Review Article

THE SIZE PRINCIPLE AND A CRITICAL ANALYSIS OF THE UNSUBSTANTIATED HEAVIER-IS-BETTER RECOMMENDATION FOR RESISTANCE TRAINING

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The size principle states that motor units are recruited in an orderly manner from the smaller (lower threshold) to the larger (higher threshold) motor units, and that the recruitment is dependent on the effort of the activity. Greater recruitment produces higher muscular force. However, the pervasive faulty assumption that maximal or near maximal force (very heavy resistance) is required for recruitment of the higher-threshold motor units and optimal strength gains is not supported by the size principle, motor unit activation studies, or resistance training studies. This flawed premise has resulted in the unsubstantiated heavier-is-better recommendation for resistance training. [*J Exerc Sci Fit* • Vol 6 • No 2 • 67–86 • 2008]

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Introduction

The purpose of this review is to show that the strongly supported size principle of motor unit recruitment has been incorrectly applied in the resistance training literature. Because greater motor unit activity produces a greater force output, it is mistakenly believed that a greater force (very heavy resistance) is required for maximal motor unit activation. This commonly held belief is an invalid reverse inference of the size principle. The belief is apparently based on a faulty premise, which was established without any supporting evidence (resistance training studies). This review also shows that the references cited by the authors, who claim that a heavier resistance produces greater strength gains, do not substantiate their training recommendations and in many instances are irrelevant to their claims. Although the section entitled *Misapplication of the Size Principle* is lengthy, it is important to show specifically how each of the authors' references failed to support their claims and recommendations. It is not sufficient simply to cite the references without noting exactly what the authors of those studies and reviews reported.

Despite the lack of supporting evidence, the heavier-is-better belief continues. Perhaps because these authors are considered by many to be the leading authorities in resistance training, their unsupported heavier-is-better training philosophy has gone unchallenged for decades.

The Size Principle

A motor unit consists of the neuron, its axon, and all the muscle fibers it innervates. A single motor unit may innervate a few to several hundred muscle fibers, and a specific muscle may contain a few to several hundred motor units. Smaller motor units are more easily excitable and innervate fewer muscle fibers than larger motor units (Guyton 1991). Although the size and specific force capability of each muscle fiber in a motor unit contribute to the total force capacity of a specific muscle, the variation in the number of innervated fibers is the predominant factor in differences in motor unit

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force and therefore total force capacity. The size principle states that when the central nervous system recruits motor units for a specific activity, it begins with the smallest, more easily excited, least powerful motor units and progresses to the larger, more difficult to excite, most powerful motor units to maintain or increase force. Gradation of force is a result of the activation of a number of active motor units (recruitment) and their rate of discharge (rate coding). This orderly recruitment of motor units provides a smooth gradation of force (Guyton 1991).

A motor neuron pool consists of all the motor units available for a specific activity. If the input to a specific pool of motor units exceeds the excitation threshold of the motor neuron, the neuron will generate action potentials (nerve impulses) to activate the innervated muscle fibers (Kossev & Christova 1998; Senn et al. 1997; Fuglevand et al. 1993; Guyton 1991). Thus, the motor neuron's recruitment threshold is dependent on the interaction between the organization and strength of the synaptic inputs and the motor neuron's intrinsic responsiveness to that input (Cope & Pinter 1995). Maximal recruitment occurs between 30% and 90% of maximal voluntary contraction (MVC), depending on the specific muscle (Enoka & Fuglevand 2001; DeLuca et al. 1996; Erim et al. 1996; Kukulka & Clamann 1981), with the threshold for maximal recruitment relatively lower in dynamic compared with static muscle actions (Linnamo et al. 2003). Smaller muscles, where smaller gradations in force are important, recruit all the motor units in the pool at relatively low force levels, and rate coding (firing more frequently) then becomes the primary means of modulating any increase in force (Fuglevand et al. 1993). Recruitment plays a greater role in force development in larger muscles, whereas rate coding is the predominant force-generating factor in smaller muscles (Seki & Narusawa 1996).

Origin of the size principle

Denny-Brown and Pennybacker (1938), who were investigating the occurrence of fibrillation in people with amyotrophic lateral sclerosis, stated that a specific voluntary movement always begins with the discharge of the same motor units. They noted that more intense contractions are accomplished by the addition of a greater number of the increasingly larger motor units, which are recruited in a specific orderly sequence. The motor units recruited first were always the smaller motor units, and the sequence of recruitment was always followed by recruitment of the larger more powerful motor units, each controlling many more muscle fibers. In addition, they observed that in muscles that were affected by the loss of motor neurons, the larger motor units became activated without sufficient previous recruitment of the smaller motor units. The result of this disease process was an uneven gradation of force.

Henneman (1957) tested Denny-Brown and Pennybacker's (1938) observations on cats with transected spinal cords. He reported that recruitment of progressively larger motor units required progressively greater increases in the intensity of the stimulus. Henneman concluded that the susceptibility of neurons to discharge is a function of their size; hence, the size principle. Henneman (1968) later noted: "The smaller a motor neuron is the more easily it can be fired; the larger it is the greater is the amount of excitatory input required to discharge it. Since the size of a motor neuron and the size of a motor unit are directly related, it follows that the participation of a motor unit in graded motor activity is dictated by its size" (p. 625).

