22

*Muscle**

Michael L. Pollock, Ph.D., James E. Graves, Ph.D., David M. Carpenter, M.S., Daniel Foster, M.S., Scott H. Leggett, M.S., and Michael N. Fulton, M.D.

Low back pain (LBP) is one of the most common and costly medical problems in western society.[2, 36, 39] The problem afflicts both the young and the old and often well-conditioned athletes. The etiology of LBP is diverse, and many factors have been associated with its incidence. Soft-tissue weakness in the area surrounding the lumbar spine is often mentioned as a primary risk factor for LBP.[2, 11, 59, 65, 68] Likewise, strengthening the lower back musculature has long been recognized as an important component in the rehabilitation of LBP.[2, 43, 54, 55] Thus it is important to study the physiologic principles associated with improving lumbar muscle strength and endurance. Training for muscular strength is also associated with the strengthening of connective tissue.[11, 84]

New technology, e.g., methods for standardizing testing procedures and computerized dynamometers, have improved evaluation techniques for determining the muscular strength and endurance of the lumbar extensor muscles. For example, the measurement of lumbar extension strength is complicated by the involvement of the stronger gluteal and hamstring muscles. Mayer and Greenberg[52] noted that the lumbar-pelvic rhythm, i.e., a compound movement that involves pelvic rotation plus lumbar extension, during lumbar testing contributed to the lumbar extension strength measurement. New technology has now made it possible to isolate the lumbar muscles by pelvic stabilization so that the lumbar musculature can be more effectively measured and trained.[38, 77]

This chapter will summarize the basic physiologic principles associated with muscular strength evaluation, as well as the development and maintenance of muscular strength through exercise training. Within this framework, much of our research experience with testing and training the isolated lumbar extensor muscles will be synthesized and reviewed. Normative data for both men and women and strength curve interpretation will be provided. Other important factors will be discussed with regard to evaluating and conditioning the lumbar extensor musculature, e.g., static and dynamic testing techniques, muscle fiber fatigue characteristics, the effect of counterweighting to account for the weight of the head and torso mass, the concept of stored energy (total torque and net muscular torque [NMT]), lumbar muscle strength curves, and the trainability of the isolated lumbar extensor muscles.

*Research funded by the MedX Corp., Ocala, Fla. The Center for Exercise Science is a multidisciplinary research laboratory and educational facility of the Departments of Medicine, Exercise and Sport Sciences, and Physiology at the University of Florida and the Geriatric, Research, Education, and Clinical Center (GRECC) of the VA Medical Center, Gainesville, Fla. Since September 1987 we have completed extensive research with specialized equipment designed to evaluate and rehabilitate the spine.

BASIC MUSCLE PHYSIOLOGY AND PRINCIPLES OF RESISTANCE TRAINING

Muscular strength refers to the maximum amount of force or tension that a muscle or muscle group can generate. Muscular endurance pertains to the ability of a muscle to sustain repeated contractions of a submaximal nature. Each plays an important role in the treatment and prevention of LBP and injury.[45] Moreover, muscular strength and endurance may be improved through a program of resistance training.[20] For this reason, clinicians should be familiar with the basic principles of resistance training. While the theory behind resistance training is simple; strengthen a muscle by making it work harder (the overload principle), the physiologic process by which a muscle becomes stronger is complex and involves neural, morphologic, and biochemical adaptations.[58]

Physiologic responses to resistance training include improvements in muscular strength and endurance and increases in muscle mass,[81] bone mass,[79] and connective tissue thickness.[79] Additional responses include alterations in stored levels of intramuscular aerobic and anaerobic metabolites and enzymes[14] and enhanced motor unit recruitment.[75] Increases in muscle mass occur primarily due to the hypertrophy of individual muscle fibers. This process is related to an accelerated synthesis of the contractile proteins within the muscle cell. The key factor initiating muscular hypertrophy is an increase in the tension or force that the muscle must generate. It is this increase in muscular tension that also causes the proliferation of associated bone and connective tissue cells.[79]

In addition to an increase in muscle mass, neural adaptations contribute greatly to improved levels of muscular strength and endurance. With regular exercise, the neural control of muscular contraction is enhanced. This occurs primarily as a result of greater motor unit recruitment and an increase in the frequency of motor unit firing.[75] Resistance training may also cause the abatement of protective sensory mechanisms (such as the Golgi tendon reflex) that normally inhibit muscular contraction and the expression of strength.[37] The relative contributions of hypertrophy and neural adaptation differ along the time course of strength development. During the initial stages of a resistance training program (the first 3 to 4 weeks) gains in strength are primarily due to neural changes. Beyond this point, hypertrophy becomes the major factor accounting for further gains in strength.[61] This has important implications concerning the duration of resistance training programs in which hypertrophy is a primary consideration.

The fiber-type composition of a muscle is another important consideration in the development of strength and endurance. Most skeletal muscles consist of a heterogeneous mixture of several fiber types. The performance or functional characteristics of a muscle are dependent on the relative distribution of these fiber types within the muscle. Although there is a broad spectrum of fiber types, generally three basic types are described. A muscle consisting mainly of slow-twitch (type I) fibers will demonstrate a limited potential for force production and an enhanced capacity for muscular endurance. A muscle consisting mainly of fast-twitch (type IIa and IIb) fibers will demonstrate an enhanced potential for force production and a limited capacity for muscular endurance. Type I fibers are associated with a high oxidative (aerobic) capacity and type IIb fibers with a high glycolytic (anaerobic) capacity. The type IIa fibers appear to adapt toward a more oxidative or glycolytic characteristic depending on how they are stimulated, i.e., trained for strength or trained for endurance.[78] A muscle consisting of an even mixture of type I and type II fibers will display moderate capacities for both strength and endurance.

The fiber-type composition of a muscle has a bearing on the degree to which the overall functional capacity of the muscle may be altered or improved through resistance training. A predominantly fast-twitch muscle possesses greater potential for improvements in strength and hypertrophy than a predominantly slow-twitch muscle does. The opposite would be true for the development of muscular endurance.

Resistance training is associated with specific alterations in the metabolic characteristics of a muscle.[12, 14, 81–83] High-intensity resistance training is associated with increases in the concentration of phosphogenic and glycolytic substrates and an increase in the activities of enzymes reflecting an anaerobic-glycolytic metabolism.[12] Long-term high-intensity strength training is also associated with the attenuation of certain aerobic-oxidative enzymes.[82] These changes reflect an overall reduction in the aerobic capacity of muscle and, as mentioned above, are associated with the transformation of the characteristics of the type IIa fiber to the type IIb fiber. Moderate to low-intensity resistance training has been shown to promote increases in the activity of enzymes associated with aerobic metabolism.[14]

Another consideration in the response of a muscle to resistance training is the order of fiber-type recruitment. Motor units are generally recruited in order of their size, with the largest-strongest motor units being recruited last.[75] When the demands of exercise require little force production from a muscle, as in lifting a light weight very slowly, motor units of slow-twitch fibers are recruited. As the weight load or speed of movement increases and greater force becomes necessary, motor units of fast-twitch fibers are also recruited. This pattern of recruitment ensures that slow-twitch fibers are recruited during the performance of low-intensity and long-duration (aerobic) activities. Fast-twitch fibers are only recruited during high-intensity (anaerobic) activities.

The components of the prescription for resistance exercise training include frequency, intensity, volume, duration, and mode of activity. Depending on the goals of the training program, these components may be manipulated in such a way as to elicit a specific training response.

The frequency of resistance training refers to the number of training sessions completed per week. Although there are relatively few studies reporting the effects of various training frequencies on the development of muscular strength, it is generally felt that a minimum of three workouts per week per muscle group is required to produce optimal improvements.[20] However, recent research has shown that training one time per week is sufficient to produce maximal improvements in the strength of the isolated lumbar extensor muscles.[26] This response to training one time per week appears to be unique to the lumbar extensors and will be discussed later in this chapter under "training responses."

The requirements for resistance exercise training frequency vary on an individual basis. Several factors determine an individual's optimal training frequency. The foremost of these is the ability to recover. This refers to the amount of rest required between training sessions. It has been demonstrated that three training sessions per week performed on alternate days (one day of rest between) allows adequate recovery, especially for the novice exerciser.[1] Several sources suggest that as one advances and is better able to tolerate resistance exercises, training frequency may be increased.[5, 20, 80] Recovery ability is therefore partially dependent on the training status of the muscle.

Recovery ability is also affected by the intensity of training. Generally, a more intense training session necessitates a longer rest period. This is likely related to the degree of "damage" inflicted on the exercising muscle. Several sources suggest using the degree of residual muscle soreness as a parameter to determine the adequacy of recovery following a training session.[20] If soreness or fatigue are still present to a great degree at the onset of subsequent training sessions, this is probably an indication of incomplete recovery. Under these circumstances, the frequency, intensity, or volume of training may have to be reduced to prevent more serious muscular injury and symptoms of overtraining.

The intensity of training refers to the degree of overload that a muscle encounters during exercise. The required intensity of resistance training differs depending on the specific goals of a program. High-intensity exercises employ a high level of resistance and a low number of repetitions. Low-intensity exercises employ a low resistance and a high number of repetitions. High-intensity exercises stimulate maximal improvements in muscular strength, whereas low-intensity exercises are best suited for developing muscular endurance. According to Fleck and Kraemer,[20] repetition maximum (RM) loads of 6 or less have the greatest effect on strength development, while RM loads of 20 or more have the greatest effect on the development of muscular endurance. RM loads ranging between 6 and 20 would stimulate improvements in both strength and endurance, although the magnitude of improvement would not be as great for either. This is why most experts recommend 8 to 12 repetitions of exercise for general fitness and strength endurance development.[73, 88] It should be noted that an increase in muscular strength is associated with an increase in muscular endurance. As maximal strength increases, the percentage of strength needed to lift a given weight load decreases.

Training volume refers to the total amount of exercise performed during a single training session. This is usually expressed in terms of the total number of sets completed per exercise session, along with the total number of repetitions completed per set. The total time under load is another way to express training volume. The general consensus in the literature is that two to five sets of exercise are required to stimulate maximal gains in strength.[20] However, substantial improvements in strength result from completing a single set of exercises performed to volitional fatigue (maximum effort).[6] There is much controversy concerning the number of sets required to develop maximal strength. This controversy exists due to the fact that training intensity varies among sets used in multiple-set training studies, i.e., volitional fatigue may not have been required for all sets. As will be discussed later in this chapter under "training responses," a recent study that compared the effect of one vs. two sets of exercise (8 to 12 RM) found one set to be equally as effective for the development of isolated lumbar extension strength.[24]

The duration of training refers to the length of a resistance training program. This is usually expressed in terms of the number of weeks or months of training. As mentioned previously, neural adaptation is primarily responsible for improvements in muscular strength during the early stages of a resistance training program, after which hypertrophy accounts for most of the strength gain. Significant increases in muscle mass have been observed within 2 months following the onset of resistance training.[81] Near-maximum improvements in strength are known to occur following as little as 12 weeks of resistance training.[12] However, peak improvements in strength and hypertrophy typically require a much longer duration of training.[20] An atrophied or weak muscle possesses a greater potential for hypertrophy and strength gain than does a trained muscle.[13, 33] Moreover, an atrophied or weak muscle will also demonstrate a faster rate of growth and strength gain than a trained muscle. However, since an atrophied muscle is further away from achieving its maximum potential for growth and strength development, it will most likely require a longer duration of training.

The mode of activity refers to the type of exercise employed during a resistance training program. Muscular strength and/or endurance may be developed through the use of either isometric (IM) or dynamic exercise. IM exercise stimulates improved levels of strength, but only at or near the specific joint angle trained.[42] With IM exercise, multiple contractions at different joint angles are required in order to stimulate improvements in strength throughout a full range of motion (ROM). Full-range improvements in strength are achieved through the use of dynamic exercise, provided that they are performed slowly throughout a full ROM.[29] Dynamic exercises that require both concentric and eccentric contractions of the exercising muscle have been shown to produce superior gains in strength vs. the same exercise requiring either concentric or eccentric contractions only.[31]

The mode of activity is related to the type of resistance training equipment used during training. The various types of resistance training equipment differ according to the nature of the resistance they provide, with most equipment providing one of three types of resistance: (1) constant load, (2) variable resistance, or (3) isokinetic (accommodating) resistance.

Constant-load devices provide a consistent, unchanging weight load throughout all points of a given ROM. This is not to be confused with constant resistance, which requires that the resistance be continually applied perpendicular to the moving limb or body segment. The most widely used form of constant-load devices are free weights or barbells. Free weights are extremely popular because of their affordability, diversity, and overall ease of use. However, strength is known to vary throughout a range of joint motion. With free weights exercise is limited by the weakest position in the ROM. In other words, one may lift only as much weight as possible at the weakest joint angle. Thus, the muscle is never required to contract maximally in its stronger positions. This compromises the potential effectiveness of these devices from the standpoint of stimulating maximal improvements in strength through a full ROM. An additional disadvantage of free weight exercise is that a partner or "spotter" is often required to safely perform certain lifts. The lower part of the back is especially vulnerable to injury if proper technique is not used in lifting and lowering the weight from the floor.

Variable-resistance devices attempt to provide a resistance curve that matches the ideal strength curve of the exercising muscle. Resistance is varied with cams and pulleys, which ultimately provides the exerciser with a mechanical advantage at certain points through the ROM. The intended effect is to allow a variable resistance through the ROM to provide a maximal overload throughout. Theoretically, this would provide a more effective stimulus to the exercising muscle and result in a greater full-range effect.

