Resistance Training for Health and Performance

William J. Kraemer, PhD, Nicholas A. Ratamess, MS, and Duncan N. French, MS

Address
The Human Performance Laboratory, Department of Kinesiology, Unit 1110, The University of Connecticut, Storrs, CT 06269-1110, USA.
E-mail: kraemer@uconnvm.uconn.edu

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Resistance training is recommended by national health organizations for incorporation into a comprehensive fitness program that includes aerobic and flexibility exercise. Its potential benefits on health and performance are numerous; it has been shown to reduce body fat, increase basal metabolic rate, decrease blood pressure and the cardiovascular demands to exercise, improve blood lipid profiles, glucose tolerance, and insulin sensitivity, increase muscle and connective tissue cross-sectional area, improve functional capacity, and relieve low back pain. Many improvements in physical function and athletic performance are associated with the increases in muscle strength, power, endurance, and hypertrophy observed during resistance training. The key element to effective resistance training is supervision by a qualified professional and the proper prescription of the program variables. Proper program design, *ie*, that which uses progressive overload, variation, and specificity, is essential to maximize the benefits associated with resistance training.

Introduction

Traditionally, strength athletes seeking to improve muscle strength, hypertrophy, power, and sports-specific fitness almost exclusively performed resistance training. Although it has been shown to have profound effects on these physical fitness components, only recently have the health-related benefits of resistance training been elucidated. It is now a popular form of exercise that is recommended by national health organizations such as the American College of Sports Medicine (ACSM), American Heart Association, and the American Association for Cardiovascular and Pulmonary Rehabilitation, in conjunction with other modalities of exercise (*ie*, aerobic, flexibility), for the maintenance and improvement of health and performance [1••,2]. Particularly when incorporated into a comprehensive fitness program, resistance training reduces several risk factors associated with many diseases and physical ailments, and improves the quality of life by preserving and improving functional capacity [2]. In addition, it can improve athletic performance by increasing muscular strength, power, speed, size, endurance, balance, and coordination [3••]. The vast body of literature examining resistance training supports its inclusion into the daily exercise regimens of the adolescent, adult, and elderly populations. However, it is important that each individual participating in a resistance training program has adequate understanding of fundamental principles and techniques, and in certain cases be supervised by qualified professionals (*eg*, inexperienced trainees, children) for the prevention of injury and for maximizing the associated benefits [4•].

Important Qualities of Resistance Training Programs

In order to maximize the benefits of resistance training, adherence to three basic principles is mandatory. These principles are 1) progressive overload, 2) specificity, and 3) variation. *Progressive overload* is the gradual increase of stress placed on the body during resistance training. In reality, resistance training is only effective for improving health and performance if the human body is continually required to exert a greater magnitude of force to meet higher physiologic demands. Thus, a gradual increase in demand of the resistance training program is necessary for long-term improvement in muscular fitness and health. *Specificity* refers to the body's responses and subsequent adaptations to certain program variables. The physiologic adaptations to resistance training are specific to the muscle actions involved [5], velocity of movement [6], exercise range of motion [7], muscle groups trained [2], energy systems involved [2], and the intensity and volume of training [8]. The most effective resistance training programs are designed individually to bring about specific adaptations. *Variation* is the systematic alteration of the resistance training program over time to allow for the training stimulus to remain optimal. It has been shown that systematic program variation is most effective for long-term progression [9].

How much resistance training can improve health and performance depends on the individual's genetic makeup, program design and implementation, and training status or level of fitness. The rate of performance enhancement differs considerably between previously untrained and

trained individuals, as trained individuals have shown much slower rates of improvement [10]. These data demonstrate the difficulty in improving with greater levels of fitness, and stress the importance of a proper resistance training program design in order to progress further. It is important to note that progression is not always the major goal. Once a certain level of fitness is attained, many individuals tailor their programs to maintain that level. In either scenario, training programs are designed accordingly through proper manipulation of program variables.

The key quality to an individualized resistance training program is the acute manipulation of program variables targeting certain areas of muscular fitness. The program variables are 1) intensity (or loading), 2) volume (the number of sets and repetitions), 3) exercises selected, 4) the order of the exercises, 5) rest intervals between sets, 6) velocity of contraction, and 7) frequency. Altering one or more of these variables significantly affects the acute responses and subsequent physiologic adaptations to resistance training. Recently, the ACSM published a position stand on recommended progression models during resistance training [1••]. This document provides recommendations for novice, intermediate, and advanced levels of training for specific improvements in muscular strength, power, hypertrophy, endurance, and motor performance. Although it is beyond the scope of this article, we encourage readers to refer to this document [1••] for more information.

