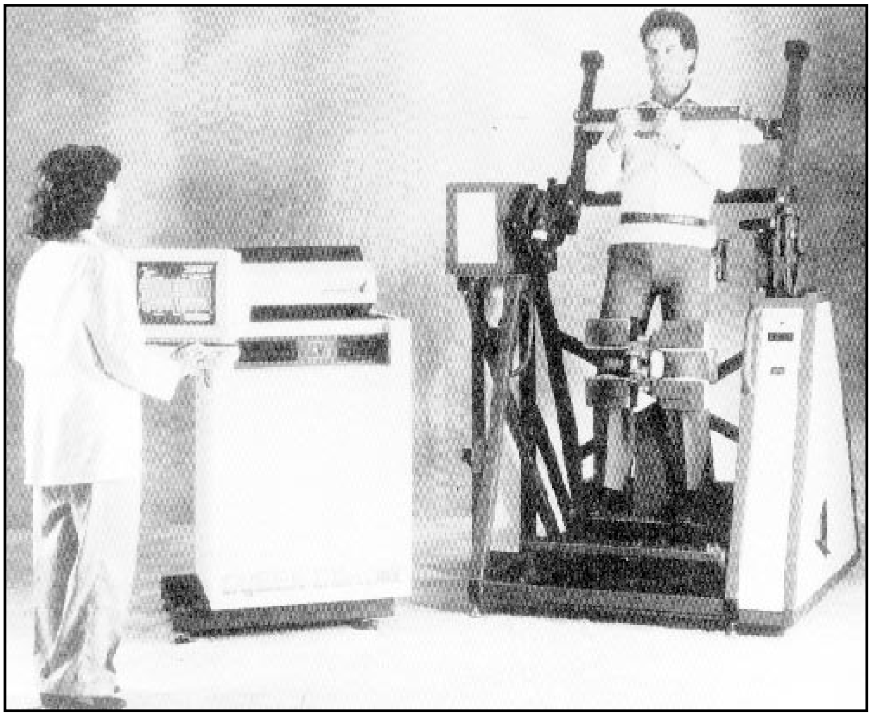

Figure 7*—Many isokinetic devices are designed to evaluate isolated joint muscle strengths. Such devices can be of great benefit in a clinical setting, but may not be as conducive to workplace assessment procedures.* (Cybex Medical, Division of Henley HealthCare, Inc., Sugarland, Texas.) [Photo courtesy of Henley HealthCare.]

Published Data

Several investigators have used dynamic isokinetic lifting devices designed to measure whole-body lifting strength.(2-5) These devices typically consist of a handle connected by a rope to a winch, which rotates at a specified constant velocity when the handle is pulled (Figure 8). The amount of force generated by the subject is thus evaluated over a specified range of motion, and the peak or average force generated during the test is recorded. As detailed below, some investigators have been able to demonstrate that the results of certain isokinetic strength tests (for example, an isokinetic exertion from floor to chest height) appear to be correlated with the amount of weight individuals were willing to lift for infrequently performed tasks.(2)