The reliability for the orderly recruitment of motor units, which is the cornerstone of movement control, has been substantiated over the last 40 years in animals (Wakeling et al. 2002; Cope & Sokoloff 1999; Cope et al. 1997; Bawa et al. 1984; Clamann & Henneman 1976; Clamann et al. 1974; Henneman et al. 1974; Henneman & Olson 1965; Henneman et al. 1965a, 1965b) and humans (Adam & DeLuca 2003; Houtman et al. 2003; Akaboshi et al. 2000; Scutter & Turker 1998; Feiereisen et al. 1997; Ivanova et al. 1997; Schmied et al. 1997; Jabre & Spellman 1996; Masakado et al. 1995; Riek & Bawa 1992; Knaflitz et al. 1990; Moritani & Muro 1987; Thomas et al. 1987; Thomas et al. 1986; DeLuca et al. 1982; Desmedt & Godaux 1981; Maton 1980; Desmedt & Godaux 1979; Goldberg & Derfler 1977; Freund et al. 1975; Milner-Brown et al. 1973). Thus, the size principle of motor unit recruitment is perhaps the most supported principle in neurophysiology.

The size principle determines the recruitment order (from smaller, low-threshold motor units to larger, higher-threshold motor units) during isometric, slow and fast muscle actions (Enoka & Fuglevand 2001; Ivanova et al. 1997; Masakado et al. 1995; Desmedt & Godaux 1977). For example, Masakado and colleagues reported the recruitment pattern during two consecutive isometric contractions of the first dorsal interosseous (index finger abduction) in five healthy males (age, 26–37 years). One smooth isometric contraction was followed by a contraction performed as fast as possible. Based on the recorded motor unit action potentials, the authors stated that there was no evidence of high-threshold motor units being selectively engaged during the fast contractions

(Masakado et al. 1995). That is, there were no observable violations of the size principle. In a similar investigation, Desmedt and Godaux (1977) noted that their data definitively excluded the hypothesis of preferential recruitment of fast-twitch higher-threshold motor units. The authors concluded that they did not observe a single instance when the faster (larger, higher threshold) motor units were recruited before the slower (smaller, lower threshold) motor units during either a slow contraction or a brisk ballistic contraction (Desmedt & Godaux 1977).

Thus, motor units are recruited in a regular, nonrandom sequence (Cope & Pinter 1995), and the predetermined order of recruitment reduces the time required to select an appropriate combination of active motor units because the input is distributed uniformly to the motor units (Senn et al. 1997). The size principle also ensures that the most frequently used and most easily excited motor units are those that are most resistant to fatigue, thereby enhancing energy efficiency (Cope & Pinter 1995). Edstrom and Grimby (1986) noted that the weaker, slower contracting, fatigue resistant motor units recruited before the stronger, rapidly contracting, fatigable motor units makes great functional sense for graded movements and prolonged exercise. Cope and Pinter (1995) concluded that the preponderance of available evidence suggests that there are no functionally meaningful violations of the size principle.

Practical application of the size principle

It is important to recognize that at the conception of the size principle, Denny-Brown and Pennybacker (1938) and Henneman (1957) specifically stated that the independent variable was the intensity of the stimulus and the dependent variable was the recruitment of higher-threshold (larger, more difficult to excite) motor units. Force was not the prerequisite for recruitment; force was the result of a more intense stimulus. The level of effort in voluntary muscle actions determines the degree of motor unit activity (see section on *Interpolated twitch technique* below). The fundamental neuromuscular concept is that all voluntary muscle actions initiate in the brain and action potentials are generated, which is analogous to the external electrical stimulus generated in Denny-Brown and Pennybacker's (1938) and Henneman's (1957) studies: the greater the stimulus (internal action potentials generated by the brain or external stimulus generated *in vitro*), the greater recruitment of motor units through the size principle. Each individual's effort determines motor neuron activation (see below).

Intensity of Effort and Motor Unit Activation

Interpolated twitch technique

The interpolated twitch technique (ITT) is an indirect measure of the level of motor unit activation during an MVC. During an MVC, a supramaximal electrical stimulus (typically a single, double or multiple stimuli) is superimposed (either manually or computer generated) with surface electrodes onto a muscle or its nerve. When the superimposed twitch technique is applied properly, the electrical stimulus fully activates all the motor units in the pool. If all the motor units have been recruited and are firing at optimal frequencies, no additional force will be detected. However, if some motor units are silent or firing at a low frequency, the interpolated stimulus will produce a twitch on top of the voluntary force. The evoked interpolated twitch is usually measured in Newtons (N) or Newton · meters (N · m). ITT cannot distinguish between incomplete recruitment and insufficient motor unit firing rate responsible for any increment in force as a result of the superimposed stimulus. Therefore, the term motor unit activation level (AL) is preferred (Folland & Williams 2006; Oskouei et al. 2003; Herbert & Gandevia 1999; Behm et al. 1996; Brown et al. 1990).

When there is an increment in external muscle force (the interpolated twitch) as a result of the superimposed stimulus during the MVC, the magnitude of the increment represents that portion of the muscle mass not activated by the voluntary effort. The interpolated twitch is typically normalized to the resting twitch force; that is, the force evoked by the same stimulus applied to the resting muscle (pre- and/or post-MVC). The formula for estimating the motor unit activation level is AL (%) = [1 − Evoked Force (superimposed on the voluntary force)/Evoked Response (control twitch force)] × 100 (Suter & Herzog 2001; Allen et al. 1998; Suter et al. 1996).