Resistance Training and Health Improvements

The potential health benefits associated with resistance training have significant impact on the quality of life and functional capacity of individuals of all ages. The safe and proper prescription of resistance exercise has been shown to reduce body fat and increase basal metabolic rate, decrease blood pressure and cardiovascular demands to activity, improve blood lipid profiles, improve glucose tolerance and insulin sensitivity, attenuate muscle sarcopenia, reduce the risk of osteoporosis and colon cancer, and maintain long-term independence and functional capacity [2,11,12,13••]. These benefits, as well as the performance-related benefits, have been shown to improve the quality of life in the elderly and clinical populations, such as those with low back pain, osteoarthritis, cardiovascular disease, HIV, neuromuscular disease (*eg*, myasthenia gravis, myotonic dystrophy), obesity, renal failure, chronic obstructive pulmonary disease, and type 2 diabetes mellitus, and those recovering from a stroke, [13••,14–18]. Although research has clearly demonstrated the value of resistance training for improving muscular performance, the influence of resistance exercise on health and physical well-being continues to be elucidated.

Resistance training and function in the elderly

Advancing age, particularly in sedentary individuals, is associated with a number of changes detrimental to health and performance. Sarcopenia, or the loss of skeletal muscle with advancing age, results in a lower basal metabolic rate, weakness, reduced activity levels, decreased bone mineral density, and increased risk of falls or injury [11,18]. This reduction in skeletal muscle mass can result in frailty and physical disability, which contribute to escalating health care costs. Resistance training is considered a promising intervention for reversing the loss of muscle function and deterioration of muscle structure that is associated with sarcopenia. Increasing evidence now indicates that elderly subjects respond favorably to weight training in a qualitatively similar manner as younger individuals. For example, in a study of physically frail 76- to 92-year-old men and women, Yarasheski *et al.* [19] reported that muscle protein synthesis was significantly greater following 3 months of supervised weight training. Other studies have shown that resistance training significantly increases the mass and quality of skeletal muscle [18]. These findings indicate that elderly individuals can respond favorably to the increased contractile activity associated with progressive resistance training.

Cross-sectional and longitudinal data indicate that muscle strength declines by approximately 15% per decade in the sixth and seventh decades of life, and by about 30% thereafter [2], leading to reductions in the ability to perform daily functions. Therefore, a resistance training intervention may be warranted to minimize these reductions in strength and performance in the elderly. A number of studies have demonstrated substantial increases in muscle strength in the elderly following resistance training [20,21]. For example, Charette *et al.* [20] reported increases in strength of 28% to 115% following 12 weeks of lower body resistance training in elderly women (mean age = 70 years). Pertinent to daily function in the elderly, other studies have shown significant improvements in local muscular endurance, balance, coordination, and functional ability (*eg*, ability to carry groceries, walk, and climb stairs, reduced risk of falls, and so forth) [22]. These studies indicate that resistance training can be performed safely by the elderly, and that such exercise significantly increases muscle strength and performance, due in part to the mechanisms associated with muscle hypertrophy. Such mechanisms serve to reverse the characteristic loss in lean body mass that is associated with sarcopenia.

Body composition and weight loss

Obesity is a chronic metabolic disorder that is associated with cardiovascular disease and increased morbidity and mortality. Multiple epidemiologic studies now show an association between body mass index and body fat with coronary heart disease, type 2 diabetes and insulin resistance, stroke, hypertension, and colon cancer [23]. The mortality rate increases by 50% to 100% when body mass index is equal to or greater than 30 kg/m^2. Central obesity appears to serve as a platform for a cascade of events that can result in a variety of clinical health problems. Proper

diet and aerobic exercise are important to weight loss and body fat reductions. In addition, resistance training is beneficial to body fat reduction and increase in lean body mass.