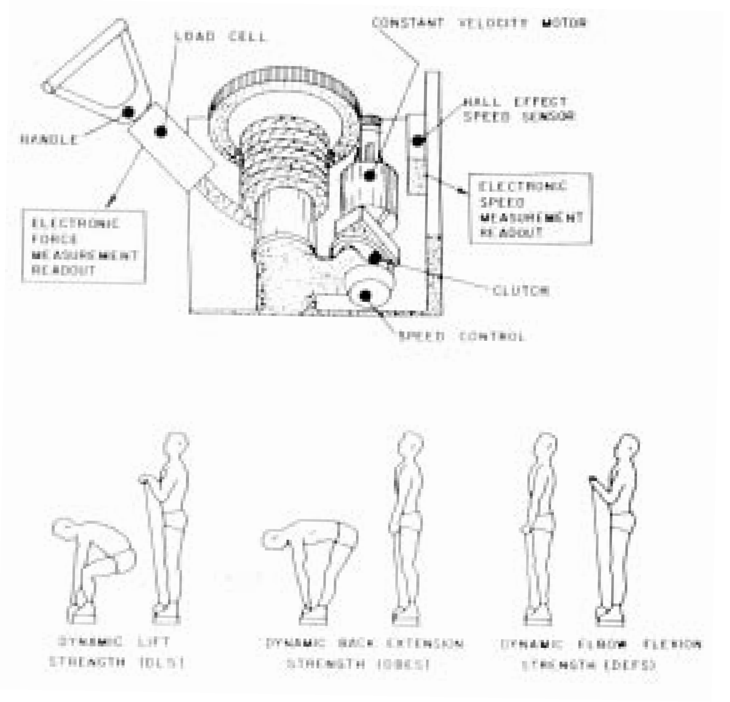

Figure 8*—An isokinetic whole-body strength measurement system. This device allows the experimenter to assess various muscular strengths (such as those shown) at a constant velocity.* (From **Kamon, E., and Pytel, J.L.:** Dynamic Strength Test as a Predictor for Maximal and Acceptable Lifting. *Ergonomics 24(9):663–672* (1981). Reprinted with permission of Taylor and Francis Ltd.)

Pytel and Kamon(2) analyzed various types of isokinetic strength in relation to maximal dynamic lifting capacity in their initial study. These investigators developed three isokinetic strength techniques and compared them to actual lifting capabilities of their subjects, consisting of 10 male and 10 female subjects. Each of the isokinetic exertions were performed at two speeds: .73 meters/second and .97 meters/second. Figure 8 illustrates the three isokinetic exercises evaluated in this study, which were named Dynamic Lift Strength (DLS), Dynamic Back Extension Strength (DBES), and Dynamic Elbow Flexion Strength (DEFS). These were compared with two tests that evaluated actual lifting capacity. The Maximal Dynamic Lift (MDL) was the amount that a subject estimated was the maximum he or she could safely lift from the floor to a level 113 cm above the floor. The Maximal Acceptable Lift was defined as the weight subjects felt they could lift safely at a rate of six lifts per minute for a regular work day.

Results of this investigation are provided in Table VI. The investigators found that the DLS (measured at .73 m/sec), in combination with the gender of the subject, was highly correlated with the MDL selected by the subject (R^2 = .941). Isokinetic tests performed at .97 m/sec did not correlate as well. Strength values obtained at this speed were consistently lower than those obtained at the slower isokinetic velocity, a finding regularly reported in tests of isokinetic strength.

Table VI

Means and Standard Deviations of the Maximal Dynamic Lift (MDL) and Peak Forces for the Dynamic Lift Strength (DLS), Dynamic Back Extension Strength (DBES), and the Dynamic Elbow Flexion Strength (DEFS) Performed at Two Speeds.(2)

Test	Speed (m/sec)	Strength (N)	
		Women (n = 10)	Men (n = 10)
MDL		250 ± 54	544 ± 109
DLS	.73	379 ± 95	601 ± 129
DBES	.73	315 ± 87	540 ± 101
DEFS	.73	167 ± 33	323 ± 55
DLS	.97	260 ± 99	398 ± 113
DBES	.97	210 ± 95	339 ± 102
DEFS	.97	120 ± 38	233 ± 39

Other investigators have taken the same type of device and devised methods of mounting it in different orientations to evaluate isokinetic strength in a variety of orientations.(3,5) Various handles attached to the end of the rope have been used to evaluate tasks such as short distance carrying or pulling in the horizontal, vertical, or transverse planes. The variations described above have been used to measure isokinetic lifting strengths using horizontal exertions at heights of 81 cm and 152 cm in a sample of male and female university students. These subjects were instructed to exert as hard as possible without jerking. Table VII provides data on the isokinetic strength of male and female students in both vertical and horizontal planes.

Table VII

Means and standard deviations for isokinetic strengths (N) of males and females in the vertical and horizontal planes.(5) Isokinetic tests include dynamic lift strength (DLS), dynamic elbow flexion strength (DEFS), and horizontal isokinetic strengths at 81 cm (DS81) and 152 cm (DS152).

Test	Strength	
	Females	Males
DLS	632 ± 251	1083 ± 297
DEFS	269 ± 132	741 ± 327
DS81	223 ± 122	344 ± 93
DS152	312 ± 156	594 ± 172

Evaluation According to Physical Assessment Criteria

Is Isokinetic Strength Testing Safe to Administer?