For both constant- and variable-resistance exercise devices, performing repetitions with a slow controlled movement is recommended. Rapid movements under load are associated with the development of momentum that minimizes potential training effects. In addition, rapid movements may be associated with dangerously high impact forces and an increased risk of injury.

Isokinetic resistance machines are designed for exercise at a preselected constant velocity of movement. Once a constant velocity is achieved, resistance is supposed to be supplied to the exercising muscle equal to the amount of force produced at all points through a given ROM. In theory, this allows the exercising muscle to contract maximally at all points through its ROM. Moreover, this could be accomplished at speeds of movement that simulate those used in the performance of certain athletic or functional activities.

A major limitation of isokinetic exercise machines is that it is impossible to move at a constant velocity through a full ROM. Acceleration and deceleration occur at the beginning and end of isokinetic exercises.[63] Acceleration occurs as the exercising body segment "catches up" to the machine's movement arm, and deceleration occurs as the limb nears its limits of joint movement. Since the exercising limb is not moving at the preset speed of movement, maximal resistance is not provided at these positions. Acceleration and deceleration of a different nature occur as the dynamometer attempts to control the speed of movement. When the exercising limb accelerates beyond the preset speed of movement, it is immediately slowed by a sudden and partial braking and releasing of the machine's movement arm. This leads to the development of potentially harmful impact forces. Greater speeds of movement result in progressively greater impact forces.[63] These impact forces are referred to as "torque overshoot" and represent an artifact of isokinetic testing. In addition to increasing the variability associated with estimating the true isokinetic torque, impact forces may result in injury to the exercising muscle or its associated joint structures. Finally, with the exception of some recent models, isokinetic resistance devices fail to provide resistance during the eccentric phase of muscular contraction. The major limitation of variable-resistance machines is that they fail to account for individual differences in the shapes of strength curves. The resistance curve provided by a particular machine may be appropriate for one individual and inappropriate for another.

A program of resistance training must be progressive in order to continue to produce gains in muscular strength and endurance. To ensure continued gains in strength, the intensity of training must be increased or maintained. In order to ensure maximal improvements in muscular endurance, the volume of training must be steadily progressed. In either case, the rate of progression should be gradual. A typical convention is to increase the resistance by 5% when the exerciser is able to complete the prescribed number of repetitions per set for a given exercise. This will minimize the risk of muscular and/or orthopaedic injury. Finally, any improvements in muscular strength and/or endurance brought about by a training program are of limited value if training is not continued. With detraining, a large part of the improvement in muscular strength and endurance will eventually be lost. Therefore, it is recommended that training be carried on systematically throughout one's lifetime. However, once a new level of conditioning is attained, maintenance of muscular strength and endurance may be achieved through a program of reduced training. This usually involves a decrease in the frequency of training. A recent study that investigated the effects of reduced training on the maintenance of isolated knee extension strength found that the improvements in strength achieved during an initial 18-week training period at a frequency of three times per week were maintained following a 12-week program of reduced training at frequencies of one or two times per week.[28] The key component in the maintenance of muscular strength appears to be the intensity of training.

If the intensity of training is maintained, improved levels of strength are not lost. Even though the long-term (greater than 12 weeks) effects of reduced resistance training have yet to be established, it appears that it takes less to maintain than it does to attain strength and endurance. It is important to recognize that missing a workout once in a while should have no significant effect on maintaining strength and endurance. The main point is not to stop training altogether.

REQUIREMENTS FOR ACCURATE EVALUATION OF LUMBAR EXTENSION FUNCTION

The primary function of skeletal muscle is to generate force. In most instances, forces generated by skeletal muscles are used for anatomic stabilization or to produce movement. The accurate quantification of the force-generating capacity of the lumbar extensor muscles requires isolation of the lumbar extensors via pelvic stabilization, compensation for the influence of gravity on upper body mass, testing through a full ROM, and a safe and reliable method of testing.

Pelvic Stabilization

As mentioned in the beginning of this chapter, only a small portion of the total trunk extension movement is due to lumbar extension. Under normal circumstances, the lumbar extensors work in conjunction with the larger, more powerful gluteus and hamstring muscles (which rotate the pelvis) to extend the trunk. This compound movement, consisting of pelvic rotation and lumbar extension, is often referred to as lumbar-pelvic rhythm and encompasses approximately 180 degrees of movement. The lumbar extensor muscles are capable of approximately 72 degrees of trunk extension.[18, 38]

To isolate the lumbar extensors from the muscles that rotate the pelvis, pelvic stabilization is required.[27, 70, 77] One method of stabilizing the pelvis when testing lumbar extension strength in the seated position is to restrict pelvic rotation by applying a restraining force to the lower extremities (Fig 22–1). When the legs are adequately restrained, backward rotation of the pelvis is minimized. Smidt et al.[77] have documented the effectiveness of this strategy for stabilizing the pelvis and have shown that a considerable error in lumbar extension strength measurement occurs when the pelvis is not adequately stabilized. Further evidence of the importance of pelvic stabilization to isolate the lumbar extensors comes from the results of lumbar extension exercise training with and without pelvic stabilization. Graves et al.[30] showed that isolated lumbar extension strength was not affected by training on "low back" exercise machines that did not stabilize the pelvis. This study will be covered in more detail later in this chapter.

Gravity Compensation

When evaluating muscular function in the sagittal plane, gravitational force will act upon the mass of the involved body parts and influence the observed torque measurements.[19, 32, 66, 89] Head, arms, and torso mass detract from lumbar extension torque measurements when the trunk is in flexed positions and adds to the measurements made in extended positions of the ROM (See Fig 22–2). Winter et al.[89] have reported that when gravitational forces are not considered during muscular strength testing, measurement errors may exceed 500%. The magnitude of error associated with a lack of gravity compensation for body

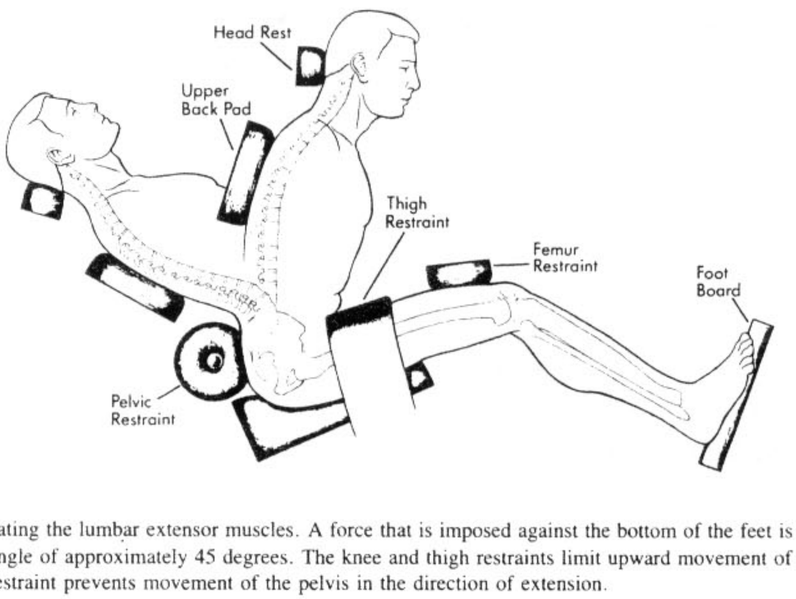

FIG 22–1.
Restraining mechanisms for isolating the lumbar extensor muscles. A force that is imposed against the bottom of the feet is transmitted by the lower parts of the legs to the femurs at an angle of approximately 45 degrees. The knee and thigh restraints limit upward movement of the knees, upper aspect of the thighs, and pelvis. The pelvic restraint prevents movement of the pelvis in the direction of extension.

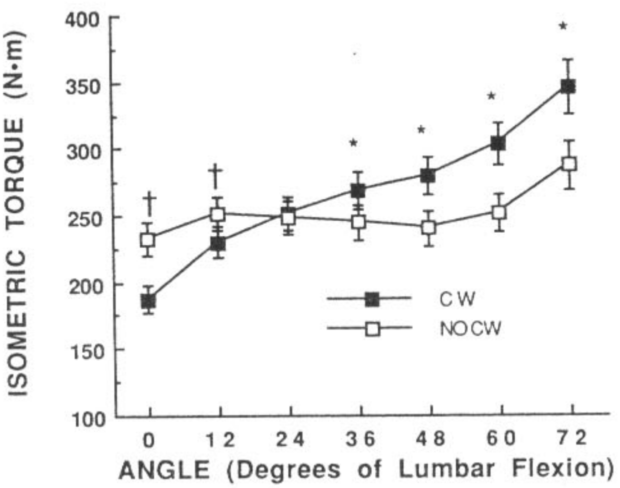

FIG 22–2.
The influence of upper-body mass during lumbar extension torque evaluation in the seated position. A group of 34 subjects was tested for isolated lumbar extension strength with a counterweight *(CW)* and again without a counterweight *(NOCW)*. *The CW trial was significantly higher than the NOCW trial ($P \leq .05$). †The NOCW trial was significantly higher than the CW trial ($P \leq .05$). (Data from Fulton M, Pollock M, Leggett S, et al: Effect of upper body mass on the measurement of isometric lumbar extension strength. Presented at the Orthopaedic Rehabilitation Association Conference, San Antonio, Tex, 1990.)

mass when evaluating lumbar extension function has been described by Fulton et al.[22] and represents as much as 25% of the mean torque values (Fig 22–2).

Some dynamometers have employed correction algorithms and/or mechanical devices to compensate for the effects of gravitational force on muscular torque measurements. However, there has been little research to validate the accuracy of these procedures. Recently, Pollock et al.[71] studied the accuracy of a counterweight procedure designed to compensate for the effect of gravity acting upon upper body mass during IM lumbar extension torque testing. The authors used a prototype lumbar extension machine (MedX; Ocala, Fla) that allowed testing in the sagittal plane while using the counterweight procedure. The machine could also be rotated 90 degrees to enable testing in the transverse plane without the need for a counterweight because gravity no longer influences upper body mass in the direction of lumbar extension (Fig 22–3). Seventy-four subjects were tested isometrically through a 72-degree ROM in both planes. The resulting torque curves indicated no significant difference between the two conditions from 72 to 12 degrees of extension (Fig 22–4). The difference observed at 0 degrees (15 newton-meters) was small, and the correlation between tests was $r = 0.91$. These data validate the effectiveness of the counterweight procedure to compensate for upper body mass during IM lumbar extension strength testing in the seated position.

Importance of Testing Through a Full Range of Motion

The normal IM lumbar extension torque curve is linear, descends from flexion to extension, and encompasses a ROM of approximately 72 degrees.[25] Patients with LBP and individuals who are predisposed for LBP due to existing pathologies often exhibit a limited ROM[21, 74] and abnormally shaped IM lumbar extension torque curves that are characterized by weakness at certain positions in the ROM (Fig 22–5) but not necessarily through the entire ROM.[21] Testing at a single position or through a limited

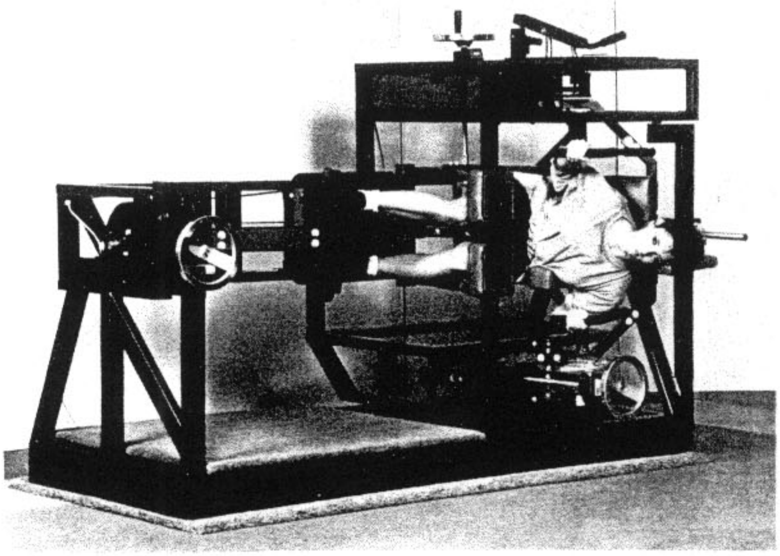

FIG 22–3.
Lateral lumbar extension machine (MedX Corp., Ocala, Fla). This machine was used for data collected in Figure 22–4.

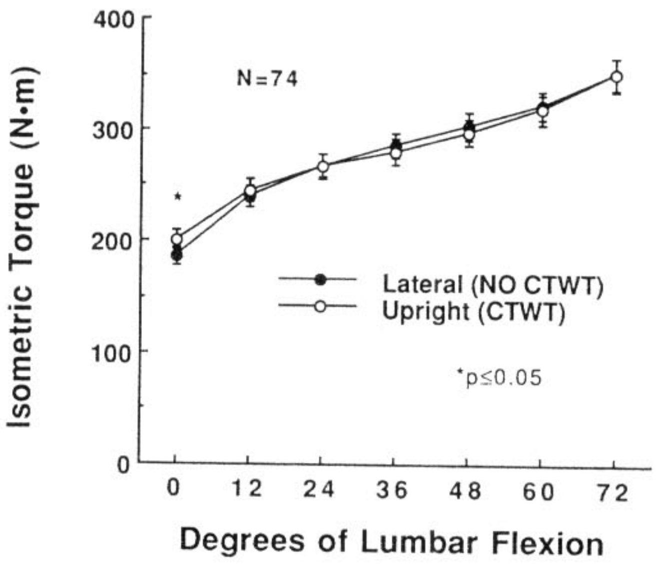

FIG 22–4.
Isometric torque values for lumbar extension strength testing in the sagittal plane with upper body mass counterweighted *(CTWT)* and in the transverse plane without the need for counterweighting *(NO CTWT)*. (From Pollock M, Graves J, Leggett S, et al: *Med Sci Sports Exerc* 1991; 23(suppl):66. Used by permission.)