A review of the literature has shown that body fat reductions of 1% to 9% are possible following resistance training programs of various durations [24]. Increases in lean tissue mass and daily metabolic rates, in addition to greater energy expenditure while exercising, are observed during resistance training, which in turn may result in body fat reductions [3••]. For example, Van Etten *et al.* [25] reported a 9.5% increase in average daily metabolic rate after 18 weeks of resistance training. High-volume workouts with short rest periods using a large muscle mass appear most conducive to body fat reductions [3••]. Weight loss, and the associated dieresis, aid in reducing blood pressure in both overweight hypertensive and nonhypertensive individuals, reducing serum triglyceride concentrations, increasing high-density lipoprotein (HDL) cholesterol concentrations, and producing reductions in low-density lipoprotein (LDL) cholesterol concentrations.

Blood pressure

Hypertension, defined as resting systolic or diastolic blood pressure greater than or equal to 140/90 mm Hg, is a major public health problem affecting approximately 24% of noninstitutionalized adults in the United States [26]. Increasing scientific evidence now indicates that progressive resistance training is an effective nonpharmacologic intervention that may slightly reduce resting systolic and diastolic blood pressure. Although these small reductions appear minimal for reducing cardiovascular disease morbidity and mortality, it is likely that such small reductions can reduce the risk of stroke and coronary heart disease. According to the guidelines from the Joint National Committee for the Detection, Evaluation, and Treatment of Hypertension, these changes in resting blood pressure represent a shift from the high normal to the normal category. Decreased resting blood pressure following resistance training is most likely due to decreased body fat, decreased body salt, and alterations in the sympathetic drive to the heart. Resistance training has also been shown to increase left ventricular and septal wall thickness, reduce double product (an estimate of myocardial work and oxygen consumption), and reduce the cardiac demands to submaximal exercise [3••].

Blood lipids

The effects of resistance training on blood lipoproteins and triglycerides are not well documented. Results of cross-sectional studies have indicated that when compared with sedentary controls, resistance-trained individuals demonstrate similar total cholesterol, LDLs, HDLs, and triglyceride concentrations, but also lower total cholesterol and LDLs, higher HDLs, and lower triglyceride concentrations [27,28]. Longitudinal resistance training studies indicate either no change or beneficial effects on blood lipid profiles [13••]. Other factors, including nutrition and genetics, probably account for much of the variability in serum lipids. It does appear that the total volume of resistance training performed is a major contributing factor that influences lipoprotein concentrations.

Bone mass

Osteoporosis is a major public health problem that is characterized by low bone mass, reduced bone mineral density, and an increased susceptibility to fractures, primarily in the hip, spine, and wrist [29]. Weight-bearing physical activity provides the mechanical stimuli important for the maintenance and improvement of bone health. Bone is sensitive to intensity, compression, strain, and strain rate. Such forces are common in resistance training (especially those observed for multiple-joint structural exercises) and are translated into the type of exercise utilized, the intensity of the resistance, the number of sets, rate of loading, direction of forces, and frequency of training. For example, high-intensity resistance training has been shown to be more effective than low-intensity training for improving bone mass in the elderly [30]. It has generally been recommended that multiple sets of moderate to heavy loads for multiple-joint exercises be used for optimal bone loading [24].

Glucose tolerance and insulin resistance

Insulin resistance, or a reduction in the rate of glucose disposal elicited by a given insulin concentration, is present in individuals who are obese, the elderly, and those with diabetes mellitus. Favorable changes in glucose tolerance and insulin sensitivity usually deteriorate within 72 hours of an exercise session, indicating that regular physical activity is imperative for sustaining glucose-lowering effects and improving insulin sensitivity. The ACSM has recommended the inclusion of resistance training due to its potential to decrease the risk factors associated with cardiovascular disease, and improve glucose tolerance and insulin sensitivity [31]. Thus, modification of the changes in body composition that occur with resistance training can delay the onset of insulin resistance.

Lower back pain

Low back pain and spinal disorders are a frequent cause of activity limitation among individuals below the age of 45 years, and are second only to cardiovascular problems for physician visit rates. As many as 80% of individuals in the Western world will suffer at least one disabling episode of low back pain during their lives. In the United States, $60 billion per year is spent treating the condition; over 60% of individuals suffering an acute episode of low back pain will experience another bout within a year, and 45% of these will have a second recurrence within the following 4 years. Low back pain leads to muscle atrophy and weakening of core muscles critical to proper posture and spinal

function (*eg*, multifidus). Research over the past 10 years now indicates that chronic lower back pain is best managed by specific, progressive, and intense lumbar extension reconditioning exercise with the pelvis stabilized [32]. Exercise increases the strength and the cross-sectional area of the vertebral musculature, thereby reducing low back pain through the maintenance of muscle balance [33]. In particular, resistance training has been an effective exercise modality. Back stability training programs, including postural and core stability exercises, as well as basic strength training exercises, appear more effective for improvement than therapy alone. Patients with chronic low back pain who resistance train can expect significant improvements in muscle strength, balance, endurance, joint mobility, and relief of pain and symptoms [32].

