Dynamic Measures of Low Back Performance

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Preface

Low back disorders (LBDs) are one of the more common and costly injuries facing society today. However, there are few reliable means to assess quantitatively and realistically the status of the low back or the dynamic motion requirements the workplace imposes on the trunk. This situation has made it difficult to evaluate occupational LBD risk from an ergonomic standpoint, assess worker capability, and measure the degree of back disorder in an injured worker. Recently an abundance of both static and dynamic strength-testing devices have become available for low back assessment, but the measure of trunk motor performance is no simple task. The commercially available devices that measure trunk performance vary greatly in their underlying logic and means of measuring performance. This guide aims to provide scientifically based perspective on the different techniques for measuring musculoskeletal motor performance of the low back. This is accomplished by comparing the objectives of a low back assessment with the information available from the testing technique. The tradeoffs associated with the various techniques and measures are discussed.

Introduction

"Human dynamic musculoskeletal performance," or strength capabilities, has generated much research interest and is of considerable practical importance for ergonomic purposes. The goal of ergonomics is to design the workplace so it accommodates human capabilities. Many researchers have tried to describe more realistically the capabilities of the worker through the use of dynamic strength-testing techniques. Kroemer et al.[1] have discussed in general terms the concepts involved in human dynamic strength testing. This guide will attempt to narrow the focus of these concepts to the low back.

A profusion of strength-testing devices have become available recently for low back assessment. Traditionally, only trunk strength measures were used to determine the status or performance capabilities of the back. In this guide, the topic of back strength testing is expanded to include "human dynamic musculoskeletal performance" or nontraditional measures of trunk performance. Trunk testing has generated much clinical and research interest and is important in many areas (e.g., medicine, rehabilitation, physical education, sports, psychology, physiology, biomechanics, and ergonomics/human factors). These disciplines unfortunately have used different definitions, terms, measurement strategies and exertion techniques in attempting to define back strength. This has led to a sizable amount of information, but most of it is tailored specifically to the areas of interest of the researcher or the user.

Generally, there are two objectives of back testing (referred to in this guide as dynamic motor performance). The first is to understand better the status of the musculoskeletal system; the second is to match task requirements to worker musculoskeletal capabilities (ergonomics).

Isometric Testing

In the early years of trunk testing, strength-testing techniques were limited by technological sophistication. Originally, only isometric trunk strength testing was possible and this remained the case for many years. Isometric or static strength is defined as the maximum force or torque one can produce with a joint (or combination of joints) when the muscle lengths are not permitted to change. Biomechanical principles associated with static trunk loading have been investigated thoroughly and have also become well-established through years of research. Recent technology, however, has advanced so rapidly that few back-testing systems have been well-anchored to underlying musculoskeletal mechanics. Hence, modern back-testing information is piecemeal, incomplete, incompatible, even contradictory.

Isometric strength testing was standardized in 1972. A group of individuals interested in the testing of voluntary muscular strength agreed that the existing disparity and confusion in strength testing warranted standardization. Consensus was that the effort to standardize should be aimed initially at the static (isometric) condition. The result of the group's efforts was a proposal for a standard procedure for static muscle strength testing.[2] This procedure, though limited, has become widely accepted. Beginning with a panel discussion on "human physical strength" at the 1986 Annual Meeting of the Human Factors Society, an effort was started to clarify and define dynamic motor performance ("dynamic strength") and set the stage for proposed standard procedures to measure such dynamic muscle performance.

Dynamic Testing

It has been suggested that dynamic measures of the back are superior to static strength testing. Some researchers argue that static strength testing does not simulate real-life work situations, and that such tests tend to underestimate spine loading during lifting. Concerns also have been voiced about the safety of static strength testing. Others argue that dynamic measuring devices are complex and need to be understood better before these data are used to set limits for manual materials handling.