ROM may not identify potentially significant abnormalities. Also, exercise training programs for prevention and rehabilitation may have a varied influence throughout the ROM.[27, 29] Testing through a full ROM is important to provide a complete profile of strength for the purposes of patient screening and evaluation. Patients undergoing treatment for LBP often improve their ROM during the healing process, and full-ROM strength testing is important to monitor this progress as their condition improves.

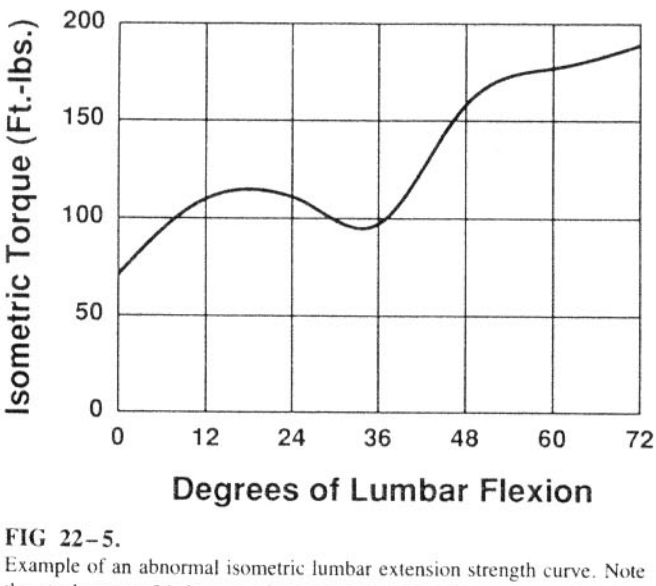

FIG 22–5.
Example of an abnormal isometric lumbar extension strength curve. Note the weakness at 36 degrees of lumbar flexion that is causing a deviation from the normal linear torque curve by angle relationship.

The importance of full-ROM evaluation is further illustrated by athletes involved in unique training programs. Waterskiing, for example, overloads the lumbar extensors in the extended portion of the ROM as the skier leans back to resist the pull of the tow boat. As a result of this overload and the principle of specificity of training, water-skiers are unusually strong in the extended portion of the ROM but not in flexion (Fig 22–6).[46] Full-ROM lumbar extension strength training generally produces the greatest effect in the extended portion of the ROM (to be discussed later in "training responses"). A case study involving 10 weeks of lumbar extension strength training at a frequency of once every 2 weeks (five training sessions) by a competitive slalom skier, however, showed a 60% increase in strength in full flexion (72 degrees of lumbar flexion) and a 22% improvement in strength at 20 degrees of lumbar flexion, which was the initial position of peak strength.[38] The specific adaptations to waterskiing and to full-ROM lumbar extension strength training in a previously untrained water-skier could only be observed by accurate full-ROM evaluation.

Dynamic exercise tests do not have the ability to assess strength through a full ROM. Isotonic tests are limited to the quantification of strength at the weakest position in a ROM. Isokinetic tests are associated with a period of acceleration at the beginning of the ROM and a period of deceleration at the end of the ROM. The acceleration and deceleration phases of the test are responsible for producing a bell-shaped curve that is characteristic of all isokinetic exercise tests, regardless of the muscle group being evaluated. The amount of information lost during an isokinetic

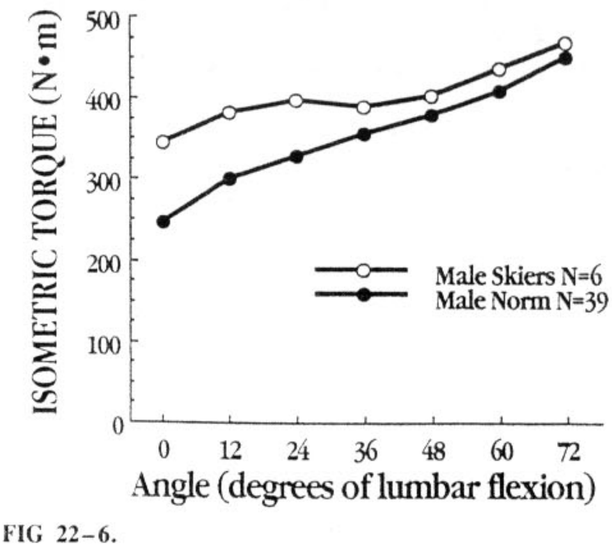

FIG 22–6.
Isometric lumbar extension torque curves for elite professional male water-skiers and normal (untrained) males. (Data from Leggett SH, Pollock ML, Graves JE, et al: Physiological evaluation of elite professional water-skiers. Presented at the International Congress on Sports Medicine and Human Performance, Vancouver, Canada, 1990.)

test depends on the speed of movement and can consist of as much as 50% of the ROM during lumbar extension strength testing.[53]

Due to the limitations of assessing strength through a ROM with dynamic exercise tests, IM measures are often used to describe strength through a ROM.[44] IM strength of compound lumbar-pelvic function has been evaluated.[52] A multi-joint angle IM exercise test has been described that can accurately assess isolated lumbar extension torque through a full ROM.[25] Advantages of this test include a high degree of reliability and low variability in addition to providing a full ROM profile for lumbar extension torque. The accuracy of isokinetic measures of muscular strength have been questioned due to the need for mathematical interpretation of the oscillations in observed torque (impact forces) caused by constant braking and releasing of the servomechanism that controls movement velocity.[4, 62, 63, 76] Because IM exercise tests involve no movement, impact forces are not found when the generation of muscular tension is slow and controlled.

While IM measures of muscular torque have the advantage of reliability, accuracy, and provision of a full-ROM profile, multi–joint-angle IM tests can be limited by fatigue associated with the testing procedure. Graves et al.[29] showed that the shape of the IM lumbar extension torque curve is influenced by the order of testing, i.e., IM lumbar extension torque measurements are affected by the previously performed IM contractions. This order effect is not influenced by exercise training. Therefore, as long as the order of testing is standardized, a multi–joint-angle test can be used to quantify changes in strength through a full ROM. When it is imperative to obtain maximal IM torque measurements at multiple positions through a ROM, a sufficient amount of time between contractions must be allowed to ensure adequate recovery.

Reliability of Isometric Testing

In order for test results to be meaningful, they must be reliable. Otherwise, it is impossible to determine whether deviations from normative data or changes resulting from intervention programs represent true differences or whether they are a reflection of the unreliability of the test. Graves et al.[25] evaluated the reliability and variability associated with measuring IM lumbar extension strength through a 72-degree ROM. One hundred thirty-six men and women completed IM lumbar extension strength tests on 3 separate days. On days 1 and 2, subjects completed two tests separated by a 20- to 30-minute rest interval. For each test, IM lumbar extension torque was measured at 72, 60, 48, 36, 24, 12, and 0 degrees of lumbar flexion. The mean IM torque values, within day reliability coefficients and test variability over the seven positions measured, improved from day 1 to day 2. Mean strength values and reliability statistics showed no further improvements from day 2 to day 3. Values for single test variability ranged from 20.3 to 24.3 newton-meters (Nm), which represented 6.7% to 11.0% of the mean torque value (see Table 22–1). Because of the improvement noticed from day 1 to day 2, a practice test is recommended to obtain the most reliable results for the lumbar extension muscles. Using the most reliable data observed, Graves et al.[25] reported normative IM lumbar extension torque for men and

TABLE 22–1.
Reliability of Multiple–Joint Angle Isometric Strength Tests

		Joint Angle							
Study	Correlation Coefficient	1	2	3	4	5	6	7	8
Knee extension*	r†	0.98	0.98	0.98	0.98	0.94	0.95	0.93	0.90
	SEE/$\sqrt{2}$%‡	4.8	4.9	5.0	4.7	7.1	6.6	8.3	10.3
Lumbar extension§	r	0.97	0.94	0.95	0.96	0.94	0.92	0.81	
	SEE/$\sqrt{2}$%	7.2	6.7	8.2	7.9	9.9	11.1	11.6	
Cervical extension¶	r	0.96	0.95	0.94	0.96	0.94	0.96	0.92	0.90
	SEE/$\sqrt{2}$%	9.8	8.8	8.0	7.4	8.4	8.4	8.6	10.2
Cervical rotation‖	r	0.97	0.96	0.97	0.97	0.97	0.94	0.91	
	SEE/$\sqrt{2}$%	7.9	8.4	7.3	6.8	6.4	8.9	15.1	
Torso rotation**	r	0.97	0.95	0.96	0.93	0.91	0.87	0.85	
	SEE/$\sqrt{2}$%	5.8	7.2	6.2	8.3	9.3	11.1	16.7	

*Knee extension joint angles are 70, 85, 100, 115, 130, 145, 160, and 171 degrees of knee extension. Data from Graves JE, Pollock ML, Jones AE, et al: *Med Sci Sports Exerc* 1989; 21:84–89.
†Pearson product-moment correlation coefficient describing test-retest reliability.
‡Single test variability described by dividing the standard error of the estimate (SEE) by $\sqrt{2}$ and expressed relative to the mean torque values at each angle.
§Lumbar extension angles are 72, 60, 48, 35, 24, 12, and 0 degrees of lumbar flexion. Data from Graves JE, Pollock ML, Carpenter DM, et al: *Spine* 1990; 15:289–294.
¶Cervical extension angles are 126, 108, 90, 72, 54, 36, 18, and 0 degrees of cervical flexion. Data from Leggett SH, et al: *Am J Sports Med.* 1991; 19:653–659.
‖Cervical rotation angles are 72, 48, 24, 0, −24, −48, and −72 degrees of cervical rotation. Data from Trinkle JP: *Quantitative assessment of isometric cervical rotation strength* (thesis). University of Florida, 1990.
**Torso rotation angles are 54, 36, 18, 0, −18, −36, and −54 degrees of torso rotation. Data from Carpenter DM, et al: *Int J Sports Med* 1991; 2:246.

women. The normal curves are linear and descend from flexion to extension (Fig 22–7).

The variability of muscular strength measures made on humans under the most carefully standardized conditions is generally 5% to 10%.[87] This variability is considered to be normal human biovariation and is caused by the fact that there are a variety of factors that can influence human strength on a day-to-day basis. Some important factors that can influence human strength measurements include but are not limited to the amount of sleep, the time of day, the time since the last meal, recent physical activity, physiologic stress, and motivation. It is prudent to standardize as many of the factors as possible to obtain the most reliable test results.

Research from our laboratory on the reliability of multiple–joint-angle IM strength testing has also been evaluated for the knee extensors, cervical extensors, and the muscles that rotate the torso and neck (MedX). Results from these studies are summarized in Table 22–1. The data show a high degree of repeatability and low variability for all muscle groups studied through a full ROM. The only exception is variability associated with the measurement of torso rotation torque in the fully contracted position (22%).

Safety

An additional advantage of IM testing is that it is a relatively safe method to evaluate muscular strength. Momentum developed during dynamic modes of exercise often results in impact forces when this momentum is suddenly halted. This occurs during isokinetic exercise when

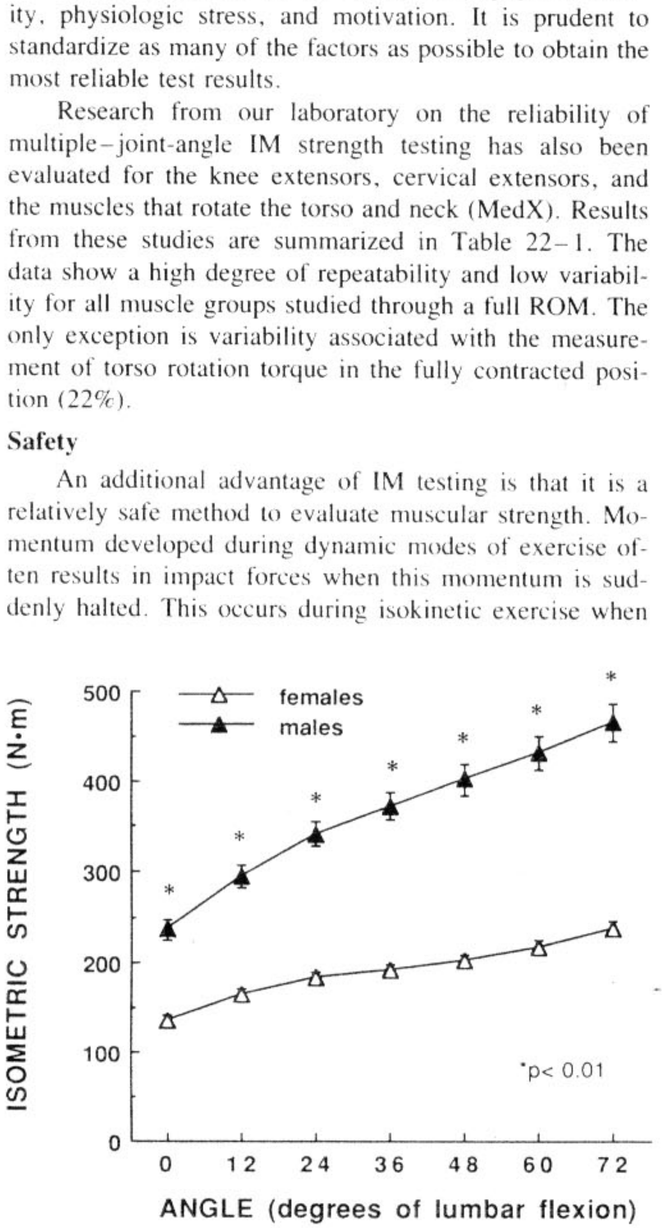

FIG 22–7.
Isometric lumbar extension torque values for normal men and women. (Data from Graves JE, Pollock ML, Carpenter DM, et al: *Spine* 1990; 15:289–294.)

the acceleration of the involved body part is halted by the movement arm of the device as it attempts to maintain preset velocity.[62, 63, 76] The impact forces resulting from this situation represent a testing artifact (described as torque overshoot) and are potentially dangerous, especially in patients with LBP.[57, 67] Research[51, 56] has shown that isokinetic trunk extension torque production can increase with increasing movement speed. This is in violation of the force-velocity relationship for muscular contraction (i.e., maximal force production decreases as movement velocity increases).[35] These data cannot be explained physiologically and probably result from the inability to accurately interpret the impact forces associated with isokinetic exercise testing, i.e., the greater the speed of movement, the greater the impact forces generated.