Performance Improvements

Resistance training has been shown to improve most health- and skill-related components of physical fitness. Health-related components include muscle strength, endurance, hypertrophy, flexibility, body composition, and aerobic capacity. Skill-related components include speed, agility, power, balance, and coordination. In addition, these components serve the basis for many motor performance skills required in various sports and athletic events.

Muscular strength

It is well documented that muscle strength increases as a result of resistance training. In a review of the more than 100 studies, mean muscular strength increased approximately 40% in untrained, 20% in moderately trained, 16% in trained, 10% in advanced, and 2% in elite participants (*ie*, status based on training experience and level of fitness) over periods ranging from 4 weeks to 2 years [1••]. Given that the duration of these studies was different, these data provide some indication as to a pattern of improvement over time. Muscle strength improvements can be attributed to improvements in neural activation, greater cross-sectional area, and changes in muscle architecture and morphology [3••]. Increasing muscle strength has many benefits, including enhanced physical function (*ie*, ability to climb stairs, sit and stand from a chair, walk, and so forth) and quality of life in middle-aged and elderly individuals [34], enhanced level of fitness in recreational trainers [2], and enhanced athletic performance in individuals of all ages [3••]. Numerous types of resistance training programs may increase muscle strength, with the magnitude dependent on the exercises selected and sequencing, movement patterns and velocity, rest intervals between sets, frequency of training, intensity, volume, and variation of the training stimulus.

Muscle hypertrophy

It is well known that resistance training induces muscular hypertrophy [35]. Increasing muscle size is beneficial for 1) its positive relationship to force production and performance, 2) attenuation of muscle sarcopenia in aging, 3) appearance (*eg*, body building), and 4) increase in lean body mass (with subsequent increases in muscle power and speed), which creates a biomechanical advantage for anaerobic sports performance, especially those involving bodily contact. Muscular hypertrophy results from an accumulation of proteins. Alterations in protein metabolism occur via an increased rate of synthesis, decreased degradation, or both, is dependent on amino acid availability and blood flow, and is more prominent in fast-twitch than slow-twitch muscle fibers [36]. Protein synthesis in human skeletal muscle increases following only one bout of resistance exercise, peaks approximately 24 hours postexercise, and remains elevated from 2 to 3 hours up through 36 hours postexercise [36]. Muscle damage, resulting from mechanical (*eg*, eccentric muscle actions) or metabolic stress (*eg*, hypoxic-related factors), are stimuli for muscle hypertrophy, which are somewhat attenuated by chronic resistance training. This tissue remodeling process has been shown to be significantly affected by the concentrations of testosterone, growth hormones, cortisol, insulin, and insulin-like growth factor 1 [37,38]. Hyperplasia is another potential mechanism contributing to greater muscle size with resistance training. Although controversial at present, recent studies in humans indicate a possibility of hyperplasia occurring with anabolic steroid use specifically [39]. Although muscle hyperplasia may occur, it appears that hypertrophy is the predominant mechanism for increasing muscle size. Resistance training programs targeting muscle hypertrophy use a large variety exercises and sequencing patterns, with various lifting velocities (mostly moderate to slow). In addition, these programs use moderate to very heavy loads, relatively short rest intervals, and are high in volume or total work.

Muscle power

The expression and development of power is important from both a sports performance and lifestyle perspective. By definition, more power is produced when the same amount of work is completed in a shorter period of time, or when a greater amount of work is performed during the same period of time. All sporting events and activities of daily living involve some degree of power production such as hitting, striking, carrying, kicking, cycling, rowing, throwing, blocking, lifting, tackling, grappling, walking/running/sprinting, agility, jumping, and climbing. Neuromuscular contributions to maximal muscle power include the ability to develop force at a high rate, muscle strength at slow and fast velocities of muscle action, training of the stretch-shortening cycle, and coordination of movement pattern and skill. Traditional resistance training may increase power, but the most effective method for increasing power is the use of ballistic resistance exercise (*eg*, exercises performed with light to moderate loading, 30% to 60% of one repetition of maximum weight (1 RM), at maximal velocity throughout

the full range of joint motion) combined with traditional strength training [40,41].