The amplitude of the interpolated twitch declines with increasing contraction intensity. A large interpolated twitch indicates a low level of voluntary activation, whereas a small or nonexistent interpolated twitch indicates near-maximal or truly maximal voluntary motor unit activation. Complete motor unit activation is indicated by no increment in force and implies that all motor units in a specific pool have been recruited and are firing at rates sufficient to produce a maximal force (Gandevia et al. 1998; Kent-Braun & Le Blanc 1996; Allen et al. 1995).

Although there are some questions concerning the resolution of force, number of control stimuli, and the sensitivity of twitch interpolation (Shield & Zhou 2004), a single stimulus, compared to a double or multiple stimuli, has been shown to provide a high enough level of sensitivity for detecting even slight decrements in voluntary drive (motor unit inactivity) and are appropriate for estimating AL. ITT is capable of detecting decrements in voluntary activation of less than 1% (Allen et al. 1998, 1995). One should expect that in any specific comparison study (see examples below), all methodological aspects such as sensitivity, variability, validity and reliability would be similar between the comparison groups.

Comparisons of activation levels

Several studies have reported the force (N) or torque (N · m) values for MVC, which is an isometric muscle action in most cases, and the AL in younger and older groups of previously untrained but healthy, physically active subjects (males and females). Values for specific muscles such as the knee extensors (Knight & Kamen 2001; Roos et al. 1999; Hurley et al. 1998), elbow flexors and extensors (Jakobi & Rice 2002; Klein et al. 2001; De Serres & Enoka 1998) and ankle plantarflexors and dorsiflexors (Klass et al. 2005; Connelly et al. 1999; Kent-Braun & Ng 1999; Kent-Braun & Le Blanc 1996; Vandervoort & McComas 1986) were reported for subjects in very different age groups (~ a half century).

For example, Roos and colleagues (1999) tested 13 younger (age ~ 26 years) and 12 older (age ~ 80 years) moderately active males for MVC and AL of the quadriceps. The younger group's force was 758 N compared with the older group's 396 N. However, there was no significant difference in motor unit AL between the younger (93.6%) and older groups (95.5%). Roos and colleagues concluded that the MVC of the older subjects was ~ 48% less than that of the younger subjects. Yet, despite the older group's significantly lower maximal force, ITT indicated that there was no significant difference in the ability of young and old subjects to activate their muscles (Roos et al. 1999).

Connelly and colleagues (1999) reported the tibialis anterior MVC and AL in six younger (age ~ 21 years) and six older (age ~ 82 years) healthy, recreationally active males. The MVC in the younger group (44 N · m) was significantly greater than that in the older group (32 N · m). However, there was no significant difference in AL between the younger (99.3%) and older (99.1%) subjects. They concluded that although the mean maximal torque was only 74% of that produced by the younger subjects, the older subjects were able to activate the tibialis anterior to a similar high level of ~ 99% (Connelly et al. 1999).

Jakobi and Rice (2002) reported the MVC and AL for the elbow flexors and extensors in six younger (age ~ 24 years) and six older (age ~ 83 years) males. MVC was significantly greater in the younger group (367 N) compared to that in the older group (208 N), but there was no significant difference in AL (98% and 96%, younger and older groups, respectively) for the elbow flexors. There was also a significant difference in elbow extensor MVC between the younger (318 N) and older (169 N) groups, with no significant difference in AL (98% and 99%, respectively). The authors concluded that although elbow flexion and extension MVC was significantly lower (43% and 47%, elbow flexors and extensors, respectively) in the older group, the maximal voluntary muscle activation was similar for the two groups (Jakobi & Rice 2002).

Klass and colleagues (2005) tested 20 younger (age ~ 26 years) and 19 older (age ~ 77 years) males and females to determine MVC and AL for isometric, concentric and eccentric muscle actions of the tibialis anterior. Although the mean MVC in the older group was 20% lower than that in the younger group, the AL (100%) was not significantly different between the younger and older groups, or between males and females (Klass et al. 2005).

Kent-Braun and Le Blanc (1996) reported the MVC and AL in a healthy group and a group with amyotrophic lateral sclerosis (ALS). The healthy group generated a higher MVC (152 N) than the ALS group (114 N), but there was no significant difference in motor unit AL following a single stimulus (100% and 96%, respectively) or double stimuli (100% and 96%, respectively). The only significant difference was following the superimposed train of multiple stimuli where the healthy group had a greater AL (96%) than the ALS group (85%).

Vandervoort and McComas (1986) reported the MVC and AL in five age groups (age ~ 20–100 years) of males and females for the dorsiflexors and plantarflexors. The males were consistently stronger than the females across the age groups (31–39% and 22–43%, dorsiflexors and plantarflexors, respectively), and the average MVC for the oldest groups (males and females) was ~ 55% of the youngest groups. However, males and females in all the age groups, including the youngest (20–32 years) and the oldest (80–100 years), were able to voluntarily fully activate (AL ~ 100%) their specific pool of motor units (Vandervoort & McComas 1986).

Practical application of ITT studies

These motor unit activation studies (Klass et al. 2005; Jakobi & Rice 2002; Klein et al. 2001; Knight & Kamen 2001; Connelly et al. 1999; Kent-Braun & Ng 1999; Roos et al. 1999; De Serres & Enoka 1998; Hurley et al. 1998; Kent-Braun & Le Blanc 1996; Vandervoort & McComas 1986), which compared different age groups, males and females, healthy and ALS patients, showed that the differences in the ability to generate force did not affect the ability to voluntarily activate specific motor units. The studies strongly support the previously discussed neurophysiological concept put forth by Denny-Brown and Pennybacker (1938) and Henneman (1957).