Given proper procedures and supervision, isokinetic musculoskeletal testing appears to be a reasonably safe method of evaluating muscular strength and endurance. Certain risks associated with use of free weights, weight machines, and other isotonic methods of assessing strength are not present in isokinetic testing. In addition, since the resistance or load experienced by the subject is directly related to the force the subject voluntarily applies, risk of injury due to overloading of the musculature would decrease, because the subject can control his or her own effort. However, it should be noted that some investigators have reported that lower velocity isokinetic exertions may be painful.(6,7)

Certain precautions have been suggested to reduce injury risk in performance of isokinetic musculoskeletal evaluations:

1. Warm-up and stretching of the involved muscle groups.
2. Performance of 5 to 10 submaximal trial repetitions to assess proper alignment, subject comfort, and subject familiarization with the test requirements.
3. Postexercise stretching.
4. Ice/compression/elevation any time postexercise effusion or swelling occurs.

In addition, subjects should wear tennis or running shoes during isokinetic muscle testing when performing standing exertions.

The American Academy of Orthopaedic Surgeons has established guidelines to meet when testing dynamic muscle performance.(8) The following summarize the guidelines developed by the AAOS Human Performance Testing Task Force:

1. Equipment must be determined safe for both the subject and the tester.
2. The reliability and validity of the equipment should be documented.
3. Equipment should be designed to ensure freedom of movement with sub-

ject comfort, and isolation of the motion should be achieved via proper stabilization techniques.

4. Training and education in correct use of the equipment should be available.

Does Isokinetic Strength Testing Give Reliable, Quantitative Values?

Several studies have reported on the reliability of values obtained using isokinetic devices. Results have generally indicated high reliability for isokinetic equipment. In a study examining the isokinetic movement of the knee extensors using a CYBEX II dynamometer, Johnson and Siegel(9) found reliability coefficients ranged from .93–.99. Furthermore, these authors reported that reliability appears to be affected more by testing over days than when comparing different trials performed on the same day. Pipes and Wilmore(10) reported test reliability in isokinetic exertions of a similar magnitude (r = .92–.99) in tests of bench press strength and leg press strength. Moffroid et al.(11) performed a test of reliability for torque measurements at various velocities with a CYBEX device and found that peak torque was reliably measured (r = .999) at velocities ranging from 4 to 12 rpm. Intratest, intertest, and intertester reliability of isokinetic strength measurements were examined in a study quantifying strength in children using a CYBEX dynamometer.(12) The authors concluded that none of these sources of measurement error were a significant source of inaccuracy.

While good reliability for the CYBEX dynamometer has been reported, some authors have expressed concern about a torque “overshoot” artifact that may appear in CYBEX torque measurements.(13) This artifact is evidenced as an initial prominent spike in the torque output curve, which is then followed by a series of progressively diminishing secondary oscillations. The cause of this phenomenon appears to be a result of “overspeeding” of the dynamometer’s input lever during a free acceleration period before its resistance mechanism is engaged. The authors concluded that the prominent initial spikes represent inertial forces and should not be confused with actual muscle tension development. Proper signal damping procedures may suppress this “overshoot”; however, damping should not be used when absolute torque values are required.

Many other isokinetic devices have been developed since the introduction of the CYBEX in 1980. Most of these devices have demonstrated reliability similar to the CYBEX. Klopfer and Greij(6) analyzed the reliability of torque production on the Biodex B-200 at high isokinetic velocities (300 deg/s–450 deg/s) and found that coefficients of correlation ranged from .95–.97, reflecting a high degree of reliability of the test equipment. Other authors reported reliability of between .94 and .99 with the same equipment.(14) A study analyzing the reliability of the Kinetic Communicator (KINCOM) device reported intraclass correlation coefficients of .94–.99.(15) Reliability of the Lido isokinetic system appears somewhat lower than the others reported here, ranging from .83–.94.(16) The reliability of the Mini-Gym (the isokinetic device best suited to analysis of occupational tasks) does not appear to have been reported in the literature.