Local muscular endurance

Local muscular endurance improves during resistance training [4•,42]. Traditional resistance training increases absolute muscular endurance (the maximal number of repetitions performed with a specific pretraining load), but limited effects are observed in relative local muscular endurance (endurance assessed at a specific relative intensity, or percent of 1 RM) [4•]. Moderate to low resistance training with high repetitions is very effective for improving absolute and relative local muscular endurance. A relationship exists between increases in strength and local muscle endurance such that strength training alone may improve local muscular endurance to a certain extent. However, specificity of training produces the greatest improvements. Training programs targeting improvements in local muscular endurance use various sequences of exercises performed with light loads coupled with high repetitions (15–20 or more) and moderate to heavy loading coupled with short rest periods.

Flexibility

Few studies have examined the effect of resistance training on flexibility. In the past, a large increase in muscle mass was thought to reduce flexibility of an individual. In reality, this may occur if an individual does not include any flexibility exercises. Resistance training alone may improve flexibility, especially in some sedentary and elderly populations [43], with the greatest magnitude observed in individuals with poor flexibility prior to beginning. The combination of resistance training and stretching appears to be the most effective method to improve flexibility with increasing muscle mass. Exercises need to be performed in a full range of motion to maximize gains in flexibility and reduce the risk of injury. It is important to note that intense stretching designed to increase flexibility should be performed following resistance exercise workouts, because some recent studies have shown intense stretching prior to resistance exercise decreases force and power output [44].

Aerobic capacity

Heavy resistance training does not significantly affect aerobic capacity (VO_{2max} [maximum oxygen consumption]). The lack of continuity during resistance exercise (*ie*, relatively long rest periods between sets) appears to pose limitations for potential improvements in aerobic capacity. Large muscle mass exercise workouts have been shown to elicit responses peaking at 60% of VO_{2max} [45], which may not reach the critical threshold needed for improvement. Circuit training and high-volume, short rest period (*ie*, 30 seconds or less) programs have been shown to improve VO_{2max} [46]. Therefore, it appears that increasing the aerobic component of resistance exercise (*ie*, decreasing the rest periods and keeping the volume high for working the total body) is the most effective way to improve VO_{2max} during resistance training, but the net effect will be considerably less than performing an aerobic exercise program.

Table 1. Motor performance increases observed during resistance training

Vertical jumping ability
Sprinting speed
Balance
Coordination
Throwing velocity
Kicking performance
Running economy
Bat swing velocity
Wrestling performance
Tennis service velocity

Motor performance

The effect of resistance training on various motor performance skills has been investigated. The importance of improved motor performance resulting from resistance training not only has implications for the training of specific athletic movements, but also for the performance of activities of daily living, *ie*, balance, stair climbing. The principle of specificity is important for improving motor performance because the greatest improvements are observed when resistance training programs are prescribed that are specific to the task or activity. Table 1 highlights some of the improvements observed in resistance training.

Conclusions

The potential benefits of resistance training on health and performance are numerous. The safe and proper prescription of resistance exercise has been shown to reduce body fat, increase basal metabolic rate, decrease blood pressure and the cardiovascular demands to exercise, improve blood lipid profiles, improve glucose tolerance and insulin sensitivity, attenuate muscle sarcopenia, reduce the risk of osteoporosis and colon cancer, maintain long-term independence and functional capacity, and relieve low back pain. In addition, the increases in muscle strength, power, endurance, and hypertrophy observed during resistance training are beneficial to improving motor performance. Proper program design, *ie*, that which uses progressive overload, variation, and specificity, is essential to maximize the benefits associated with resistance training.

References and Recommended Reading

Papers of particular interest, published recently, have been highlighted as:

- • Of importance
- •• Of major importance

1.•• American College of Sports Medicine: **Progression models in resistance training for healthy adults.** *Med Sci Sports Exerc* 2002, **34:**364–380.

Provides recommendations for resistance training progression.

2. Feigenbaum MS, Pollock ML: **Prescription of resistance training for health and disease.** *Med Sci Sports Exerc* 1999, **31:**38–45.

3.•• Kraemer WJ, Ratamess NA: **Physiology of resistance training: current issues.** In *Orthopaedic Physical Therapy Clinics of North America: Exercise Technologies.* Philadelphia: WB Saunders; 2000:467–513.