Testing for Lumbar Extension Net Muscular Torque

The mechanical properties of skeletal muscle have elastic and contractile components.[10] Elastic and strain (compression) energy may also be stored in connective tissue and bone. Measured torque resulting from voluntary muscular contraction is a combination of torque generated by the stored energy of the stretched (or contracted) muscle and its associated joint structures and force generated by the excitation-coupling process. Although both the elastic and contractile properties of muscle have been studied in vitro and in vivo, there has been no attempt to separate and quantify these two components in vivo by using computerized dynomometry.

The total torque generated during lumbar extension testing in the seated position consists of voluntary and involuntary components. Involuntary torque has been observed in the flexed positions of the ROM when subjects have been instructed to relax prior to voluntary contraction. Presumably this involuntary or "stored energy" torque represents the sum of the elastic energy of the fully stretched lumbar extensor muscles: the upward force on the torso caused by compression of the abdomen and the downward force of gravity acting upon the torso (if no counterweight is used to compensate for torso mass).

To quantify the involuntary and contractile components of measured torque during lumbar extension, an experiment was conducted in which subjects were secured in a lumbar extension machine with the addition of a harness that was designed to hold the torso against the movement arm of the machine.[8] The movement arm was positioned and locked at the first test angle (72 degrees of lumbar flexion), and the subjects were instructed to relax. The subjects' involuntary torque (stored energy) was displayed on a computer monitor (Fig 22–8) and recorded.

After the involuntary torque was recorded by the computer, the subjects were requested to perform a maximal IM contraction. The maximal or total torque value ob-

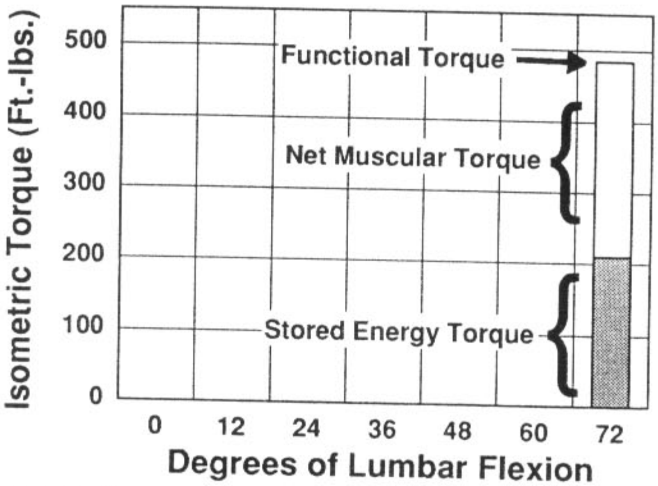

FIG 22–8.
Resting involuntary torque is first recorded by the computer. The subject then performs a maximal isometric contraction, and the total torque is recorded. The difference between the total torque and the torque due to involuntary factors represents the net muscular torque.

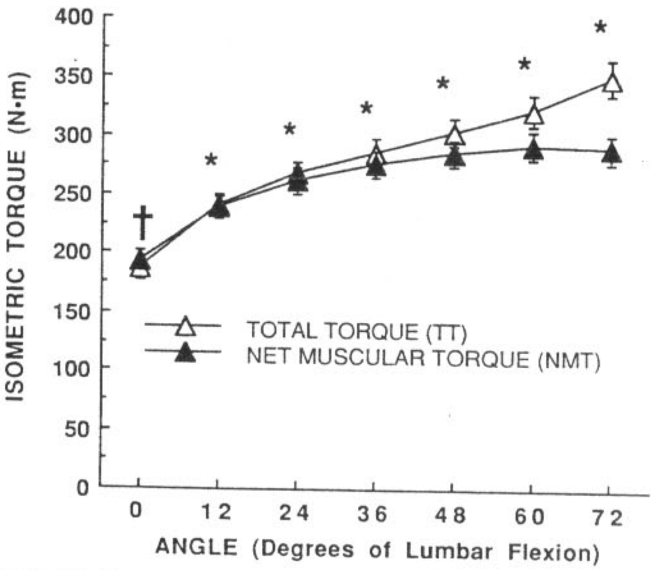

FIG 22–9.
Total torque and net muscular torque through 72 degrees of lumbar motion. (Data from Carpenter DM, Leggett S, Pollock M, et al: *Med Sci Sports Exerc* 1991; 23(suppl):65.)

served represents the torque generated by muscular contraction plus the torque due to the previously described involuntary factors. Subtracting the involuntary torque from the total torque measurement yields a measure of NMT. The NMT measure is the torque generated by volitional muscular contraction.

This procedure was then repeated at six additional test positions through the 72-degree ROM. Following the test, total-torque and NMT curves were compared. The area between these two curves represents the involuntary torque that was generated throughout the lumbar extensor ROM. As illustrated in Figure 22–9, involuntary factors can dramatically affect total functional torque. At 72 degrees of lumbar flexion, involuntary factors accounted for over 20% of the total torque value.

The concept of NMT is unique because it describes the force due to volitional contraction with the exclusion of other variables that can influence muscular torque measurements. Because of the limitations associated with dynamic torque measurements NMT can only be obtained during IM strength testing. The ability to quantify NMT will improve the ability to interpret and monitor measurements of lumbar function.

Fatigue Characteristics of the Lumbar Extensors

The fatigue characteristics of skeletal muscle have been studied and described in detail.[16] As previously described in this chapter, the fatigue characteristics of skeletal muscle are to a large extent related to the fiber-type composition of the muscle. The most common methodology used to investigate muscle fiber–type composition has been the histochemical treatment of muscle biopsies. This technique is invasive, requires sophisticated biochemical laboratory equipment and highly trained personnel, and obviously cannot be applied practically by the average health care professional interested in muscle fatigue characteristics. In addition, the technique is limited in its inability to differentiate along a continuum of fiber types and produces highly variable results in humans due to the inability to obtain sufficient quantities of muscle for evaluation. More importantly, while histochemical analysis of muscle biopsies may qualitatively describe muscle fiber–type composition, it does not provide a measure of muscular performance.

Fatigue characteristics of the isolated lumbar extensors may be evaluated by using the following three-part testing procedure.[38] This procedure has been referred to as a fatigue response test (FRT). Subjects are first positioned and secured in the lumbar extension machine so that the pelvis is stabilized as previously described. Then the multi–joint-angle IM lumbar extension test described earlier is performed through a full ROM. Immediately following the IM test, subjects complete a dynamic exercise with a preselected weight load. We have successfully used a weight load equal to 50% of the peak torque generated at 72 degrees of lumbar flexion during the IM lumbar extension torque test. Subjects perform as many dynamic variable-resistance lumbar extensions as possible until the weight load can no longer be lifted through a full 72 degrees of ROM (volitional fatigue). To ensure standardization of the procedure, subjects/patients are instructed to maintain an exercise cadence of 2 seconds for the concentric phase of the contraction (lifting the weight), a 1-second pause in the extended position, and 4 seconds for the eccentric phase of the contraction (lowering the weight). Finally, within 60 seconds following the final dynamic repetition, subjects complete a second, seven-angle, maximal-effort IM test. A subject's "fresh" IM torque curve and the IM torque curve generated immediately following the dynamic exercise are compared for analysis. The area separating the two curves represent the fatigue associated with performing the dynamic exercise.

The fatigue response of subjects completing the three-part FRT is a continuum. Figure 22–10 illustrates the results of two subjects who demonstrate dramatically different responses to the FRT. The two bottom test results (at 72 degrees) represent a subject whose fresh IM strength was increased by 8% following six dynamic lumbar extensions with a moderate level of resistance. The top two test results (at 72 degrees) represent a subject who lost 45% of his fresh IM strength following only six dynamic lumbar extensions, also to moderate fatigue. Both subjects exercised with the same work load (200 lb). These two varied responses are likely due to differences in fiber-type composition. The relationship between muscle fiber–type composition and the fatigue characteristics of skeletal muscle is well documented.[16, 20]

Current pre-employment strength testing procedures often use peak torque as a predictor of how well suited an individual may be for job-related tasks requiring a frequent amount of lifting.[40] The basis for this rationale is that stronger individuals are less likely to suffer a low back injury when placed in situations requiring repetitive or heavy lifting. There is evidence to suggest, however, that in certain situations it is the stronger worker who is at a greater risk for injury.[3] This may be due to the fact that stronger individuals often fatigue rapidly. It cannot be overlooked, however, that stronger individuals may be more likely to be placed into high-risk jobs.

The FRT may be a better predictor of an individual's risk for back injury than peak torque is. Those individuals who demonstrate a large decrement in strength with only a few repetitions of exercise may not be suited for jobs requiring repetitive lifting despite their ability to generate high levels of peak torque. Thus, the FRT may provide a useful method of evaluating the risk of low back dysfunction in an industrial setting. In addition, fatigue response characteristics are important to consider for the most appropriate prescription of resistance training exercises for the development and maintenance of muscular strength.

Most individuals (approximately 70%) show a 10% to 25% decrease in strength following the FRT. Approximately 10% are fatigue resistant and show less than a 10% reduction in strength. Another 20% show a high degree of fatigue (>25% decrease in strength). Individuals with greater than 25% fatigue responses tend to be either very strong individuals or patients with LBP. Patients/subjects who show extreme fatigability during the FRT should train less frequently and with fewer repetitions (6 to 8 repetitions) of exercise. Those who show little or no fatigue can train more frequently and with a greater number of repetitions (15 to 20 repetitions). Continued research is warranted to clarify the relationship between muscular endurance of the lumbar spine, risk of LBP, and the prescription of low back exercise.

EXERCISE TRAINING RESPONSES OF THE LUMBAR SPINE

Lumbar Extension Exercise Training in Subjects Without Low Back Pain

This section will deal with our 5 years' experience in exercise training of the isolated lumbar extensor muscles. Where appropriate, comparisons with other training studies from the literature will be made and recommendations

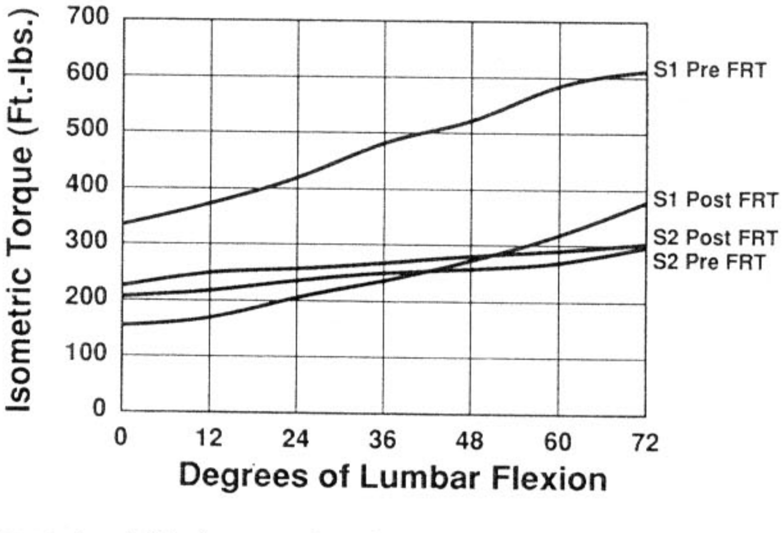

FIG 22–10.
Isometric torque values prior to and following an acute bout of dynamic lumbar extension exercise (fatigue response test *[FRT]*).

for exercise prescription inferred. The MedX lumbar extension machine (Ocala, Fla) was used for all investigations.

One of our first training studies was conducted on 25 healthy volunteers: 18 men (aged 33 ± 11 years) and 7 women (22 ± 1 years).[72] Fifteen of these subjects were assigned to an exercise group that trained 1 day per week for 10 weeks. Ten were assigned to a nonexercising control group. Training consisted of one set of full-ROM, variable-resistance lumbar extension exercises with a weight load that allowed 6 to 15 repetitions to volitional fatigue (maximal effort). Both groups were tested before and after training by using the multiple-joint, seven-angle IM testing protocol mentioned earlier.

The results showed that the exercise group significantly improved their isolated IM lumbar extension strength through a full 72 degrees of ROM while the controls did not change (Fig 22–11). A unique finding of this study was the magnitude of the training response of the isolated lumbar extensor muscles. The 42% increase at 72 degrees (full flexion) to a 102% increase at 0 degrees (full extension) is much higher than what is normally found following training of other muscle groups. A review by Fleck and Kraemer[20] showed that the average increase in strength for most studies using IM or isotonic testing and training of a variety of different muscle groups was between 20% and 30%. It has been shown that participants who are untrained and who are low in strength with respect to their potential for strength gain have a greater capacity to acquire strength than do those who are highly trained or who are already close to their maximum strength potential.[13, 33] de Vries[13] and Fleck and Kraemer,[20] in recent reviews of exercise prescription for resistance training, alluded to the importance of this concept when evaluating the effectiveness of training programs. Thus, the magnitude of the training response observed for the isolated lumbar extensor muscles shows that they were initially very weak. Another significant factor was that 10 of the 15 subjects in the exercise group had been training regularly on the Nautilus low back machine (Nautilus Sports Medical Industries, Inc., Independence, Va). If the lumbar extensor muscles had been trained, further increases in strength would not have been expected.