It is the intensity of the effort (maximal in the aforementioned ITT studies) that determines the AL of motor units and the resultant force output. A greater effort produces greater motor unit activation. Maximal effort produces maximal, or near maximal, activation of motor units. The resultant force, which is the dependent variable—not the independent variable—is a maximal force produced in a specific individual for a specific exercise. It is entirely dependent on the intensity of effort. However, it is important to recognize that none of the authors of the aforementioned ITT studies speculated on a minimal recruitment threshold for strength gains.

The motor unit AL required for an optimal stimulus to increase muscular strength is unknown, and may be considerably less than the 85–100% AL reported in the ITT studies. Therefore, a maximal or near maximal effort may not be required for optimal strength gains. A maximal effort only ensures maximal voluntary motor unit activation.

Perhaps the most relevant interpolated twitch study with the greatest practical application to resistance training was conducted by Behm and colleagues (2002). They measured recruitment properties by testing 14 resistance trained males (age ~ 21 years) for voluntary and evoked contractile properties before and after performing dynamic 5, 10 and 20 RM (repetition maximum) elbow flexion exercise (dumbbell curls) at recovery intervals of 30 seconds, 1, 2 and 3 minutes. Repetition duration was consistent across trials at 3 seconds concentric, 1 second isometric, and 3 seconds eccentric, with a resultant time-under-tension of 35, 70 and 140 seconds for the 5, 10 and 20 RM, respectively. The 12 sessions were randomly allocated and separated by at least 48 hours. The force amplitudes of superimposed stimulation compared with post-contraction stimulation was used to estimate the extent of activation during the MVC. The superimposed stimulation activated those motor units left inactivated by the maximal voluntary muscle action. There was no significant difference in voluntary motor unit activation following 5 RM (95.5%), 10 RM (93.5%) and 20 RM (95.1%). The three different loads (amount of resistance) in the 5, 10 and 20 RM protocols, and the very different time-under-tension (35, 70 and 140 s, respectively), elicited similar AL of motor units (93.5–95.5%). Behm and colleagues (2002) noted that the most important result of their study was that the 5 RM protocol did not produce greater motor unit activation than the 10 RM or 20 RM protocols. They concluded: "The commonly repeated suggestion that maximal strength methods [resistance heavier than a 6 RM] produce greater neural adaptations or increases in neural drive was not substantiated in this study" (p. 213). In fact, their study unequivocally demonstrated the direct relationship between intensity of effort—not the amount of resistance or time-under-tension—and voluntary motor unit activation.

Misapplication of the Size Principle

Although the size principle is described reasonably accurately in the resistance training literature, it is often followed by a misunderstanding of the underlying neurophysiological concept and its practical application to resistance training. Many resistance training authors state that in order to produce maximal muscular force, the larger and more difficult to excite motor units must be stimulated through a size principle continuum. That statement is supported by the size principle (Adam & DeLuca 2003; Houtman et al. 2003; Akaboshi et al. 2000; Scutter & Turker 1998; Feiereisen et al. 1997; Ivanova et al. 1997; Schmied et al. 1997; Jabre & Spellman 1996; Masakado et al. 1995; Riek & Bawa 1992; Knaflitz et al. 1990; Moritani & Muro 1987; Thomas et al. 1987; Thomas et al. 1986; DeLuca et al. 1982; Desmedt & Godaux 1981; Maton 1980; Desmedt & Godaux 1979; Goldberg & Derfler 1977; Freund et al. 1975; Milner-Brown et al. 1973). However, many authors (see below) also claim that in order to recruit the larger motor units, and more importantly to maximize strength gains, a maximal—or near maximal—resistive force is required. The latter statement is an invalid reverse inference of the size principle.

Science places the entire burden of proof on those who recommend heavier-is-better resistance training to support their claims and recommendations with resistance training studies and sound neurophysiological principles. However, the size principle, interpolated twitch studies, and resistance training studies do not support the contention that individuals must train with maximal or near maximal resistance to achieve optimal strength gains. The following are specific examples of misapplication of the size principle.

Fleck and Kraemer (1997) noted that based on increasing demands of a specific activity, higher-threshold motor units are progressively recruited after lower-threshold motor units. That statement is supported by the size principle. However, they also stated: "Heavier resistances (e.g., 3 to 5 RM) require the recruitment of higher-threshold motor units than lighter resistances (e.g., 12 to 15 RM)" (p. 61). It should be clearly understood that a 3–5 RM range does not merely describe the execution of 3, 4 or 5 repetitions. A 3–5 RM range specifically refers to the termination of the set because of the inability to perform another repetition. A 3 RM designates the completion of the 3rd repetition, with the inability to execute a 4th repetition; a 4 RM designates the completion of the 4th repetition, with the inability to execute a 5th repetition; and a 5 RM designates the completion of the 5th repetition, with the inability to execute a 6th repetition. With each specific RM, the completion of an additional repetition in good form is not possible. Similarly, a 12–15 RM range describes a set where the 12th, 13th, 14th or 15th repetition is a maximal effort. Regardless of the specific amount of resistance used (e.g., 3 RM, 4 RM, 5 RM, 12 RM, 13 RM, 14 RM or 15 RM), the progressive recruitment of lower- to higher-threshold motor units is similar because the effort is similar at the completion of the set—maximal. Therefore, the statement by Fleck and Kraemer that recruitment of the higher-threshold motor units is possible only with the heavier resistance (3–5 RM) and not the lighter resistance (12–15 RM) appears to be based on their misapplication of the size principle.