It is important to recognize that two types of stresses (forces) load the spine. Generally, these forces can be divided into those that are external and those internal to the body. External forces are those applied to the body from the outside, such as the forces acting on the body due to the weight of an object being lifted or the actual weight of the assisting limb. Internal forces are those restorative forces that must be supplied internally within the body to produce movement and counterbalance the external forces. For example, forces supplied by the muscles and ligaments act to supply a counter-moment relative to the spine to the moment created between the spine and the external forces. Usually, the internal forces must act at a biomechanical disadvantage relative to the external forces because of the differences in moment arm length. The internal forces, therefore, usually far exceed the external forces and might easily become excessive. These external and internal forces are transmitted to the spine and the nature of spine loading (compression, shear, and/or torsion) depends on the orientation of the internal loading structures. In spine compression, the internal forces become the primary source of spine loading. Thus, one must understand the implementation of the internal force-producing mechanisms to evaluate the status of the musculoskeletal system.

Some experts believe that this relationship between external and internal forces can be the basis for functional assessments of the trunk musculoskeletal system. Following this logic, if the goal of an evaluation is to determine the status of the musculoskeletal system around the spine or the spine loading itself, it is important to understand the status of the musculoskeletal system (internal forces). Dynamometers often permit one to observe indirectly the functional outcome of synergistic activations of the internal force-producing structures. Most of these back-testing devices have focused on the capabilities and loading on the lumbar spine. Much of the interest in dynamic back activities have been stimulated by research that has reported increased internal back loading under these conditions.

Here are some cases in point:

Garg et al.[3] reported that peak compressive forces at the L5/S1 disc showed moments and forces in the back muscles when lifting weights of approximately 30 kg that were two to three times greater than the moments and forces calculated for static biomechanical simulation. In the same study, it was reported that the peak compressive forces occurred at approximately 0.225 to 0.628 seconds from the beginning of the lift.

Leskinen et al.[4] reported that when lifting a 15-kg box from 10 cm off the floor, the predicted forces on the lumbar spine were 30 to 60 percent higher with the dynamic model. The differences in predicted forces were based on which lifting technique was used. In 1985, McGill and Norman reported a 20 percent greater moment with the dynamic model compared with the static model for lifting an 18-kg load.[5]

Other studies have shown that the dynamic loading is greater than static load by as much as 40 percent.[6] Troup et al.[7] and Bush-Joseph et al.[8] reported differences between the dynamic and static analysis that seem to depend on the acceleration of the load being lifted and the weight of the torso and upper limbs, including the head. These differences are less apparent when loads and lifts are smaller and slower.

To evaluate the dynamic aspects of trunk function, research has been conducted to evaluate trunk motion using the isokinetic test mode.[9-16] Isokinetic testing involves the measurement of force or torque production while motion is permitted under constant velocity conditions. These investigations have shown that trunk musculature and the resultant forces in the spine change dramatically as a function of motion. It also has been shown that the motor recruitment patterns of the trunk muscles change dramatically with changing velocity.[17] The torques generated by the spinal extensors were found to be velocity-dependent by Thorstensson and Nilsson in 1982[18] and Marras et al. in 1984.[19]

This guide aims to provide a scientifically based perspective of different techniques for measuring musculoskeletal motor performance of the back. This will assist in understanding the internal and external aspects of dynamic trunk motor performance.

Elements of Dynamic Motor Performance

In order to appreciate dynamic strength measures better we must first formally define several basic elements of strength testing.

Dynamic Motor Performance: According to Kroemer et al.,[1] "Dynamic Motor Performance is the output of the human muscles attempting to move body segments." A major aspect of that definition is the reference to the dynamic nature of the exertion. Muscles move body segments and often external objects. Per-