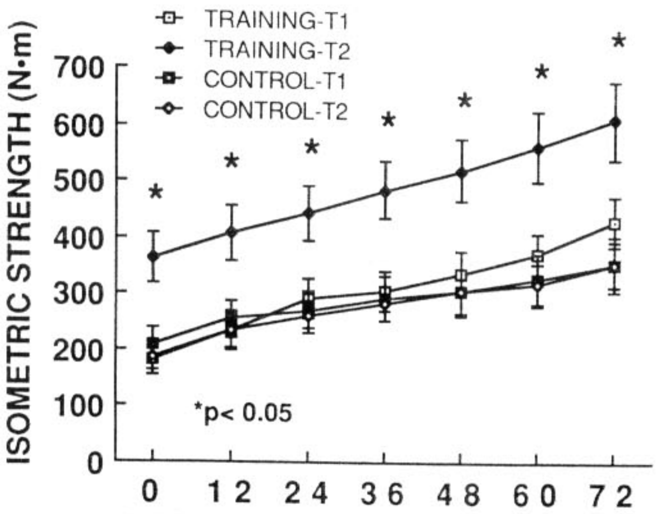

FIG 22–11.
Torque (newton-meters) measurements for isometric strength of the lumbar exterior muscles at 0, 12, 24, 36, 48, 60, and 72 degrees of lumbar flexion. T1 and T2 show measurements before and after 10-week training, respectively. Data represent means ± SEM. (From Pollock ML, Leggett SH, Graves JE, et al: *Am J Sports Med* 1989; 17:624–629. Used by permission.)

How can these unusually large increases in strength of the lumbar extensors, in particular, the latter half of the ROM, be explained? A reasonable explanation is that the strength of these muscles is not normally developed or maintained with existing exercise methods. These machines do not isolate the lumbar extensor muscles through pelvic stabilization. As mentioned earlier in this chapter, without proper stabilization of the pelvis, the larger, stronger gluteus and hamstring muscles do most of the exercise in back extension. This situation may be equivalent to that of a muscle that has been placed into a cast; it is in a state of chronic disuse, atrophies quickly, and loses its size and strength.[15–17, 47, 49, 64, 85] Thus, it appears that the lumbar extensor muscles never develop strength to their full potential and become atrophied from chronic disuse. This has important implications for primary prevention and rehabilitation of LBP since the lumbar extensor muscles seem to be the weak "link" in the "muscle chain" that protects the lower part of the back.

Whether the magnitude of strength gain found in this study was attributable to hypertrophy related to specific biochemical or histochemical adaptations to training or neural factors was not studied. But based on the time course of strength improvement discussed earlier by Moritani and de Vries,[61] most likely some of the early changes in strength could be attributable to neural factors, with hypertrophy being predominant thereafter. Some have suggested that a learning factor may have influenced the magnitude of strength gain. As mentioned in the evaluation and reliability section of this chapter, the learning associated with the testing procedure takes place during the initial test.[25] Since the subjects in this study had multiple tests initially and since the control group showed no increase in strength during the course of the study, learning was not considered an attributable factor in the results of this study.

As mentioned earlier, frequency of training is an important component of the exercise prescription for resistance training. Most experts recommend three training sessions per week for optimal results.[20, 73, 88] Although the strength increase from our initial training study was considered unusually large, only 1 day per week of training was used. Would a lesser or greater frequency of training elicit a different response? To answer this question 72 healthy men (31 ± 9 years old) and 42 women (28 ± 10 years old) volunteered to train for 12 weeks and were randomly assigned to training frequencies of one time every 2 weeks, one time per week, two times per week, or three times per week or to a nonexercising control group.[26] Each training session consisted of one set of full-ROM dynamic, variable-resistance exercise with a work load that allowed 8 to 12 repetitions to volitional fatigue. Figure 22–12 shows the adjusted post-training IM torque values for the various groups. When compared with the control group all exercise training groups improved their strength through a full ROM. Although there was a trend for the once-every-2-week group to show a smaller strength increase with training, the increases in torque found post-training were not statistically significant among groups.

Whether the groups exercising twice or three times per week would improve to a greater extent if they were allowed a longer time period to adapt to training was investigated in a follow-up study. Eighty-five of the subjects from the previously mentioned 12-week training study continued to exercise in the same manner for an additional 8 weeks for a total of 20 weeks of training. Increases in IM torque found at 20 weeks of training for the various exercise groups again showed no significant difference among groups.[7] Since the group training once every 2 weeks increased their dynamic training weight to a lesser extent than did the other exercise groups and because there were no differences among the groups training once, twice, or three times per week, 1 day per week of lumbar extension training is recommended for normal use.

The aformentioned studies of Pollock et al.,[72] Graves et al.,[26] and Carpenter et al.[7] all showed unusually large increases in isolated lumbar extension strength, with a greater magnitude of gain shown in the latter half of the ROM. Since most training studies in the literature have been conducted for 10- to 12-week durations, little evidence is available concerning further increases in strength beyond 12 weeks.[20] Also, most studies have only reported peak strength; thus inference as to whether strength increases are proportional through the full ROM is not well documented.

Carpenter et al.[7] evaluated the shape of the IM torque curve following 12 and 20 weeks of isolated lumbar extension training. The data from Figure 22–13 show that most of the increase in strength associated with lumbar extension exercise occurred during the first 12 weeks of training. Training up to 20 weeks showed no change in peak strength (72 degrees of lumbar flexion) from the 12-week testing period, but significant increases were found from 48 to 0 degrees of lumbar flexion. The time-by-angle interaction statistic showed that there was a change in the shape

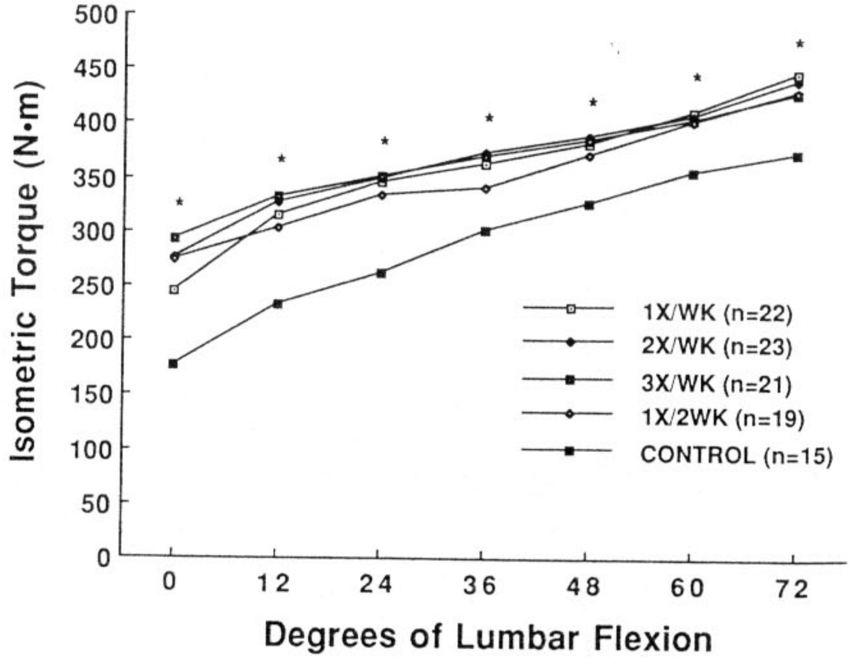

FIG 22–12.
Adjusted post-training isometric torques for the control group and the groups that trained dynamically every other week (1×/2WK), once per week (1×/WK), twice per week (2×/WK), and three times per week (3×/WK). *Control is less than 1×/2WK, 1×/WK, 2×/WK, 3×/WK ($P \leq .05$). (From Graves JE, Pollock ML, Foster D, et al: *Spine* 1990; 15:504–509. Used by permission.)

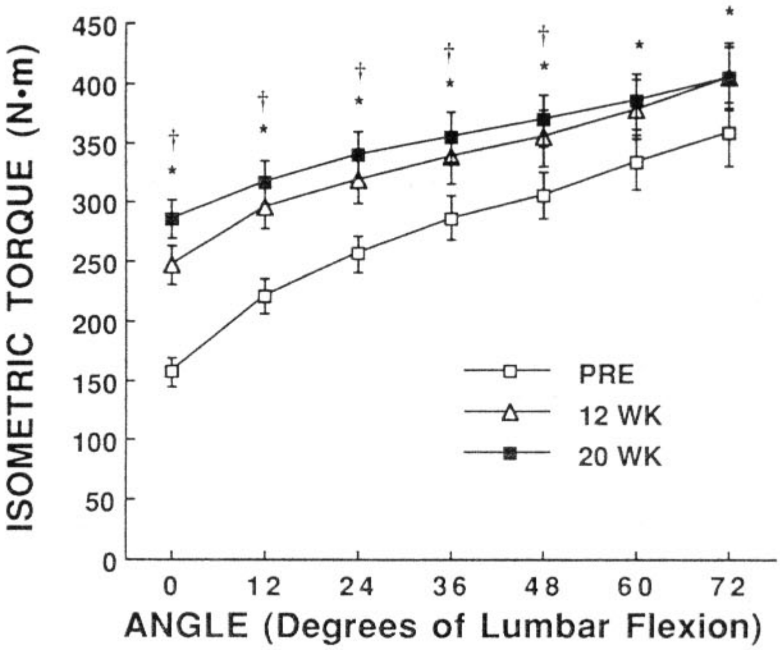

FIG 22–13.
Initial *(PRE)*, 12-week, and 20-week isometric torque values for the combined group. *PRE is less than 12-week and 20-week torques ($P \leq .01$). †Twelve-week is less than 20 week ($P \leq .05$). Values represent means ± SEM. (From Carpenter DM, Graves JE, Pollock ML, et al: *Phys Ther* 1991; 71:580–588. Used by permission.)

of the lumbar extension IM strength curve. The ratio of torque from 72 to 0 degrees of lumbar flexion was reduced from 2.3:1 prior to training to 1.6:1 at 12 weeks and 1.4:1 at 20 weeks. The flattening of the torque curve in the extended positions following training supports the contention that the lumbar extensor muscles are disproportionately weak in the mid to extended parts of the ROM. One of the more important points that can be surmised from this study is the importance of full-ROM testing and training, for if only peak torque were measured, inferences made from the results would have been different and limited.

To evaluate the specificity of IM training for developing lumbar extension strength, 14 volunteers trained with IM exercise at the same seven angles that are used for testing.[26] They trained one time per week for 12 weeks and were compared with a group that exercised dynamically once per week with variable resistance. Figure 22–14 shows that both the IM and variable-resistance training groups made significant and similar improvements in IM torque through the full ROM when compared with the control group. Thus, the results show that multiple–joint-angle IM training is as effective as dynamic training for developing full-ROM IM lumbar extension strength.

The full-range effect of the IM training was not surprising since it has been shown that both IM and dynamic training at specific joint angles results in a strength effect on either side of trained areas.[23, 27, 41, 48] The dynamic exercise was performed in a slow controlled manner that simulated the multiple IM efforts.[69] This plus the variable-resistance cam were effective in ensuring a full-ROM training response. Thus, either IM or dynamic variable-resistance training can be recommended for developing lumbar extension strength. Also, improvements in strength from periodic IM testing can be expected to stimulate improvement in some patients or research subjects.

To evaluate the effects of volume of training on lumbar extension strength, 110 volunteers exercised one time per week for 12 weeks with either one ($n = 42$) or two ($n = 53$) sets with 8 to 12 repetitions per set to volitional fatigue.[24] The results showed significant and similar full-ROM strength improvements for both exercise groups as compared with the controls (see Fig 22–15). Although the multiple-set (volume of training) issue is controversial, it appears that with the lumbar extensor muscles an added set of exercise has no advantage for most subjects.[20] Whether three sets of lumbar extension training would be superior to one set is not known, but based on the magnitude of results already found with one set plus the added time and cost that would result from a program of three sets per day, it would not be recommended.

To evaluate the effect of pelvic stabilization during variable-resistance lumbar extension training on isolated IM lumbar extension strength, 72 healthy men and women (aged 31.8 ± 10 years) trained 1 day per week for 12 weeks.[30] Subjects were randomly assigned to one of four

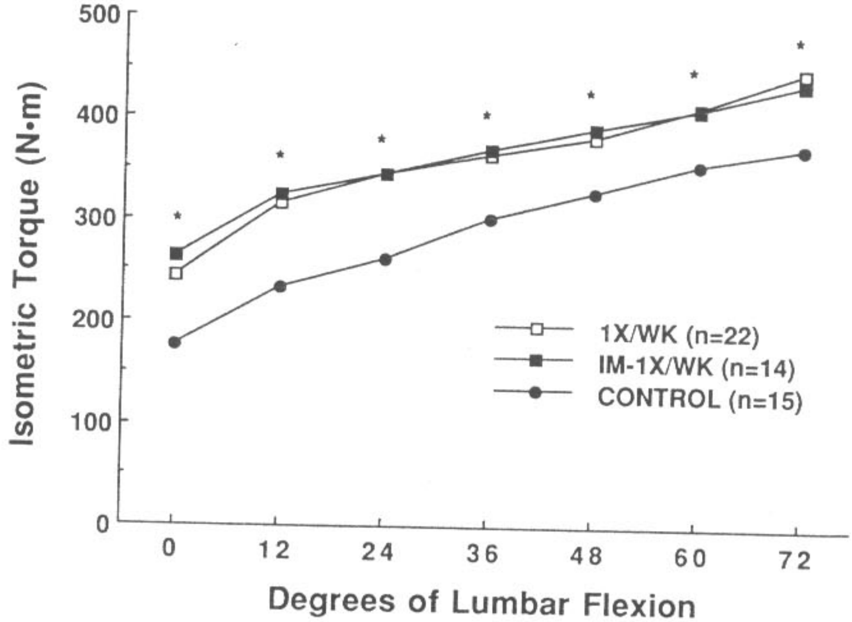

FIG 22–14.