Fleck and Kraemer (1997) concluded that when performing a set of repetitions, the higher-threshold motor units are recruited as the required force increases. However, higher-threshold motor units are recruited as the effort increases throughout the set, not because of increased force. If the exercise form and repetition duration remain constant as one progresses through a set of repetitions, the force requirement at any specific point in the range of motion does not increase. Because of fatiguing motor units—not increased force requirement—recruitment of larger motor units and greater rate coding activity are required to maintain the force required to complete the set. Therefore, the degree of effort—not force—increases with each repetition. Another important distinction is that the completion of an RM set (e.g., attempting the 7th repetition with a 6 RM) is an MVC, but does not involve a maximal load (force). Relatively speaking, it is a maximal force output for the fatigued muscle.

The simplest example of increasing effort and a constant force is during an isometric muscle action. If a person is holding a 20 kg dumbbell at an elbow angle of 90 degrees, the internal (muscular) torque of the elbow flexor muscles is equal to the external (resistance) torque. The first 10 seconds may feel relatively easy. As the task becomes increasingly more difficult because of the gradual fatigue of the recruited motor units, the brain increases recruitment (through the size principle) and rate coding in order to maintain the required muscular force. If after about 60 seconds—despite a maximal effort to hold the resistance—the external torque exceeds the internal torque, the person will no longer be able to hold the 20 kg mass. Despite the increasing effort throughout the 60 seconds duration, the muscular force remained constant until it decreased at 60 seconds when the individual was no longer capable of producing a substantial muscular force to maintain the required internal torque. At the point of maximal effort (~ 60 seconds), all the motor units in the pool were recruited (including the larger motor units) for that specific isometric muscle action.

Fleck and Kraemer (1997) stated: "The factor that determines whether to recruit high- or low-threshold motor units is the total amount of force necessary to perform the muscular action" (p. 62), and "Typically Type II motor units have a high twitch force and so are not recruited unless high forces are needed" (p. 138). These are more examples of the misapplication of the size principle. That is, it does not require a maximal or near maximal resistance (external) force to recruit the larger motor units. According to the size principle, it simply requires a maximal or near maximal effort, which occurs near or at the end of any commonly used RM performance (e.g., 3–5 RM, 8–10 RM, 10–12 RM, 12–15 RM).

Kraemer and colleagues (1988) noted that the amount of resistance is probably one of the most important aspects of resistance training and that 6 RM loads result in the largest strength gains. They cited four references (Fleck & Kraemer 1987; Anderson & Kearney 1982; Atha 1981; Clarke 1973) in an attempt to support those statements. Anderson and Kearney (1982) compared 6–8 RM, 30–40 RM and 100–150 RM protocols. Because they did not compare any other commonly used and tested protocols (e.g., 3–5 RM, 8–10 RM, 10–12 RM, 12–15 RM), which may have produced similar increases in strength, the claim by Kraemer and colleagues lacks support. In the review by Atha (1981), he noted that there were several attempts to show that training with the heaviest loads produces the greatest gains in strength and he cited studies by Berger (1963) and O'Shea (1966). As described in a critical analysis (Carpinelli et al. 2004) of these and other resistance training studies, Berger (1963) reported no significant difference in strength gains for the bench press exercise as a result of training with a 2 RM (17%), 6 RM (21%) or 10 RM (20%); O'Shea (1966) reported no significant difference in strength gains for the squat exercise as a result of training with 2–3 RM (22%), 5–6 RM (27%), or 9–10 RM (20%). Atha concluded: "From these studies, one begins to believe that the importance of load magnitude may have been exaggerated" (p. 13). Then, without any explanation, Atha antithetically claimed: "Tension, not fatigue, is the strengthening stimulus…" (p. 15). Atha claimed that because an RM load such as a 10 RM does not result in an absolutely greater tension than a 5 RM, all the motor units available for the specific exercise would not be activated. That statement was probably the result of an incorrect application of the size principle by Atha.

The third reference cited by Kraemer and colleagues (1988) is a review by Clarke (1973), who cited two other studies by Berger (1962a, 1962b). Berger (1962a) trained 199 male college students three times a week for 12 weeks. All the participants performed the free weight bench press for 1 set of 2, 4, 6, 8, 10 or 12 RM. Berger and Clarke claimed that the gains in 1 RM bench press in the 4, 6 and 8 RM groups were significantly greater than in the 2, 10 and 12 RM groups (neither the pretraining data nor the percent gains were reported). According to Berger's Table 2 (p. 337), strength gains as a result of 4, 6 and 8 RM were significantly greater than 2 RM, and strength gains using the 8 RM protocol were significantly greater than 2, 10 and 12 RM. However, there was no significant difference in strength gains between the 2 RM group and the 10 or 12 RM groups, which indicated that there was no significant difference in strength gains as a result of training with the lightest (12 RM) and the heaviest (2 RM) loads. And, contrary to the statement by Clarke and in Berger's narrative, Berger's Table 2 (p. 337) showed no significant difference between the 6 RM group and the 4, 8, 10 and 12 RM groups.