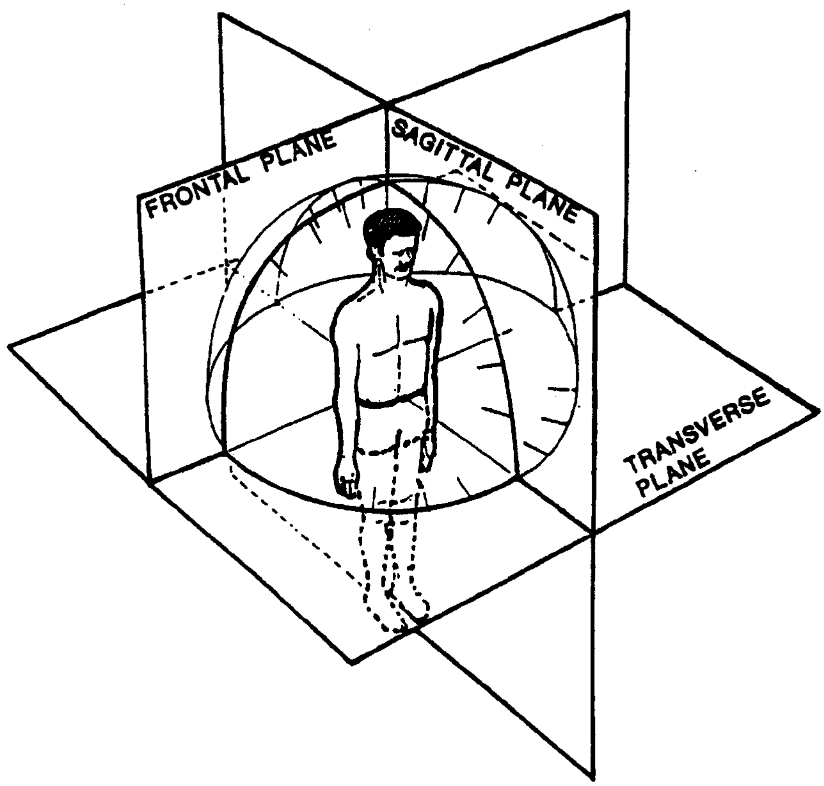

Figure 1. Coordinate system for the back.

formance need not be a maximal effort. The word performance indicates that the human motor activities go beyond the exertion of static force or torque.

Test Positions: Any trunk motion measurement system requires a precise description of the motion. Thus, a taxonomy is necessary to specify exactly the position and motion of body landmarks in three-dimensional space. This position or motion specification should be in such detail that it may be duplicated by someone not familiar with the task without any additional documentation. Furthermore, the taxonomy, if possible, needs to be complete, unambiguous and feasible, and suitable to be computerized.

We recommend that trunk position be specified in terms of the thorax relative to the pelvis in a planar polar coordinate system. Figure 1 shows the position of the trunk relative to such a system. This figure shows that trunk position should be described as the position of the trunk in the sagittal, frontal, and transverse planes. The intersection of these planes is defined at the lumbro-sacral junction. We propose that the position of the thorax at the point of the dynamometer contact or system interface (i.e., point of marker attachment) be described along with the degree or extent of travel encountered in each plane. Also, any motion characteristics (such as angular velocity or angular acceleration profiles—reported as a function of the trunk angles in each plane) should be reported.

In situations in which exertions made on objects outside the body are of interest (when lifting a box, for example) a similar coordinate system may be used. This requires describing the object origin and destination position relative to the axes intersection and may include a description of the positions of the trunk or other body parts during the exertion. The object's motion characteristics (speed and/or acceleration characteristics) also must be included. If the motion of the moved object is linear, this system description becomes very simple.

Experimental Variables in Dynamic Motor Performance: It is necessary to describe completely and correctly the variables present in a back test. They usually are divided into the following groups:

- Independent variables are those that are purposely manipulated to generate the experimental conditions.
- Dependent variables are those that are observed or recorded to provide information about the effects of the manipulations of the independent variables.
- Controlled variables are those that are maintained purposely at defined conditions. They do not interfere with the relationships between independent and dependent variables.
- Confounding variables are those that can, or do, interfere with the relationships between independent and dependent variables.

Examples of typical experimental situations in which one tries to assess trunk dynamic motor performance are listed in Table I. Note that virtually all variables listed are either independent, dependent, controlled, or confounding. Their assignment to variable categories and observation is an essential part of the experimental design and procedure.

Techniques to Assess Dynamic Motor Performance

A variety of techniques exist, or are conceivable, by which one can document back performance. One may manipulate independent variables and observe variations in dependent variables. Current human performance measures can be viewed with isometric strength being at one end of the continuum and free dynamic exertions at the other. Table II lists various possible dynamic human performance measures in relation to the independent and dependent experimental variables. This table shows the variable(s) displacement and its time derivatives (velocity and acceleration), force, mass, and repetition and their assignments either to independent, controlled, or dependent variable categories. Two exam-

Table I. Generic Variables in Motor Performance Measurments.