The foregoing data suggest that isokinetic strength testing equipment generally exhibits a high degree of reliability. However, it should be noted that results obtained using one system may not be comparable to results collected on other systems. Several studies have attempted to compare results between systems, and all have found significant differences. Torque values may vary as much as 10%–15% between different systems.(17,18) These discrepancies indicate that data collected on different devices cannot be compared, and normative data generated on one system cannot be used on other systems.

Is Isokinetic Strength Testing Practical?

Several issues may impact the practicality of using isokinetic devices to examine an individual's muscular capabilities. Not the least of these is the significant cost of purchasing an isokinetic measurement system. Many of the systems discussed in this section cost tens of thousands of dollars, which may render such systems impractical for many applications. Another important issue related to practicality for job-specific strength assessment is the ability of these devices to easily simulate a variety of occupational tasks. Although certain isokinetic devices have been specifically designed to mimic lifting tasks,(2) many are designed simply for quantifying of strength of isolated muscle groups in a clinical setting without regard to accurate simulation of work tasks.

Is Isokinetic Strength Testing Related to Specific Job Requirements?

The answer to this question depends upon the type of isokinetic device and how it is used. As discussed previously, isokinetic machines that test isolated muscle groups do not meet this criterion if the job requires use of many muscle groups or body segments. On the other hand, the Mini-Gym can be used to evaluate the dynamic strength necessary to perform many types of occupational tasks, and results of strength tests using this device appear to be related to lifting capacity, at least under certain conditions.(2) However, many industrial tasks are clearly too complicated to be evaluated using current isokinetic technologies. Great care must be taken to ensure that isokinetic strength measurements are appropriate for analysis of strength requirements associated with specific occupational tasks.

Does Isokinetic Strength Testing Predict Risk of Future Injury or Illness?

A recent prospective epidemiological investigation analyzed whether isokinetic lifting strength could predict who would be at risk of occupational low-back pain.(19) Subjects were required to perform maximal whole-body lifting exertions using an isokinetic linear lift task device, and were then followed for 2 years to evaluate whether this measure of strength predicted who would experience LBP. Results of this study indicated that isokinetic lifting strength was a poor predictor of subsequent LBP or injury. It should be noted, however, that no attempt was made in this study to compare job strength requirements to individual strength capabilities. Whether isokinetic strength tests can be used to predict future LBP when a careful comparison of job demands and individual strength capacity is made has yet to be determined.

Summary

Isokinetic strength assessment is a technique of assessing dynamic muscle function where the velocity of motion is constant. Numerous isokinetic devices are available on the market, most of which focus on quantifying strength about isolated joints or body segments. Devices that perform isolated joint assessment are typically quite expensive and may be well-suited to clinical and rehabilitative use. However, such devices may be limited in their ability to assess occupational demands at the workplace. This is because isolated joint or segment strengths may be unrelated to a person's ability to perform a specified occupational task. For example, the ability to perform a lifting task may be unrelated to isokinetic trunk strength; rather, the ability to perform such a task may be limited by strength capabilities of other muscle groups (such as those of the arms or legs).

A different sort of isokinetic device has been used by some to measure whole-body lifting strength. 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. Good correlations have been reported between isokinetic lifting strength (typically a lift from floor to chest height) and psychophysical lifting results of tasks having similar vertical displacement. However, while validity of whole-body isokinetic strength has been demonstrated for relatively simple lifting tasks, the more complex lifting tasks often seen in industry are not well simulated using current isokinetic apparatus.

Isokinetic muscle testing appears to be a relatively safe and highly reliable technique of assessing dynamic muscle function. The practicality of using isokinetic systems may depend heavily on their substantial cost. The limitations of assessing job-specific strength demands by such systems has been noted above. When assessing isokinetic strength, one must always bear in mind that this mode of contraction is not quite physiologic, that is, isokinetic movements are not used in everyday human motion. The ability of isokinetic muscle testing to predict risk of future injury or illness has not yet been demonstrated. Thus far, prospective studies have shown that generic isokinetic strength tests (like generic static strength tests) do not predict those who might experience low back pain. Whether isokinetic strength tests can be used to predict injury or illness when careful comparisons of job demands and individual strength capabilities are performed has not yet been investigated.