This paper provides a comprehensive review of the acute responses and chronic adaptations to resistance training, as well as changes in muscular performance.

4.• Mazzetti SA, Kraemer WJ, Volek JS, *et al.*: **The influence of direct supervision of resistance training on strength performance.** *Med Sci Sports Exerc* 2000, **32:**1175–1184.

Demonstrates the benefits of direct supervision on performance increases during resistance training.

5. Dudley GA, Tesch PA, Miller BJ, Buchanan MD: **Importance of eccentric actions in performance adaptations to resistance training.** *Aviat Space Environ Med* 1991, **62:**543–550.
6. Dudley GA, Tesch PA, Harris RT, *et al.*: **Influence of eccentric actions on the metabolic cost of resistance exercise.** *Aviat Space Environ Med* 1991, **62:**678–682.
7. Bandy WD, Hanten WP: **Changes in torque and electromyographic activity of the quadriceps femoris muscles following isometric training.** *Phys Therapy* 1993, **73:**455–467.
8. Häkkinen K, Pakarinen A, Alen M, Komi PV: **Serum hormones during prolonged training of neuromuscular performance.** *Eur J Appl Physiol* 1985, **53:**287–293.
9. Stone MH, Potteiger JA, Pierce KC, *et al.*: **Comparison of the effects of three different weight-training programs on the one repetition maximum squat.** *J Strength Cond Res* 2000, **14:**332–337.
10. Häkkinen K, Komi PV, Alen M, Kauhanen H: **EMG, muscle fibre and force production characteristics during a 1 year training period in elite weightlifters.** *Eur J Appl Physiol* 1987, **56:**419–427.
11. Evans WJ: **Reversing sarcopenia: how weight training can build strength and vitality.** *Geriatrics* 1996, **51:**46–47, 51–53.
12. Kelley GA, Kelley KS: **Progressive resistance exercise and resting blood pressure: a meta-analysis of randomized controlled trials.** *Hypertension* 2000, **35:**838–843.
13.•• Pollock ML, Franklin BA, Balady GJ, *et al.*: **Resistance exercise in individuals with and without cardiovascular disease: benefits, rationale, safety, and prescription.** *Circulation* 2000, **101:**828–833.

A position stand recommended by the ACSM, American Heart Association, Committee on Exercise, Rehabilitation, and Prevention, and Council on Clinical Cardiology for the use of resistance training in individuals with cardiovascular disease.