Independent Variables	Dependent Variables	Controlled Variables	Confounding Variables*
Muscle	Muscle	Individual:	Motivation
Motions:	Motions:	age	Fatigue
displacement	displacement	gender	Health
velocity	velocity	anthropometry	Fitness
acceleration	acceleration	Environment:	Skill
jerk	jerk	temperature	
Mass	Mass	humidity	
Repetition	Repetition	air velocity	
Resistance	Output:	radiation	
Body Posture	force	noise	
	torque	vibration	
	work		
	power		

* should be controlled.

ples: One may assign "displacement" to be either an independent or a dependent variable. Setting displacement to zero generates the isometric testing condition, in which case velocity, etc., also are zero. When resistance is controlled, however, force and/or repetition become the dependent variables. It might help to refer to Table II in the following discussion.

Isometric Assessment

Isometric testing involves a constant length of the muscles involved in the exertion. Thus, the controlled variable displacement is set to zero. The position of the trunk is frozen. Hence, no other motion-related variables (velocity, acceleration, etc.) are possible. The output of this test could be force level or this variable may be fixed, in which case the output either becomes endurance or the number of times a subject can successfully repeat the task. Isometric measurements have been widely used for strength testing.

Isokinetic Assessment

In the isokinetic technique, trunk velocity or object velocity is set to a constant. This means that displacement becomes a controlled variable while the time derivatives of velocity, acceleration, and jerk (the derivative of acceleration) are zero. In terms of the dependent variables, force and torque (or work or power), and the number of repetitions (if not controlled) are possible outputs for this measuring technique. The subject tested often is expected to perform maximal voluntary exertions. This technique has been used increasingly in recent years.

Isoacceleration Assessment

In an isoacceleration test, the trunk or object lifted experiences a constant linear or angular acceleration. The trademark of the test in this case is control of acceleration. Displacement can be controlled in terms of range of motion or it might be a dependent variable, in which case the range of motion would be measured. Velocity also can be controlled or one may simply observe the velocity at which one no longer is able to produce a constant acceleration. If that happens, it would be a dependent variable. Jerk forces would be zero under those conditions. Force and repetition could be either dependent or independent, as with isometric exertions. Commercially available devices have been used to study isoaccelerations of the body.

Isojerk Assessment

The rate of change of acceleration is the jerk. Therefore, an isojerk test would require that the back acceleration constantly increases or decreases. In this case, the relationship between independent and dependent variables would be the same as for isoacceleration except acceleration could be controlled or used as an output. If controlled, the acceleration could be predetermined. If an output, the point at which the acceleration no longer is constant can be used as a dependent measure. We are unaware of any commercial isojerk devices. Considering the pace of technology, however, such a device is feasible.

Isoforce Assessment

In the isoforce technique, muscle force remains constant during the testing time. This usually is achieved by keeping the external load (force, torque) constant. In the past, the isoforce effort was combined with the isometric conditions, as in holding a weight motionless. In that case, any of the motion or displacement measures can be used as dependent measures.

Isoinertial Assessment

The isoinertial technique usually is one that is applied to a situation in which an object is lifted outside the body. In the isoinertial technique, a mass to be moved by a musculoskeletal effort is set to a constant. That means displacement, velocity, acceleration and jerk, force or torque, as well as the number of repetitions can be dependent variables. Derivatives such as acceleration and jerk can be computed.

Free Dynamic Assessment

As shown in Table II, in a free dynamic exertion no variables are controlled other than the mass, moment of inertia, resistance, or repetition. In other words, the subject is allowed to move freely without any restrictions. In that case, any combination of the experimental variables can be considered dependent measures.

Table II. Independent and Dependent Variables in Several Techniques to Measure Motor Performance.

Variables \ Names of Technique	Isometric (Static)	Isokinetic	Isoacceleration	Isojerk	Isoforce	Isoinertial	Free Dynamic
	Indep. Dep.	Indep. Dep.	Indep. Dep.	Indep. Dep.	Indep. Dep.	Indep. Dep.	Indep. Dep.
Displacement, linear/angular	[constant* (zero)]	C or X	C or X	C or X	C or X	C or X	X
Velocity, linear/angular	O	[constant]	C or X	C or X	C or X	C or X	X
Acceleration, linear/angular	O	O	[constant]	C or X	C or X	C or X	X
Jerk, linear/angular	O	O	O	[constant]	C or X	C or X	X
Force, Torque	C or X	C or X	C or X	C or X	[constant]	C or X	X
Mass, Moment of Inertia	C	C	C	C	C	[constant]	C or X
Repetition	C or X	C or X	C or X	C or X	C or X	C or X	C or X

Legend
C = variable can be controlled
* = set to zero

O = variable is not present (zero)
X = can be dependent variable

The [boxed] constant variable provides the descriptive name.