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6. Conclusion

In spite of advances in measurement techniques and an explosive increase in the volume of research, our understanding of human strength remains in its introductory stages. It is clear that muscle strength is a highly complex and variable function that depends on a large number of factors. It is not surprising, therefore, that large differences in strength exist not only between individuals, but even within the same individual tested repeatedly on a given piece of equipment. The issue is compounded by the fact that correlations of strength among different muscle groups in the same individual are generally low, and tests of isometric strength do not necessarily reflect the strength an individual might exhibit in a dynamic test. As a result of these and other influences, great care needs to be exercised in designing, evaluating, reporting, and interpreting muscular strength assessments.

Traditionally, tests of muscular strength were in the domain of the orthopaedist, physical therapist, and exercise physiologist. Such tests are also an important tool for the ergonomist, however, because of the high strength demands on workers in manual materials-handling tasks. In some cases, task demands may approach or even exceed the strength that an individual is voluntarily willing to exert in a test of strength. In such cases, evidence suggests that the likelihood of injury is significantly greater than when the task demands lie well within an individual's strength capacity. Because the relationship among strength capabilities, job demands, and musculoskeletal injury has been established, it is apparent that tests of muscular strength may benefit the ergonomist both in designing jobs and in ensuring that individuals have sufficient strength to safely perform physically demanding jobs. Several strength assessment techniques have been employed for these purposes, each possessing unique characteristics and applicability to job design and worker selection procedures. Our main purpose has been to elucidate these strengths and weaknesses, so that tests of strength may be properly applied in designing jobs and selecting workers.

One of the crucial points we have emphasized is that any test of strength used in job design or worker selection *must be directly related to the demands of the job*.(1) For example, if an occupational lifting task has a high dynamic component, a test of isometric strength is not likely to provide the data necessary for proper design of the job. Of course, dynamic strength tests would also be misapplied in assessing a job requiring isometric exertions. Another potential pitfall is using tests of strength on isolated muscle groups and assuming that they are indicative of whole-body strength. For example, one might mistakenly assume that dynamic trunk extension strength represents a person's capability to perform a lifting task. However, an individual's lifting capacity may be entirely unrelated to trunk extension strength. It may, instead, be limited by an individual's arm or leg strength, depending on the task being performed.

A final point on strength assessment should be made. An individual's strength capability cannot be considered a fixed human attribute. Strength training regimens can increase an individual's strength capability by 30%–40%. Whether such changes have a preventive effect when a person performs heavy physical work has yet to be established in epidemiologic studies; however, some anecdotal evidence supports the possibility.(1)

It should be clear from this publication that muscular strength tests are tools that can be used to prevent occupational musculoskeletal disease. However, if these techniques are to be applied successfully, it is imperative that they be applied with a clear understanding of the advantages and limitations associated with each strength assessment procedure.

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Appendix

Typical Written Instructions for Isometric Strength Testing

“The strength tests you will participate in today will be isometric — that is, there will be no actual movement of the body during the test. Instead, you will be exerting a force against [*here enter the description of the interface between the testee and the testing hardware*]. The attached photographs (sketches) show examples of people doing the tests.”

“The test procedure will be conducted as follows:

1. Each test will be explained to you.
2. Each motion you will be asked to perform will be demonstrated. If there is anything you do not understand, please ask questions.
3. You will be placed into position at the [*interface*].
4. The test motion you are to perform will be demonstrated again.
5. You will try the test motion. If you have an questions about the test motion, please ask questions.
6. You will be given a 1-minute rest.
7. You will perform the first trial of the test.
8. You will be a given a rest of at least 2 minutes.
9. You will perform the second trial of the test. In some cases, you will receive additional 2-minute rests and perform additional test trials.”

“During each test, I will position you for the test. I will tell you to ‘begin when you are ready.’ You can begin your exertion any time after that. While you are performing the test, I will be giving you a slow four count ‘one, two, three, four, relax.’ Do not stop your exertion until I tell you to relax.”

“Do not jerk against the interface. Gradually increase your strength to the maximum you feel comfortable exerting, and then hold that force level until you are asked to relax. It is important for you to maintain your maximum exertion during the entire test. When the relax command is given, you may relax as fast as you want to.”