14. Clyman B: **Exercise in the treatment of osteoarthritis.** *Curr Rheumatol Rep* 2001, **3:**520–523.
15. Mazzeo RS, Tanaka H: **Exercise prescription for the elderly: current recommendations.** *Sports Med* 2001, **31:**809–818.
16. Storer TW: **Exercise in chronic pulmonary disease: resistance exercise prescription.** *Med Sci Sports Exerc* 2001, **33:**S680–S692.
17. Ansved T: **Muscle training in muscular dystrophies.** *Acta Physiol Scand* 2001, **171:**359–366.
18. Hurley BF, Roth SM: **Strength training in the elderly: effects on risk factors for age-related disease.** *Sports Med* 2000, **30:**249–268.
19. Yarasheski KE, Pak-Loduca J, Hasten DL, *et al.*: **Resistance exercise training increases mixed muscle protein synthesis rate in frail women and men _ 76 yr old.** *Am J Physiol* 1999, **277:**E118–E125.
20. Charette SL, McEvoy L, Pyka G, *et al.*: **Muscle hypertrophy response to resistance training in older women.** *J Appl Physiol* 1991, **70:**1912–1916.
21. Häkkinen K, Kallinen M, Izquierdo M, *et al.*: **Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people.** *J Appl Physiol* 1998, **84:**1341–1349.
22. Brochu M, Savage P, Lee M, *et al.*: **Effects of resistance training on physical function in older disabled women with coronary heart disease.** *J Appl Physiol* 2002, **92:**672–678.
23. Williams PT: **Health effects resulting from exercise versus those from body fat loss.** *Med Sci Sports Exerc* 2001, **33:**S611–S621.
24. Fleck SJ, Kraemer WJ: *Designing Resistance Training Programs,* edn 2. Champaign, IL: Human Kinetics Books; 1997.
25. Van Etten LM, Westerterp KR, Verstappen FT, *et al.*: **Effect of an 18-wk weight-training program on energy expenditure and physical activity.** *J Appl Physiol* 1997, **82:**298–304.
26. Kelley GA, Kelley KS: **Progressive resistance exercise and resting blood pressure: a meta-analysis of randomized controlled trials.** *Hypertension* 2000, **35:**838–843.
27. Cuppers HJ, Erdmann D, Schubert H, *et al.*: **Glucose tolerance, serum insulin, and serum lipids in athletes.** *Curr Probl Clin Biochem* 1982, **11:**155–165.
28. Giada F, Zuliani G, Baldo-Enzi G, *et al.*: **Lipoprotein profile, diet and body composition in athletes practicing mixed anaerobic activities.** *J Sports Med Phys Fitness* 1996, **36:**211–216.
29. Layne JE, Nelson ME: **The effects of progressive resistance training on bone density: a review.** *Med Sci Sports Exerc* 1999, **31:**25–30.
30. Vincent KR, Braith RW: **Resistance exercise and bone turnover in elderly men and women.** *Med Sci Sports Exerc* 2002, **34:**17–23.
31. American College of Sports Medicine: **Position stand: exercise and type 2 diabetes.** *Med Sci Sports Exerc* 2000, **32:**1345–1360.
32. Carpenter DM, Nelson BW: **Low back strengthening for the prevention and treatment of low back pain.** *Med Sci Sports Exerc* 1999, **31:**18–24.
33. Hides JA, Richardson CA, Jull GA: **Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain.** *Spine* 1996, **21:**2763–2769.
34. Weiss A, Suzuki T, Bean J, Fielding RA: **High intensity strength training improves strength and functional performance after stroke.** *Am J Phys Med Rehabil* 2000, **79:**369–376.
35. Staron RS, Karapondo DL, Kraemer WJ, *et al.*: **Skeletal muscle adaptations during early phase of heavy-resistance training in men and women.** *J Appl Physiol* 1994, **76:**1247–1255.
36. Biolo G, Tipton KD, Klein S, Wolfe RR: **An abundant supply of amino acids enhances the metabolic effect of exercise on muscle protein.** *Am J Physiol Endocrinol Metab* 1997, **273:**E122–E129.
37. Kraemer WJ, Gordon SE, Fleck SJ, *et al.*: **Endogenous anabolic hormonal and growth factor responses to heavy resistance exercise in males and females.** *Int J Sports Med* 1991, **12:**228–235.
38. Kraemer WJ, Marchitelli L, Gordon SE, *et al.*: **Hormonal and growth factor responses to heavy resistance exercise protocols.** *J Appl Physiol* 1990, **69:**1442–1450.
39. Kadi F, Bonnerud P, Eriksson A, Thornell LE: **The expression of androgen receptors in human neck and limb muscles: effects of training and self-administration of androgenic-anabolic steroids.** *Histochem Cell Biol* 2000, **113:**25–29.
40. Häkkinen K, Komi PV: **The effect of explosive type strength training on electromyographic and force production characteristics of leg extensor muscles during concentric and various stretch-shortening cycle exercises.** *Scand J Sports Sci* 1985, **7:**65–76.

41. Newton RU, Kraemer WJ, Häkkinen K: **Short-term ballistic resistance training in the pre-season preparation of elite volleyball players.** *Med Sci Sports Exerc* 1999, **31:**323–330.
42. Marx JO, Ratamess NA, Nindl BC, *et al.*: **The effects of single-set vs. periodized multiple-set resistance training on muscular performance and hormonal concentrations in women.** *Med Sci Sports Exerc* 2001, **33:**635–643.
43. Barbosa AR, Santarem JM, Filho WJ, Marucci Mde F: **Effects of resistance training on the sit-and-reach test in elderly women.** *Strength Cond Res* 2002, **16:**14–18.
44. Behm DG, Button DC, Butt JC: **Factors affecting force loss with prolonged stretching.** *Can J Appl Physiol* 2001, **26:**262–272.
45. Tesch PA: **Short- and long-term histochemical and biochemical adaptations in muscle.** In *Strength and Power in Sport.* Boston: Blackwell Scientific Publications; 1992:239–248.
46. Gettman LR, Culter LA, Strathman T: **Physiological changes after 20 weeks of isotonic vs isokinetic circuit training.** *J Sports Med Phys Fitness* 1980, **20:**265–274.