In Berger's other study (1962b), there was no significant difference in strength gains (1 RM bench press) between groups using the lightest load (10 repetitions) and the heaviest load (2 repetitions) for either the lower volume 1-set protocol (12.2 and 11.3 kg, 10 and 2 repetition protocol, respectively) or the higher volume 3-set protocol (13.0 and 13.3 kg, 10 and 2 repetition protocol, respectively). That is, the heavier resistance did not elicit a significantly greater strength gain. The fourth reference cited by Kraemer and colleagues (1988) is the first edition (Fleck & Kraemer 1987) of the previously discussed book by the same authors (Fleck & Kraemer 1997). The four references cited by Kraemer and colleagues (1988) do not support their claims.

Fleck and Kraemer (1988) also recommended 2–6 RM loads for increasing strength (Figure 1, p. 165) and stated that loads lighter than 6 RM (7 RM or lighter) result in progressively smaller strength gains. For example, they claimed that strength gains as a result of training with a 6 RM are 50% greater than with a 10 RM. However, they did not cite any evidence to support their statements or recommendation.

Kraemer and Bush (1998) described the size principle as the orderly recruitment of motor units, which is dependent on the recruitment threshold, and that maximal force production requires the recruitment of the high-threshold motor units at a sufficiently high activation rate. However, they recommended 2–3 sets of 3–5 repetitions for increasing strength. They also claimed that advanced weightlifters may not require the orderly recruitment stipulated by the size principle because these advanced trainees can inhibit the lower-threshold motor units and preferentially activate the higher-threshold motor units. Kraemer and Bush did not cite any references to support their training recommendation, their incorrect application of the size principle, or violations of the size principle.

Kraemer and colleagues (1998) noted that motor unit activation is governed by the size principle, and they described the process: "Specifically, motor units are recruited according to their size and recruitment thresholds" (p. 111). However, they did not cite any references to support their statement that a resistance equal to or greater than a 6 RM has the greatest effect on strength gains (p. 114).

Kraemer and Newton (2000) stated that according to the size principle, the smaller low-threshold motor units are recruited first and the progressively higher-threshold motor units are recruited with increasing demands of the activity. However, their statement is followed by four misapplications of the size principle:

1. "Heavier resistances (e.g., 3–5 RM) require the recruitment of higher-threshold motor units than a lighter resistance (e.g., 12–15 RM)" (p. 363). As previously noted, by their description of RM loads, the demands (effort) with both the heavier and lighter resistance are similar at the end of the set.
2. "Lifting heavier resistances according to the size principle, however, starts with the recruitment of low-threshold motor units (Type I). The high-threshold

motor units (Type II) needed to produce greater force are recruited as the needed force increases" (p. 363). As previously discussed, the force does not increase throughout a set of repetitions with a specific resistance such as 3–5 RM or 12–15 RM.

3. "Exercises performed by weightlifters such as the clean and jerk lift may have the potential for recruitment patterns not adhering to the size principle to enhance power production. Rather than starting with the recruitment of low-threshold motor units, high-threshold motor units are recruited first. This means that the low-threshold motor units are not recruited in the activity but are skipped over to recruit the high-threshold motor units first" (p. 363). There was no reference cited to support their opinion that the size principle is violated.
4. "The determining factor of whether to recruit high- or low-threshold motor units is the total amount of force necessary to perform the muscular action" (p. 363). As previously discussed, their statement is not supported by the size principle or interpolated twitch studies.

In a book edited by Kraemer and Hakkinen, Kraemer claimed that a 6 RM load or heavier is required for strength gains (Kraemer 2002); Fleck (2002) recommended 2–6 repetitions to increase strength; Hasegawa and colleagues (2002) recommended 1–5 repetitions. None of these authors cited any references to substantiate their heavier-is-better training philosophy.

Kraemer and Gomez (2001) noted that the size principle is one of the primary concepts in neuromuscular activation, and that lower-threshold motor units are recruited before the higher-threshold units. They also claimed that there is documentation that shows inhibition of lower-threshold motor units, which supposedly allows the brain to more quickly activate higher-threshold motor units. However, they did not cite any evidence to support their belief that the size principle is violated.

Kraemer (2003) cited the previously discussed review by Atha (1981), and claimed that heavier resistance is associated with greater strength gains than lighter resistance. Kraemer (1983) expressed a similar opinion when he claimed that changing from a 10 RM to a 5 RM protocol would dramatically affect strength training outcomes, and that a 10 RM builds strength at a slower rate than a 5 RM. The only reference he cited was the previously discussed training study by Anderson and Kearney (1982) who compared 6–8 RM, 30–40 RM and 100–150 RM protocols. They did not use a 5 RM or 10 RM protocol, which was incorrectly reported by Kraemer (1983).

Kraemer and Ratamess (2004) noted that motor unit activity increases during the last few repetitions of a set. They stated: "Maximizing strength, power, and hypertrophy may only be accomplished when the maximal numbers of motor units are recruited. Thus, heavy loading in experienced individuals is needed to recruit the high-threshold motor units that may not be activated during light-to-moderate lifting" (p. 677). There is no reference cited to support either of their statements.

Kraemer and Fragala (2006) stated that by exercising larger muscles first, a superior training stimulus is applied to the involved muscles and that this would enhance the ability to lift a greater resistance. The authors claimed that a heavier resistance creates an optimal stimulus for strength gains. They also recommended a resistance heavier than 6 RM or greater than 85% 1 RM for optimal strength gains. However, they did not cite any evidence to support their heavier-is-better training philosophy (Kraemer & Fragala 2006).

