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 too*l (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]

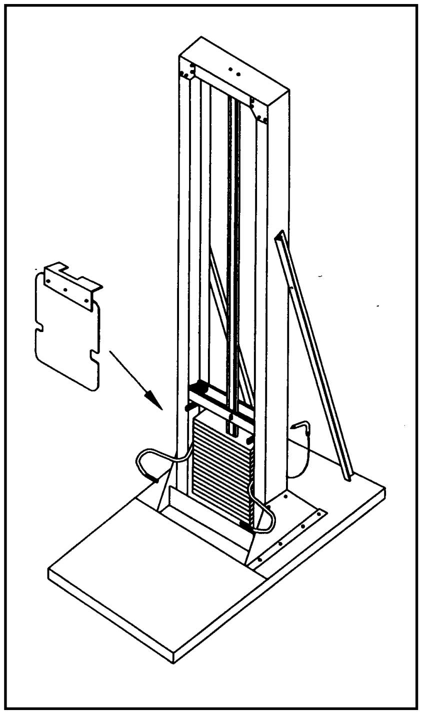

Figure 4*—Incremental Weight Lift Machine. The barrier has been removed to expose the stack of weights.* (Reprinted from **McDaniel, J.W., R.J. Shandis, and S.W. Madole:** *Weight Lifting Capabilities of Air Force Basic Trainees* (AFAMRL–TR–83–0001). Dayton, Ohio: Wright–Patterson AFBDH, Air Force Aerospace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

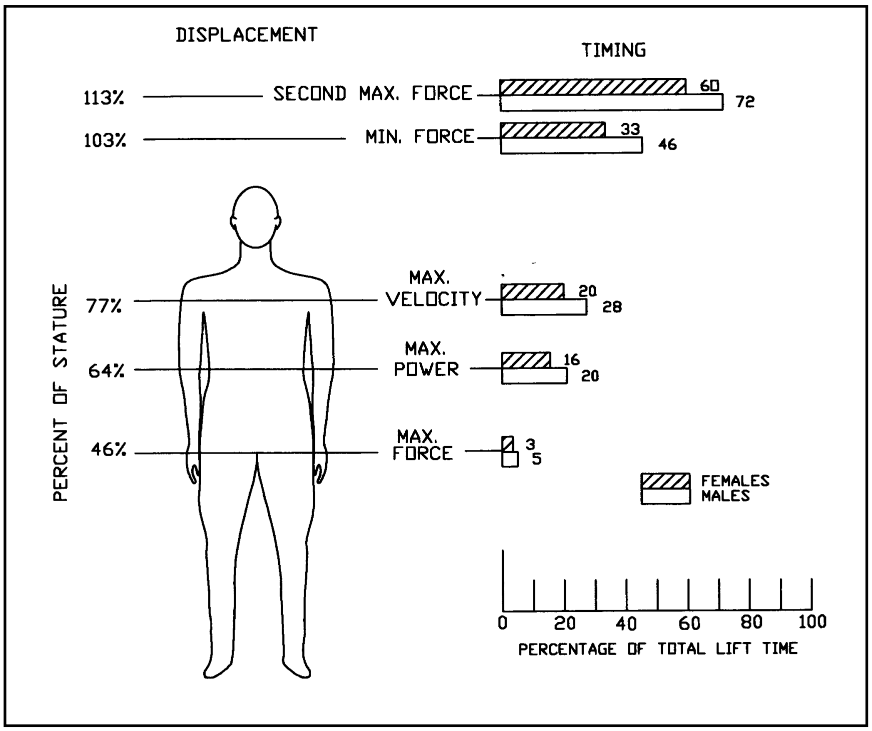

Figure 5*—Displacement and timing parameters for a 1.83 m maximal isoinertial lift. Figure illustrates anatomical landmarks for the location of key events, found to be consistent for both genders.* (From **Stevenson, J.M., et al.:** Dynamic Analysis of Isoinertial Lifting Technique, *Ergonomics 33(2):*161–172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

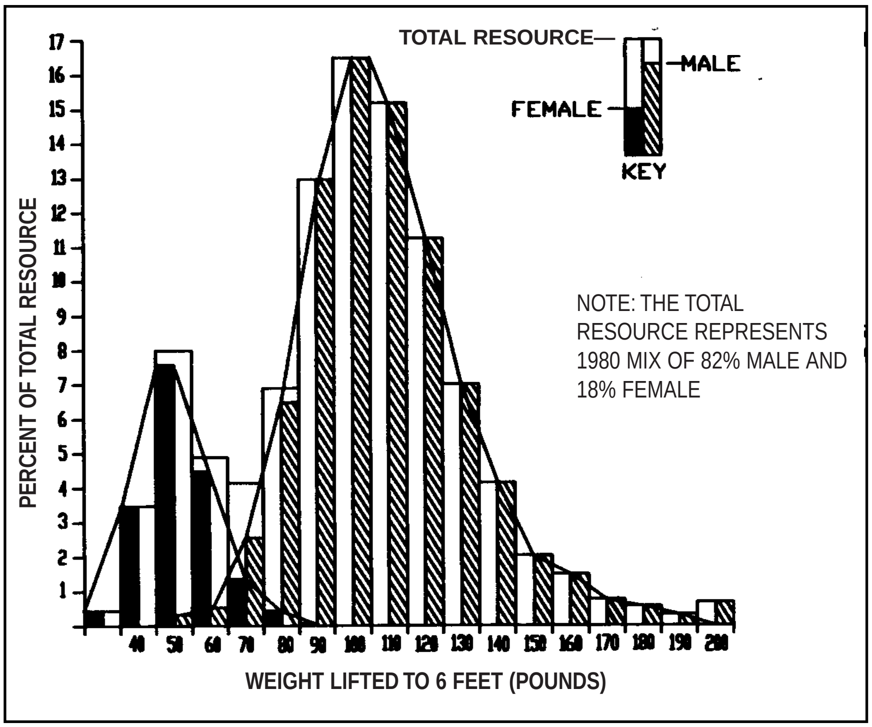

Figure 6*—Distribution of weight lifted in a 1.83 m maximal isoinertial lift for male and female United States Air Force recruits.* (Reprinted from **McDaniel, J.W., R.J. Shandis, and S.W. Madole:** *Weight Lifting Capabilities of Air Force Basic Trainees* (AFAMRL–TR–83–0001). Dayton, Ohio: Wright–Patterson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