Adjusted post-training isometric torques for the control and the groups that trained isometrically one time per week (IM-1×/WK) and dynamically one time per week (1×/WK). *Control is less than IM 1×/WK, 1×/WK ($P \leq .05$). (From Graves JE, Pollock ML, Foster D, et al: *Spine* 1990; 15:504–509. Used by permission.)

groups: Eagle (n = 19; Cybex, Ronkonkoma, NY); Nautilus (n = 19; Nautilus Sports Medical Industries, Independence, Va); MedX (n = 19; Ocala, Fla); and a control (n = 15). Only the MedX lumbar extension machine isolated the lumbar extensor muscles through pelvic stabilization. All training groups improved significantly in the dynamic training weight used for each specific apparatus (Eagle, 19.8 kg; Nautilus, 18.8 kg; and MedX, 23.8 kg). Adjusted post-training isolated IM torques, however, increased significantly only in the MedX group (see Fig 22–16). These data showed that pelvic stabilization is required to effectively condition the lumbar extensor muscles. Improve-

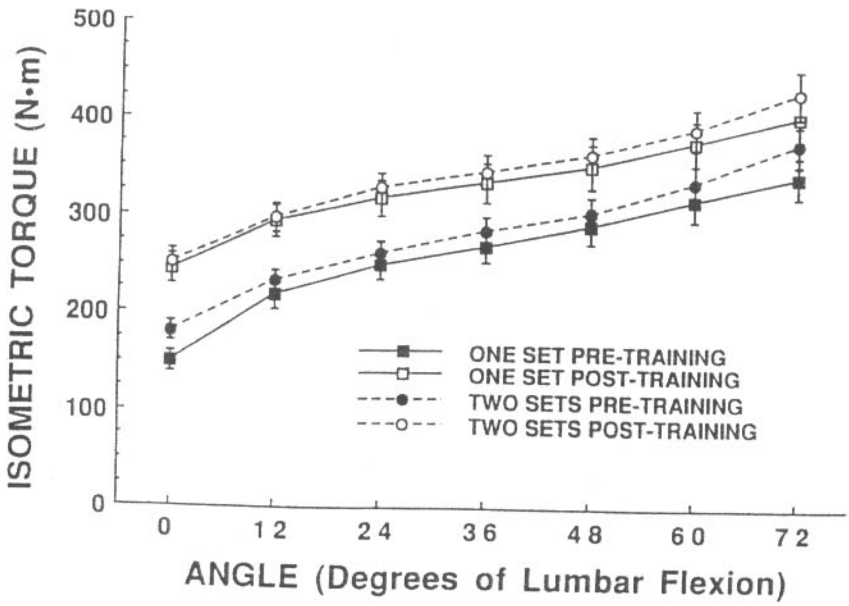

FIG 22–15.

Torque (newton-meters) measurements for isometric strength of the lumbar extensor muscles at 0 to 72 degrees of lumbar flexion. Data show pre-training and post-training results of groups that trained by doing either one set or two sets of exercises. (Data from Graves JE, Holmes BL, Leggett SH, et al: Single versus multiple set dynamic and isometric lumbar extension training. Presented at the World Confederation for Physical Therapy 11th International Congress, London 1991, pp 1340–1342.)

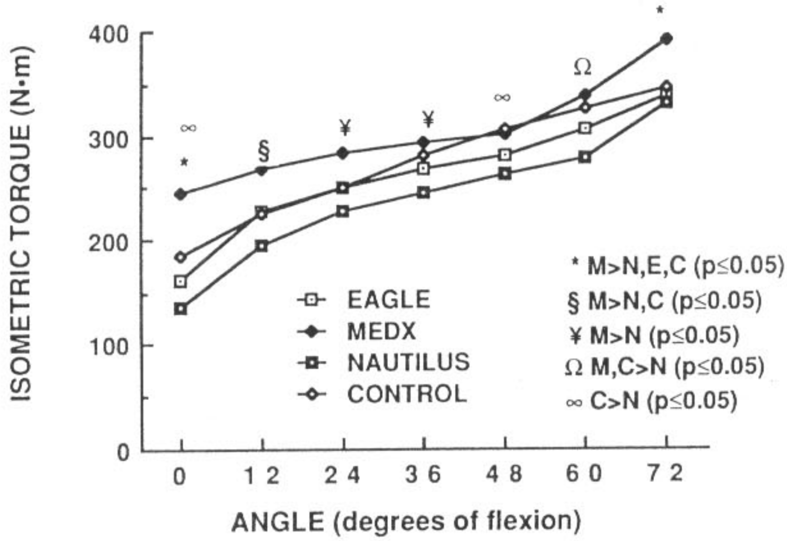

FIG 22–16.
Adjusted post-training isometric torque for the control group and the groups that trained by using Nautilus, MedX, or Eagle equipment. (From Graves JE, Webb D, Pollock ML, et al: *Int J Sports Med* 1991; 10:43. Used by permission.)

ments in the dynamic training weight noted for those groups that exercised without pelvic stabilization were likely due to strength increases in the gluteus and hamstring muscles.

An important question concerning both the primary prevention and rehabilitative settings is how much exercise training is necessary to maintain strength once it has been attained? It is generally known for both aerobic endurance and strength training exercise that it takes less to maintain fitness than it does to attain it.[28, 34] The key factor is not to stop altogether (detrain). It appears that frequency and duration of training can be greatly reduced, and as long as intensity of effort is maintained, a significant reduction in fitness will not occur. For example, Graves et al.[28] trained 50 healthy volunteers aged 25 ± 5 years two to three times per week for up to 18 weeks. Training consisted of one set of seven to ten repetitions of bilateral knee extension exercise to fatigue. Subjects were then placed into groups who stopped or reduced their training to 2 or 1 day/week for 12 weeks. The detraining group lost 68% of the IM strength that they gained during training, while the groups that completed at least one quality workout per week maintained their strength.

Although the above-mentioned study has important implications for long-term fitness and rehabilitation programs, how might it relate to the lumbar extensor muscles that need to be exercised only 1 day per week? To investigate this question Tucci et al.[86] trained 50 volunteers for 10 to 12 weeks with isolated lumbar extension exercise. After this training period, subjects were randomized into a group that detrained and into two groups that reduced their training to once every 2 weeks or once every 4 weeks for 12 weeks. Training consisted of one set of 8 to 12 repetitions of dynamic variable-resistance exercise to fatigue. The detraining group lost strength significantly through the full ROM (Fig 22–17). Both reduced training groups were able to maintain their lumbar extension strength with only a nonsignificant trend for the group training once every 4 weeks to decrease in strength from 0 to 24 degrees of ROM (see Figs 22–18 and 22–19). The important finding of this study is that once a participant/patient reaches a certain strength level in a preventive/rehabilitative program, he can maintain most if not all of his strength by returning to the clinic just one time per month. This would be considered cost-effective for long-term management of LBP and feasible for patients who have busy schedules or who live in an outlying area to the clinic.

The importance of accurate full-range testing was evident in the reduced-training study because if only peak torque were known, interpretation of the results would have been limited. For example, the detraining group lost 89% of their previous gains in their strongest position but were able to maintain approximately 60% at their weakest point.

Because reduced training frequency has important implications for long-term preventive and rehabilitative programs, more research is necessary to evaluate lesser frequencies of training and to conduct experiments over a longer time period. Even so, because of the trend for a decrease in strength in the last 24 degrees of ROM for the group training once every 4 weeks, it can probably be considered the minimal threshold of training necessary for full-ROM strength maintenance of the lumbar muscles (Fig 22–19).

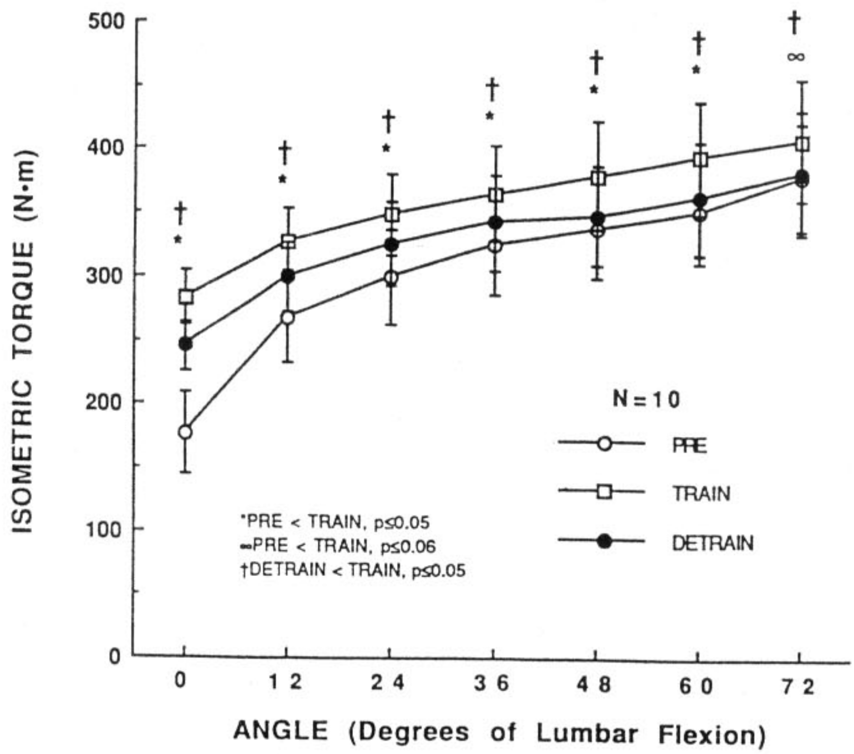

FIG 22-17.

Isometric torque (newton-meters) following 12 weeks of training *(TRAIN)* and 12 weeks of detraining *(DETRAIN)*. *PRE* = pretraining results. (From Tucci JT, Carpenter DM, Pollock ML, et al: *Spine*, in press. Used by permission.)

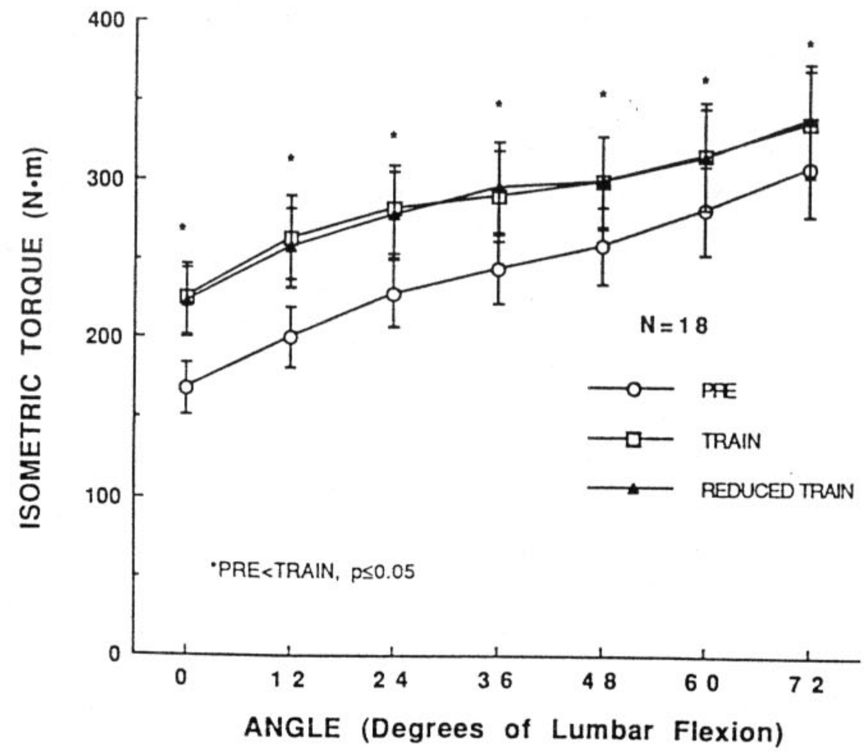

FIG 22-18.

Isometric torque (newton-meters) following 12 weeks of training *(TRAIN)* and 12 weeks of reduced training one time every 2 weeks. *PRE* = pretraining results. (From Tucci JT, Carpenter DM, Pollock ML, et al: *Spine*, in press. Used by permission.)