In describing the size principle, Kraemer and Vingren (2007) stated that motor units with progressively higher thresholds are recruited based on increasing demands of the activity. They claimed that a 3–5 RM requires the recruitment of higher-threshold motor units than a 12–15 RM. "If only a low resistance (e.g., 12–15 RM) is used, then the largest motor units will not be recruited and thus will not benefit. Therefore, to maximize strength gains from a resistance training program, high resistance (1–5 RM) must also be used to stimulate adaptation in the largest motor units" (p. 19–20). Their Figure 1.10 (p. 20) depicts a high motor unit activation threshold for the 1 RM and 5 RM, and a low activation threshold for 15 RM and 20 RM. Kraemer and Vingren also claimed that the high activation threshold for the larger motor units is not attained unless high levels of force or power are produced, that there are specialized high-power motor units that are recruited only during high-power muscle contractions, and that during high-velocity movements, smaller motor units are skipped over (inhibited activation) so that larger motor units can be recruited first. They did not cite any evidence to support their heavier-is-better opinions, their invalid reverse inference of the size principle, or their claim for violations of the size principle.

Kraemer and colleagues (2007) noted: "The amount of resistance used for a specific exercise is one of the key factors in any resistance training program. It is the major stimulus related to changes in strength …" (p. 49). They claimed that if the goal is to maximize strength gains, then heavy loads with a few repetitions are required. The authors did not cite any references to support their recommendation.

Brown and colleagues (2007) stated that improving maximal strength is most successful when heavy loads are used; that is, 2–4 repetitions with loads close to the 1 RM. They did not cite any evidence to support their claim. Brown and colleagues also stated that loads between 85% and 95% 1 RM create the overload required for maximal strength gains and they cited a meta-analysis (Peterson et al. 2004) to support their recommendation. The credibility of the meta-analysis by Peterson and colleagues has been previously challenged (Otto & Carpinelli 2006). For example, Peterson and colleagues claimed that there was a trend for increased strength gains with a greater percent 1 RM up to 85% 1 RM. However, their own data actually failed to support that claim. Their effect sizes for training with 70%, 75%, 80% and 85% 1 RM were 0.07, 0.73, 0.57 and 1.12, respectively. The reported effect size was 10 times greater for training with 75% 1 RM compared with 70% 1 RM, decreased for 80% 1 RM, and then doubled for 85% 1 RM. Their data also implied the unlikely scenario that training with 70% 1 RM to muscular fatigue had no effect on strength gains. More importantly, there is no known physiological hypothesis to explain why a 5% difference in resistance, performed for one or two fewer or greater repetitions with a similar effort (RM), would result in such large differences in outcomes. In addition, many studies in the meta-analysis had no control group, which required the use of a pooled standard deviation rather than the pre-training standard deviation employed by Peterson and colleagues. Most of the studies included in their meta-analysis did not compare different RMs or percent 1 RM; they simply reported the effects of one specific protocol (e.g., with or without dietary supplements) on different outcomes. The data from this meta-analysis do not support the claims by Peterson and colleagues (2004) or Brown and colleagues (2007).

Stone (1993) noted that the size principle describes the recruitment process from the smaller to the larger motor units and the evidence suggests that this orderly sequence is similar for gradual or explosive voluntary and reflex muscle actions. However, he also stated that the larger motor units are only recruited when high force or high power outputs are required, and that in order to activate the larger motor units, very high forceful contractions must be employed. The former statement is valid. The latter statement is inconsistent with the size principle, which has resulted in unsubstantiated resistance training recommendations. According to the size principle, there is no reason to believe that non-explosive, lower-power repetitions performed with a moderate resistance and a reasonable effort—rather than explosive high force or high power repetitions—are any less effective for the recruitment of the larger motor units.

Stone (1982) also stated that purposefully slow movements reduce the training effect because the lower forces require the recruitment of fewer motor units; therefore, the larger motor units will not be effectively trained. He did not cite any training studies to support his opinion that the size principle is violated. As previously discussed, the size principle dictates that motor unit recruitment is determined by the degree of effort, which can be maximal or near maximal at the end of a set of repetitions, regardless of repetition duration or absolute muscular force.

Stone and O'Bryant (1984) stated: "Tension, not fatigue, is the major factor in developing maximum strength" (p. 148). Because the only reference to support their questionable application of the size principle was the previously discussed review by Atha (1981), their statement remains unsubstantiated.

Garhammer (1987) described the size principle as the recruitment of smaller motor units first and larger motor units last. He also claimed that performing 3 sets of 5 repetitions for the bench press and squat exercises was the most productive way to train, but recommended 10–15 repetitions for other exercises such as the thigh curl. No rationale was presented for his apparent incorrect interpretation of the size principle (heavier weights to recruit the larger motor units), or why the hamstring and quadriceps would require a different range of repetitions.

Berger (1982) noted: "The actual force of a muscle depends on the number of stimulated motor units and their frequency of firing or MUI [motor unit involvement]" (p. 15). However, he then stated: "To increase force capacity of a muscle, relatively heavy loads must be lifted" (p. 30). Berger's statement is surprising because his own studies (Berger 1963, 1962a, 1962b) do not support his claim, and because he specifically distinguished between force and effort. That is, Berger correctly stated that if a specific load (resistance) is held until fatigue occurs, the force of contraction remains constant as motor unit involvement increases (Berger 1982).

Palmieri (1983) noted that there is an orderly recruitment of motor units based on the size principle, with the smaller motor units recruited first followed by the larger motor units. However, his claim that the resistance (load) must be high because moderate loads do not require the recruitment of larger motor units is inconsistent with the size principle.