Relationships Between Testing Techniques and Internal Forces

As discussed earlier, both external and internal forces affect musculoskeletal loadings in the body and the ability to perform a task. During back testing, the investigator usually looks for clues to the status or loading of the internal system. The external forces are measured at the human-device interface. Many different measuring devices, both commercial and custom-made are available to measure the interface. These devices are unique to the variables classified in Table II. Some devices measure applied force or torque, some control or measure velocity, and some measure acceleration.

The internal forces surrounding the back are not directly measurable *in vivo* with existing technology. There are, however, several established methods to investigate the status of the internal force production system indirectly. These methods include electromyography (EMG), intra-abdominal pressure (IAP), and intradiscal pressure. Each of these requires some assumptions and can be used under various restricted conditions.

EMG measures the electrical activity of a muscle associated with its contraction. Just before a muscular contraction, a depolarization of the muscle fiber occurs and an electrical signal is generated. This signal can be measured and represents the muscle activity level and under certain circumstances, the force present within the muscle. This signal can be monitored by placing an electrode over or within the muscle and amplifying the signal received at the electrode site. EMG measurement is expensive, time-consuming, and might require invasive procedures.

IAP measurements assess the pressure within the trunk cavity. This technique is not specific in that it does not measure force of any particular internal structure but measures the net result of force production in several unidentified trunk structures. Some researchers also believe that it provides a restorative force to the trunk itself. The relationship between spine loading and IAP, however, is still a topic of considerable controversy. This pressure can be measured either by placing a catheter-transducer into the stomach via the throat or by ingesting a pressure sensitive pill that transmits pressure information to a receiver outside the body. Both of these devices also may be used to measure IAP rectally. This technique is invasive and might restrict motion if a catheter is placed in the stomach via the throat.

Intradiscal pressure measurement does not indicate the action of a particular internal force-generating structure. It measures the net result that many internal force-producing structures have on the spinal discs. This is an invasive procedure that measures the pressure within the disc by inserting a needle transducer into the nucleus of the disc. This technique requires great care and might be dangerous if the needle is not inserted properly. Because of human subject restrictions, it also is a technique that cannot be performed in the United States.

As discussed previously, it is very difficult to assess the status of the trunk's musculoskeletal system using traditional internal measures of internal forces. Many of these techniques are invasive and some are quite time-consuming, which makes them impractical for routine use. Therefore, many have tried to assess the status of the internal system through evaluation of the external force one can produce. Some experts believe that the internal forces within the body combine about a joint to develop external forces outside the body. By comparing the internal and external responses of the body, some researchers have been able to identify normal reactions of the internal force production system to external event changes. The relationships between these internal and external measures can be used as follows:

Under certain controlled conditions, there exists a known relationship (often linear) between muscle force and the rectified and smoothed (processed) EMG signal. The conditions under which these EMG-force relationships hold are those that sample a given portion of the muscle under isometric[20)] or constant velocity also known as isokinetic conditions.[21)] It is important to ensure that a given portion of the muscle is sampled since factors such as the length-strength relationship of the muscle might confound the results. Only under these conditions may one make statements about the relative amount (percentage of voluntary maximum) of force in a muscle. A linear relationship between EMG and back muscle force has been reported by Andersson, Herberts and Ortengren[22)] and Andersson, Ortengren and Herberts.[23)]

IAP may be a measure of internal trunk force or loading within the body that is not associated directly with a particular muscle force but may relate to general back internal forces. There has been much controversy throughout the years about the meaning and source of IAP. Davis[24-26)] found that IAP was related to the moment imposed about the spine and found that the magnitude of the IAP might be related to trunk acceleration and torque production about the spine.

Later quantitative studies[27,28)] showed that under static conditions IAP increased linearly with both trunk flexion angle and increased load. Schultz et al., on the other hand, found weak correlations between IAP and other measures of trunk load.[29)] Under isokinetic trunk velocity conditions, Marras et al.[19,30)] found that IAP decreased as a function of increasing velocity and found that under these conditions IAP was related more to trunk angle than to torque. They stated that IAP was more of a preparatory response to dynamic activity than an indicator of internal force. In summary, the role of IAP during dynamic activities is still under evaluation.