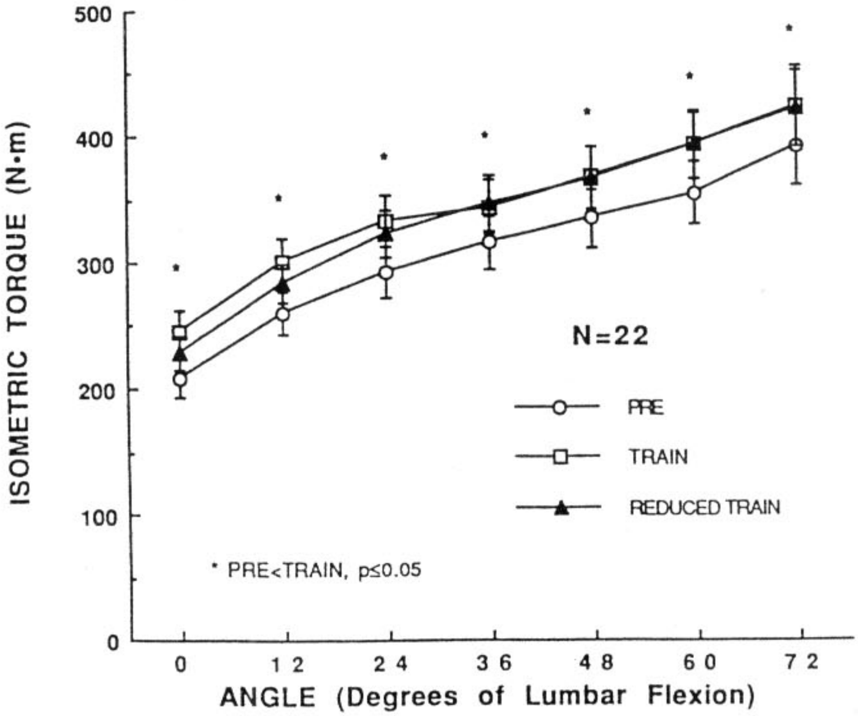

FIG 22–19.
Isometric torque (newton-meters) following 12 weeks of training *(TRAIN)* and 12 weeks of reduced training one time every 4 weeks. *PRE* = pretraining results. (From Tucci JT, Carpenter DM, Pollock ML, et al: *Spine*, in press. Used by permission.)

Exercise Training for Patients With Chronic Low Back Pain

Most of the preceeding information on exercise training has been with healthy subjects without LBP. This section will describe our training studies with patients with chronic LBP.

Our first group experience with chronic LBP included 12 subjects (aged 41 ± 3 years) who had mild chronic LBP for at least 2 years.[50] The purpose of the study was to determine the effects of variable-resistance training of the isolated lumbar extension muscles on the development of muscular strength and reduction of symptoms of chronic LBP. The evaluation included the seven-angle IM isolated lumbar extension test, a clinical examination, and the assessment of symptoms by the Prolo pain and Oswestry LBP disability questionnaires. Training consisted of one set of 10 to 15 repetitions of variable-resistance lumbar extension exercise 1 day per week for 12 weeks. Post-training adjusted values showed that IM torque increased significantly at all angles for the patients with LBP (Fig 22–20). A comparison group of normal healthy subjects made a slightly higher increase in strength from 0 to 24 degrees of lumbar flexion than did the patients. Training weights increased from 60 to 101 kg for patients with LBP and 68 to 110 kg for the subjects with no LBP.

The important finding of this study was the fact that LBP decreased significantly with training in patients with chronic LBP: 10 of 12 patients reported reduced functional status initially and 5 of 12 post-training (Prolo score), and the average Oswestry disability rating was 8% initially and 1% post-training. Thus, patients with mild chronic LBP may not present with lower-than-normal lumbar extension strength and appear to respond to resistance training in a similar fashion as normal subjects. More importantly, symptoms of LBP were decreased with specific training of the lumbar extensor muscles.

Even though the above-mentioned study showed promising results for relief of symptoms in patients with LBP, the study included a small sample and lacked the sophistication of having a randomized control group. Thus, a randomized clinical trial was designed and implemented with 55 patients with chronic LBP.[74] Patients ranged from 22 to 65 years of age, and the average duration of pain was 65 months. Forty-six percent of the sample were not working due to LBP, and 35% reported workmen's compensation as their primary income. Prior to participation in the study, patients completed the West Haven–Yale Multidimensional Pain Inventory (WHYMPI) and Sickness Impact Profile and were tested for isolated IM lumbar extension strength. Subjects were than randomly assigned to a 10-week exercise group (n = 31) or a wait-list control

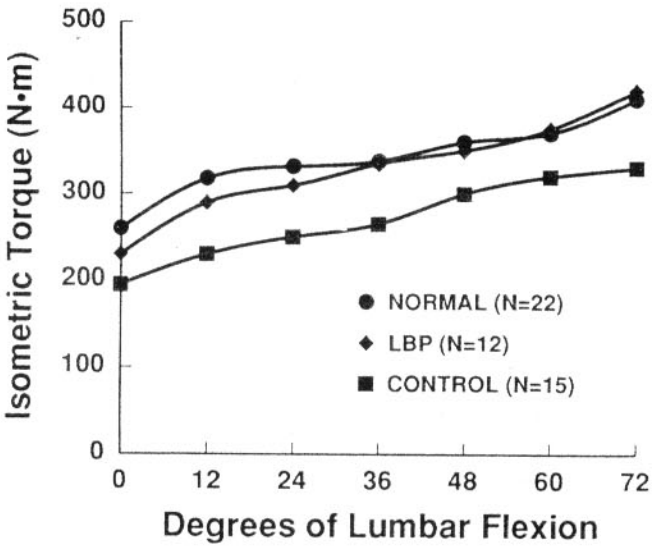

FIG 22–20.
Adjusted post-training isometric torques for the control group, normal group, and group with chronic low back pain *(LBP)*. Training was once per week for 12 weeks. Control is less than normal and patients with LBP at all angles tested ($P \leq .05$). (Data from MacMillan M, Pollock ML, Graves JE, et al: Effect of lumbar extensor resistance training on symptomatology and strength of patients with mild chronic low back pain (unpublished data). Department of Orthopaedics and the Center for Exercise Science, University of Florida, 1988.

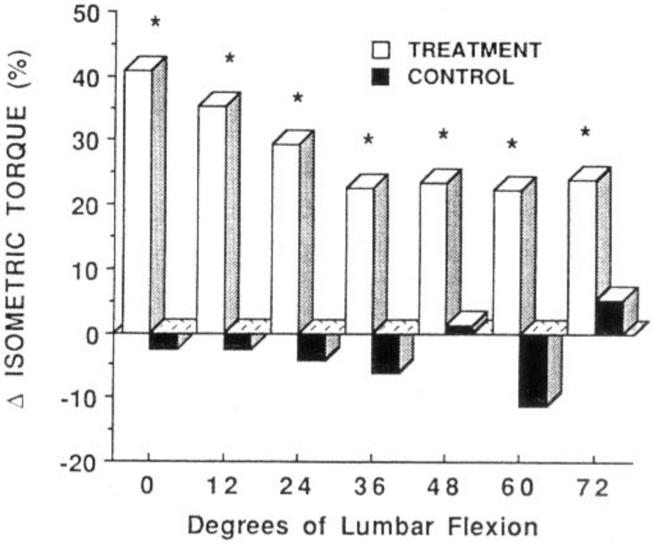

FIG 22–21.
Data show the percent change in isometric torque for a control and treatment group from 0 to 72 degrees of lumbar flexion. The treatment group performed lumbar extensor exercise once per week for 12 weeks. (Data from Risch SV, Norvell NK, Pollock ML, et al: *Spine*, in press.)

group ($n = 23$). The exercise group trained with variable-resistance dynamic exercise two times per week for 4 weeks followed by one time per week for 6 weeks for a total of 10 weeks. The control group did not train and were instructed not to change their life-style.

There were no pretreatment differences between groups on measures of strength, prior medical history, self-reported pain, psychological distress, stress, or activity levels. Post-treatment results showed that the exercise group increased IM strength through a full ROM while the control group did not change (Fig 22–21). Self-reported pain was measured by a subscale of WHYMPI that ranged from 0 for no pain to 6 for severe pain. The exercise group reported a significant decrease in pain as compared with the control group as well as decreases in scores on the physical and psychosocial subscale of the Sickness Impact Profile. Thus, the findings from this randomized clinical trial support the results from our earlier study, i.e., increased full-range strength and decreased symptoms in the exercise group, as well as an increase in physical and psychosocial function in the exercise group.

Since progressive resistance exercise training has been shown to be so effective in increasing isolated lumbar extension strength in both primary and rehabilitative programs and because many patients with LBP have limited range of lumbar motion, there was a need to evaluate the influence of limited-ROM exercise training on the development of full-ROM lumbar extension strength. Therefore, 58 healthy men and women (aged 30 ± 11 years) were randomly assigned to one of three training groups or to a control group that did not train.[29] Training was conducted one time per week for 12 weeks and consisted of one set of 8 to 12 repetitions of variable-resistance lumbar extension exercise to volitional fatigue. One group trained from 72 to 36 degrees of lumbar flexion (A), one from 36 to 0 degrees of lumbar flexion (B), and one at full ROM from 72 to 0 degrees of lumbar flexion (AB). The seven-angle isolated IM lumbar extension test described earlier was used to evaluate the training response. Post-training adjusted scores showed that all training groups increased in lumbar extension torque at all angles measured vs. the controls (Fig 22–22). Also, the greatest increases in torque were found for groups A and B in their respective ranges of training. These results are in agreement with research concerning the specificity of exercise and its effect on improvement of muscular strength.[27, 38, 58] For example, the data presented earlier on elite water-skiers showed a disproportionate strength curve in the latter half of the ROM (see Fig 22–6).[46] This was produced by specific limited-range heavy work near full extension.

The above findings also indicated that limited ROM lumbar extension training through a 36-degree ROM was effective for developing strength in an adjacent range of lumbar extension. These findings are in agreement with other investigators who have shown an extension of the training effect in an adjacent untrained area.[23, 27, 41, 48]

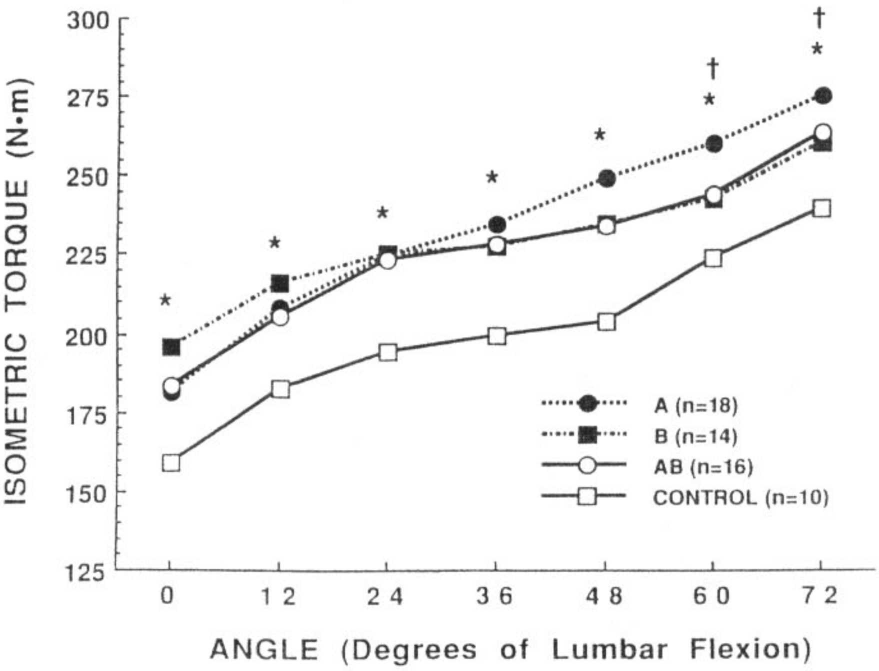

FIG 22–22.
Adjusted post-training isometric torque values (newton-meters) for the limited-ROM training (*A* and *B*), full-ROM training (*AB*), and control groups. Group A trained through a ROM limited between 72 and 36 degrees of lumbar flexion. Group *B* trained through a ROM limited between 36 and 0 degrees of lumbar flexion. Group *AB* trained through a 72-degree range of lumbar motion. *Control is less than *A*, *B*, *AB* ($P \leq .05$). †*A* is greater than *B* ($P \leq .05$). (From Graves J, Pollock M, Leggett S, et al: *Med Sci Sports Exerc* 1992; 24:128–133. Used by permission.)

Since many patients with LBP have limited ROM in the lumbar spine, the above findings have important implications for rehabilitation programs. Patients who are limited in ROM due to muscle weakness may benefit beyond their range of training and increase ROM. Thus, conservative progression in ROM will not compromise strength gain in the adjacent ROM not exercised.