Intradiscal pressure represents a means of evaluating the synergistic contribution of the internal forces specifically in the spine. It is considered by some a semidirect means of evaluating spinal load *in vivo* but one that does not provide much information about the musculoskeletal system status. Nachemson and Morris[31)] used this method to monitor the spinal load as a function of various positions of the spine. Andersson et al.[28)] also investigated intradiscal pressure during sitting. Andersson found a linear relationship between disc pressure and trunk moment

Table III. Relationship Between Techniques to Measure Dynamic Motor Performance and Known Indirect Measures of Internal Force.

Internal Measure \ Technique	Isometric	Isokinetic	Isoaccel	Isojerk	Isoforce	Isoinertial	Free Dynamic
EMG	W	W	X	?	X	?	?
IAP	X	X	?	?	?	?	?
IDP	W	?	?	?	?	?	?

W = well established X = possible relationship ? = unknown

during static positioning of the trunk. However, no definite relationships have been established between this measure and dynamic activities or with activities requiring significant muscular exertions.

The measures that have been discussed and their relationship with various dynamic trunk motor performance measures are summarized in Table III. This table indicates that for the most part the relationship between internal forces and dynamic motor performance measures is well-established only under isometric conditions and for EMG under isokinetic conditions.

Whenever a dynamic motor performance test is administered to a subject, the statistical significance of the test must be considered. This should be considered for two reasons: First, one must ensure that the performance observed is part of the subject's true capability rather than an anomaly. This could be achieved through test-retest procedures. Second, differences in performance between conditions or days must be evaluated for statistical significance. Standard statistical comparisons (t-test, ANOVA, etc.) may be used for this purpose. After performing any of the above-mentioned tests one must ask whether the design of the test equipment or the data acquisition system has altered the human performance measure. One should be sure that what one measures truly is human performance and not a machine performance artifact or anomaly.

In Summary

It is apparent from the preceding discussion that measuring trunk dynamic motor performance is not a simple task. When choosing an appropriate measure of dynamic motor performance, one must first consider the objective of the testing procedure and determine the type of information (internal or external force) that is desired. Several factors must be considered when selecting the testing conditions that are appropriate for an evaluation. Generally, the more realistic the measurement techniques the more dynamic components are involved. However,

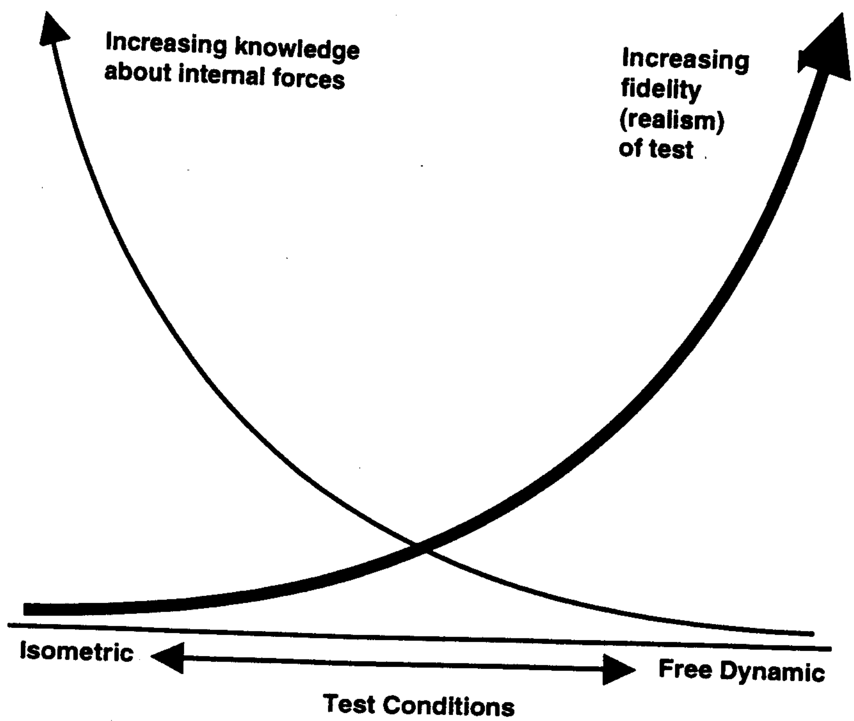

Figure 2. Tradeoff associated with measures.

the vast majority of the currently obtainable information concerning the status of the internal force production system (which governs the dynamic motor performance) applies only to isometric or isokinetic conditions.