REFERENCES

1. Atha J: Strengthening muscle. *Exerc Sport Sci Rev* 1981; 9:1–73.
2. *Back Injuries: Cost, Causes, Cases, and Prevention.* Washington DC, Bureau of National Affairs, 1988.
3. Battie M, Bigos S, Fisher L, et al: Isometric lifting strength as a predictor of industrial back pain reports. *Spine* 1989; 14:851–856.
4. Bemben M, Grump K, Massey B: Assessment of technical accuracy of the Cybex II isokinetic dynamometer and analog recording system. *J Orthop Sports Phys Ther* 1988; 10:12–17.
5. Berger RA: Application of research findings in progressive resistance exercise to physical therapy. *J Assoc Phys Ment Rehabil* 1965; 19:200–203.
6. Braith RW, Graves JE, Pollock ML, et al: Comparison of two versus three days per week of variable resistance training during 10 and 18 week programs. *Int J Sports Med* 1989; 10:450–459.
7. Carpenter DM, Graves JE, Pollock ML, et al: Effect of 12 and 20 weeks of resistance training on lumbar extension torque production. *Phys Ther* 1991; 71:580–588.
8. Carpenter D, Leggett S, Pollock M, et al: Quantitative assessment of isometric lumbar extension net muscular torque. *Med Sci Sports Exerc* 1991; 23(suppl):65.
9. Chaffin DB, Herrin GD, Keyserling WM: Preemployment strength testing. *J Occup Med* 1978; 67:403–408.
10. Chapman AE: The mechanical properties of human muscle. *Exerc Sport Sci Rev* 1985; 13:443–501.
11. Colletti LA, Edwards J, Gordon L, et al: The effects of muscle building exercise on bone mineral density of the radius, spine, and hip in young men. *Calcif Tissue Int* 1989; 45:12–14.
12. Costill DL, Coyle EF, Fink WF, et al: Adaptations in skeletal muscle following strength training. *J Appl Physiol* 1979; 46:96–99.
13. deVries HA: *Physiology of Exercise for Physical Education and Athletics,* ed 4. Dubuque, Iowa, WC Brown, 1986, p 14.
14. Dudley GA: Metabolic consequences of resistive-type exercise. *Med Sci Sports Exerc* 1988; 20(suppl):158–161.
15. Edstrom L: Selective atrophy of red muscle fibers in the quadriceps in long-standing knee joint dysfunction. Injuries to the anterior cruciate ligament. *J Neurol Sci* 1970; 11:551–558.
16. Edwards R: Human muscle function and fatigue, in Porter R, Whelan J (eds): *Human Muscle Function and Fatigue: Physiological Mechanisms.* London, Pitman Medical, 1981.
17. Edwards RHT, Jones DA: Diseases of skeletal muscle, in

Peachey LD (ed): *Handbook of Physiology*, section 10, *Skeletal Muscle*. Bethesda, Md, American Physiological Society, 1983, pp 633–672.

18. Farfan H: Muscular mechanism of the lumbar spine and the position of power and efficiency. *Orthop Clin North Am* 1975; 6:135–144.
19. Fillyaw M, Bevins T, Fernandez L: Importance of correcting isokinetic peak torque for the effect of gravity when calculating knee flexor to extensor muscle ratios. *Phys Ther* 1986; 66:23–31.
20. Fleck SJ, Kraemer WJ: *Designing Resistance Training Programs*. Champaign, Ill, Human Kinetics Books, 1987.
21. Fulton M, Jones G, Pollock M, et al: Rehabilitation and testing . . . conservative treatment for lower-back and cervical problems. *Rehabil Management* 1990; 3:2–40.
22. Fulton M, Pollock M, Leggett S, et al: Effect of upper body mass on the measurement of isometric lumbar extension strength. Presented at the Orthopaedic Rehabilitation Association Conference, San Antonio, Tex, 1990.
23. Gardner GW: Specificity of strength changes of the exercised and nonexercised limb following isometric training. *Res Q* 1963; 34:98–101.
24. Graves JE, Holmes BL, Leggett SH, et al: Single versus multiple set dynamic and isometric lumbar extension training. Presented at the World Confederation for Physical Therapy 11th International Congress, London, 1991, pp 1340–1342.
25. Graves JE, Pollock ML, Carpenter DM, et al: Quantitative assessment of full range-of-motion isometric lumbar extension strength. *Spine* 1990; 15:289–294.
26. Graves JE, Pollock ML, Foster D, et al: Effect of training frequency and specificity on isometric lumbar extension strength. *Spine* 1990; 15:504–509.
27. Graves JE, Pollock ML, Jones AE, et al: Specificity of limited range of motion variable resistance training. *Med Sci Sports Exerc* 1989; 21:84–89.
28. Graves JE, Pollock ML, Leggett SH, et al: Effect of reduced training frequency on muscular strength. *Int J Sports Med* 1988; 5:316–319.
29. Graves J, Pollock M, Leggett S, et al: Limited range-of-motion lumbar extension strength training. *Med Sci Sports Exerc* 1992; 24:128–133.
30. Graves JE, Webb D, Pollock ML, et al: Effect of training with pelvic stabilization on lumbar extension strength (abstract). *Int J Sports Med* 1991; 10:403.
31. Hakkinen K, Komi PV: Effect of different combined concentric and eccentric muscle work regimens on maximal strength development. *J Hum Move Studies* 1981; 7:33–44.
32. Herzog W: The relation between the resultant moments at a joint and the moments measured by an isokinetic dynamometer. *J Biomech* 1988; 21:5–12.
33. Hettinger T: *Physiology of Strength*. Springfield, Ill, Charles C Thomas, 1961.
34. Hickson RC, Foster C, Pollock ML, et al: Reduced training intensities and loss of aerobic power, endurance and cardiac growth. *J Appl Physiol* 1985; 58:492–499.
35. Hill A: The heat of shortening and the dynamic constants of muscle. Presented at the Royal Society of London, 1938, pp 136–195.
36. Holbrook TL, Grazier K, Kelsey JL, et al: *The Frequency of Occurrence, Impact and Cost of Selected Musculoskeletal Conditions in the United States*. Chicago, American Academy of Orthopaedic Surgeons, 1984.
37. Ikai M, Steinhaus AH: Some factors modifying the expression of human strength. *J Appl Physiol* 1961; 16:157–163.
38. Jones A, Pollock M, Graves J, et al: *The Lumbar Spine*. Santa Barbara, Calif, Sequoia Communications, 1988.
39. Kelsey JL, White AA, Pastides H, et al: The impact of musculoskeletal disorders on the populations of the U.S. *J Bone Joint Surg [Am]* 1979; 61:959–964.
40. Kishino N, Mayer T, Gatchel J, et al: Quantification of lumbar function. Part 4: Isometric and isokinetic lifting simulation in normal subjects and low-back dysfunction patients. *Spine* 1985; 10:921–927.
41. Knapik JJ, Mawdsley RH, Rammos NV: Angular specificity and test mode specificity of isometric and isokinetic strength training. *J Orthop Sports Phys Ther* 1983; 5:58–65.
42. Knapik JJ, Wright JE, Mawdsley RH, et al: Isometric, isotonic, and isokinetic torque variations in four muscle groups through a range of joint motion. *Phys Ther* 1983; 63:938–947.
43. Kraus H, Nagler W: Evaluation of an exercise program for back pain. *Am Fam Physician* 1983; 28:153–158.
44. Kulig K, Andrews J, Hay J: Human strength curves. *Exerc Sport Sci Rev* 1984; 12:417–466.
45. Lee C: The use of exercise and muscle testing in the rehabilitation of spinal disorders. *Clin Sports Med* 1986; 5:271–276.
46. Leggett SH, Pollock ML, Graves JE, et al: Physiological evaluation of elite professional waterskiers. Presented at the International Congress on Sports Medicine and Human Performance, Vancouver, Canada, 1990.
47. Lindboe CF, Platou CS: Disuse atrophy of human skeletal muscle. *Acta Neuropathol* 1982; 56:241–244.
48. Lindh M: Increase in muscle strength from isometric quadriceps exercises at different knee angles. *Scand J Med* 1979; 11:33–36.
49. MacDougall JD, Elder GCB, Sale DG, et al: Effects of strength training and immobilization on human muscle fibers. *Eur J Appl Physiol* 1980; 43:25–34.
50. MacMillan M, Pollock ML, Graves JE, et al: Effect of lumbar extensor resistance training on symptomatology and strength of patients with mild chronic low back pain (unpublished data). Department of Orthopaedics and the Center for Exercise Science, University of Florida, Gainesville, 1988.
51. Marras J, King A, Joynt R: Measurements of loads on the lumbar spine under isometric and isokinetic conditions. *Spine* 1984; 9:176–188.
52. Mayer L, Greenberg B: Measurement of the strength of trunk muscles. *J Bone Joint Surg* 1942; 4:842–856.
53. Mayer T, Gatchel R: *Functional Restoration for Spinal Disorders*. Philadelphia, Lea & Febiger, 1988.
54. Mayer T, Gatchel R, Kishino N, et al: Objective assess-

ment of spine function following industrial injury. A prospective study with comparison group and one-year follow-up. *Spine* 1985; 10:482–493.
55. Mayer T, Smith S, Keeley J, et al: Quantification of lumbar function. Part 2: Sagittal plane trunk strength in chronic low-back pain subjects. *Spine* 1985; 10:765–772.
56. Mayer TG, Gatchel RJ, Mayer H, et al: A prospective two-year study of functional restoration in industrial low back injury. *JAMA* 1987; 258:1763–1767.
57. Mayhew T, Rothstein J: Measurement of muscle performance with instruments, in Rothstein J (ed): *Measurement in Physical Therapy*. New York, Churchill Livingstone, 1985, pp 57–102.
58. McArdle W, Katch F, Katch V: *Exercise Physiology: Energy, Nutrition, and Human Performance*, ed 3. Philadelphia, Lea & Febiger, 1991.
59. McNeill T, Warwick D, Anderson GBJ, et al: Trunk strengths in attempted flexion, extension and lateral bending in healthy subjects and patients with low back disorders. *Spine* 1980; 5:529–538.
60. Meuller EA, Rohmert W: Die geschwindigkeit der muskelkraftzunahme bei isometrischem training. *Arbeitsphysiologie* 1963; 19:403–419.
61. Moritani T, deVries HA: Neural factors versus hypertrophy in the time course of muscle strength gain. *Am J Phys Med* 1979; 58:115–130.
62. Murray D: Optimal filtering of constant velocity torque data. *Med Sci Sports Exerc* 1986; 18:603–611.
63. Murray DA, Harrison E: Constant velocity dynamometer: An appraisal using mechanical loading. *Med Sci Sports Exerc* 1986; 18:612–624.
64. Musacchia XJ, Steffen JM, Fell RD: Disuse atrophy of skeletal muscle, animal models. *Exerc Sport Sci Rev* 1988; 16:61–87.
65. Nachemson AL, Lindh M: Measurement of abdominal and back muscle strength with and without low back pain. *Scand J Rehabil Med* 1969; 1:60–69.
66. Nelson S, Duncan P: Correction of isokinetic torque recordings for the effect of gravity. *Phys Ther* 1983; 63:674–676.
67. Nisell R, Ericson M, Nemeth G: Tibiofemoral joint forces during isokinetic knee extension. *Am J Sports Med* 1989; 17:49–54.
68. Nordgren B, Scheile R, Linroth K: Evaluation and prediction of back pain during military field service. *Scand J Rehabil Med* 1980; 12:1–7.
69. Osternig LR, Bates BT, James SL: Isokinetic and isometric force relationships. *Arch Phys Med Rehabil* 1977; 58:254–257.
70. Peterson C, Amundsen L, Schendel M: Comparison of the effectiveness of two pelvic stabilization systems on pelvic movement during maximal isometric trunk extension and flexion muscle contractions. *Phys Ther* 1987; 67:534–539.
71. Pollock M, Graves J, Leggett S, et al: Accuracy of counterweighting to account for upper body mass in testing lumbar extension strength. *Med Sci Sports Exerc* 1991; 23(suppl):66.
72. Pollock ML, Leggett SH, Graves JE, et al: Effect of resistance training on lumbar extension strength. *Am J Sports Med* 1989; 17:624–629.
73. Pollock ML, Wilmore JH: *Exercise in Health and Disease: Evaluation and Prescription for Prevention and Rehabilitation*, ed 2. Philadelphia, WB Saunders, 1990.
74. Risch SV, Norvell NK, Pollock ML, et al: Lumbar strengthening in chronic low back pain: Physiological and psychological benefits. *Spine*, in press.
75. Sale DG: Neural adaptation to resistance training. *Med Sci Sports Exerc* 1988; 20(suppl):135–145.
76. Sapega A, Nicholas J, Sokolow D, et al: The nature of torque "overshoot" in Cybex isokinetic dynamometry. *Med Sci Sports Exerc* 1982; 14:368–375.
77. Smidt G, Herring T, Amundsen L, et al: Assessment of abdominal and back extensor function: Quantitative approach and results for chronic low-back patients. *Spine* 1983; 8:211–219.
78. Staron RS, Hikida RS, Hagerman FC: Reevaluation of human muscle fast-twitch subtypes evidence for a continuum. *Histochemistry* 1981; 78:33–39.
79. Stone M: Implications for connective tissue and bone alterations resulting from resistance exercise training. *Med Sci Sports Exerc* 1988; 20(suppl):162–168.
80. Stone M, O'Bryant H: *Weight Training: A Scientific Approach*. Minneapolis, Bellweather Press, 1987.
81. Tesch PA: Skeletal muscle adaptations consequent to long-term heavy resistance exercise. *Med Sci Sports Exerc* 1988; 20(suppl):132–134.
82. Tesch PA, Komi PV, Hakkinen K: Enzymatic adaptations consequent to long-term strength training. *Int J Sports Med* 1987; 8(suppl):66–69.
83. Tesch PA, Thorsson A, Kaiser P: Muscle capillary supply and fiber type characteristics in weight and power lifters. *J Appl Physiol* 1984; 56:35–38.
84. Tipton CM, James SL, Mergner W, et al: Influence of exercise on the strength of the medial collateral knee ligaments of dogs. *Am J Physiol* 1970; 218:894–901.
85. Tomanek RJ, Cooper RR: Ultrastructural changes in tenotomized fast- and slow-twitch muscle fibers. *J Anat* 1972; 113:409–424.
86. Tucci JT, Carpenter DM, Pollock ML, et al: Effect of reduced training frequency and detraining on lumbar extension strength. *Spine*, in press.
87. Wakim K, Gersten J, Elkins E, et al: Objective recording of muscle strength. *Arch Phys Med* 1950; 31:90–100.
88. Wescott W: *Strength Fitness: Physiological Principles and Training Techniques*, ed 3. Dubuque, Iowa, WC Brown, 1991.
89. Winter D, Wells R, Orr G: Errors in the use of isokinetic dynamometers. *Eur J Appl Physiol* 1981; 46:397–408.