Thus, there are significant tradeoffs that must be considered when selecting an appropriate testing measure. These tradeoffs are summarized in Figure 2. In this figure the abscissa represents a continuum of dynamic motor performance conditions. One ordinate indicates the degree of reality associated with the test. The other ordinate indicates the amount of information relative to the internal force-generating structures that can be gained from the test. Thus, the more realistic the testing conditions become, the less available the information regarding the status of the internal force generation system. It also is important to realize that this is the present status of internal force status knowledge. As our knowledge of internal force production generation under various conditions increases (as it is expected to with technological advances), it will become more feasible to derive greater amounts of information from dynamic tests.

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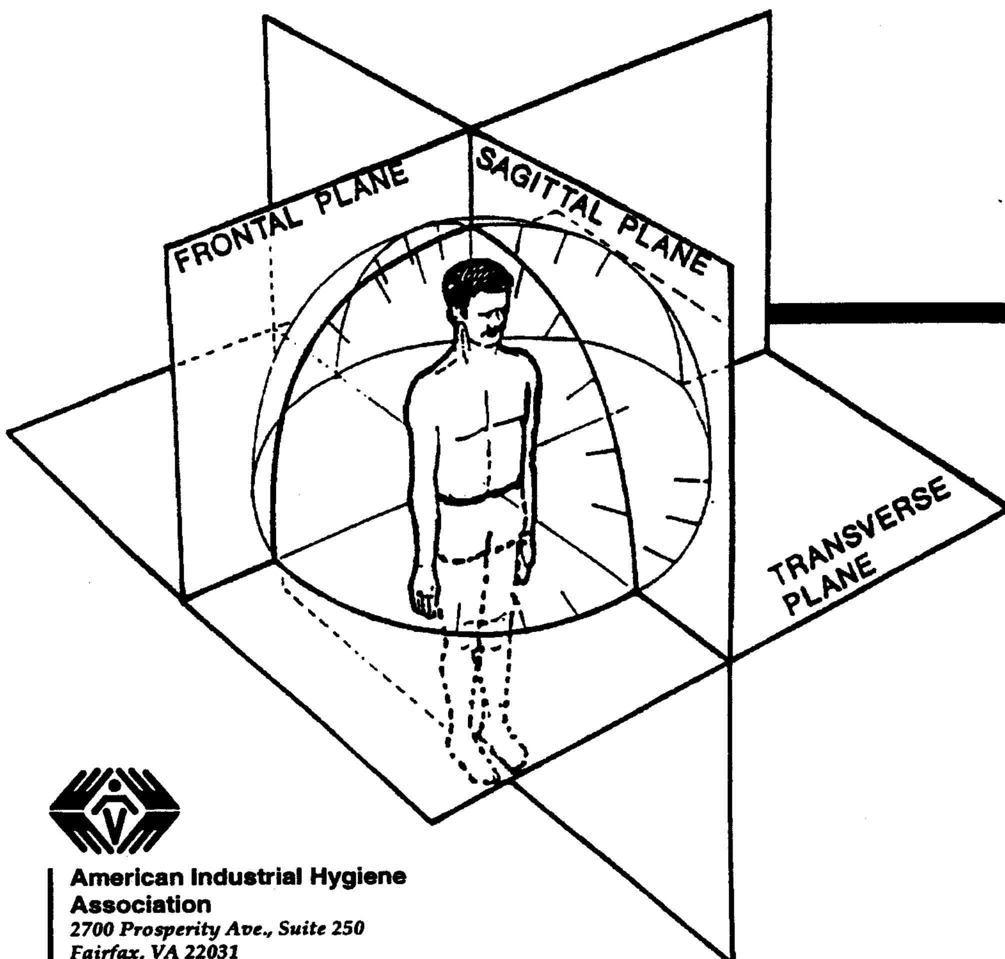

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