Haff and Potteiger (2001) described the size principle, but they then claimed that "... larger more powerful motor units are recruited only when high force or high power outputs are demanded by the activity. Thus, in order to activate the larger motor units, explosive exercises—which generally require high force and high power outputs—are needed" (p. 14). The authors did not cite references to support their statement, which was an apparent misapplication of the size principle.

Hoffman (2002) described the size principle as the orderly recruitment of motor units from the smaller, lower-threshold motor units to the larger, higher-threshold motor units. However, he also stated that with high-velocity, high-power muscle actions, the larger, higher-threshold motor units may be recruited first. He defined exercise intensity as the percent of an individual's RM for a specific exercise, and noted: "To maximize muscular strength gains, the muscle needs to be stimulated with a resistance of relatively high intensity" (p. 72); and "It appears that RM loads of 6 or fewer have the greatest effect on maximal strength or power output" (p. 80). Hoffman also recommended specific ranges of repetitions for different outcomes. Interestingly, he recommended 6–8 RM for maximal strength, which contradicted his previous claim of 6 or fewer repetitions, and 10–12 RM for muscular hypertrophy. He cited no references to support his recommendations or his erroneous interpretation of the size principle. In fact, there is very little evidence to suggest that his recommended differences in the range of repetitions elicit different outcomes (Carpinelli et al. 2004).

In an extensive review of resistance exercise intensity, Fry (2004) operationally defined intensity as the percent of maximal strength (%1 RM) for a specific exercise. He noted that exercise intensity is one of the most important training variables, and that the greatest percent increase in maximal strength occurs with loads approaching 100% 1 RM. He claimed that his Figure 3 "clearly illustrates" (p. 670) this specificity of training. His Figure 3 shows that resistance training with 95% 1 RM increased 1 RM by approximately 60% compared with training loads of 80%, 60% and 40% 1 RM (~ 36%, 34% and 36% increases, respectively) for the leg press exercise. However, the same figure also shows that the gains in 1 RM for the knee extension exercise were similar when using loads of 95%, 80% and 60% 1 RM (~ 58%, 51% and 52% increases, respectively). That is, Fry claimed that training the leg press with 95% 1 RM produced almost twice the strength gain as training with 80% 1 RM, but using 95% 1 RM and 80% 1 RM with the knee extension exercise produced similar strength gains (58% and 51%, respectively). Fry did not address the disparity in outcomes between these two exercises; that is, he did not explain what factors could possibly contribute to such large differences in the strength gains between these muscle groups.

A much more revealing issue is the examination of the four studies (Green et al. 1998; Hakkinen & Pakarinen 1993; Hakkinen et al. 1990; Thorstensson et al. 1976) that Fry (2004) cited to support his clearly illustrated data in Figure 3 (p. 670). Green and colleagues (1998) trained six previously untrained males (age, 19.2 years) three times a week for 12 weeks. All the participants performed 3 sets of 6–8 RM in the squat, leg press and knee extension exercises. Green and colleagues reported on histochemical analyses of the quadriceps muscles (fiber area, fiber-type distribution, enzyme activity, and capillarization). They reported the resistance (6–8 RM) used at the beginning and the end of the study. However, contrary to what Fry stated, there was no report of pre- or post-training 1 RM. In addition, Fry did not explain how he was able to determine the percent 1 RM (training intensity, according to Fry) from the range of repetitions. It has been shown that the number of repetitions performed to fatigue differs among individuals as well as among different exercises within an individual at a specific percent of the 1 RM (Hoeger et al. 1990, 1987).

Hakkinen and Pakarinen (1993) reported the acute hormonal responses in 10 male strength athletes (age, 29.7 years) to specific resistance training protocols. In one session, the athletes performed 20 sets of 1 RM squats with 3 minutes of rest between sets. At another session (separated by 48 hours), the subjects performed 10 sets of 10 RM squats with 3 minutes of rest between sets. Because of fatigue, the resistance was adjusted during the sessions so that the subjects were able to complete the designated number of repetitions in each of the 20 sets of 1 RM and each of the 10 sets of 10 RM. Resistance was reduced 10.3% during the 1 RM session and 24.6% in the 10 RM session. This was not a longitudinal training study. Therefore, the study does not support what Fry (2004) claimed in his Figure 3 (p. 670).

Hakkinen and colleagues (1990) reported neuromuscular adaptations, hormonal concentrations, and force production in seven non-competitive physically active females (age, 24.7 years) after 16 weeks of various body-weight jumping exercises. Strength training during the last 12 weeks consisted of several sets of 5–6 repetitions with 40–80% 1 RM for the leg press or squat exercise. Neither pre- nor post-training 1 RM was reported. Therefore, Fry's use of this study to support his claim for changes in 1 RM as a result of training with a specific percent of the 1 RM (40%, 60%, 80% or 95% 1 RM) is highly questionable (Fry 2004).

Thorstensson and colleagues (1976) trained 14 physical education students (age, 19–31 years) with 3 sets of 6 RM squats, three times a week for 8 weeks. The 1 RM squat increased 67%. However, they did not report the percent 1 RM used in training, and as previously discussed, the percent of the 1 RM for a specific exercise in a group of subjects cannot be accurately estimated from the number of repetitions performed. There was insufficient information reported in the four studies (Green et al. 1998; Hakkinen & Pakarinen 1993; Hakkinen et al. 1990; Thorstensson et al. 1976) cited by Fry (2004) to support his attempt to clearly illustrate a specificity (percent 1 RM) of training, and none of the studies he cited actually compared the effects of training with different percents of the 1 RM. Therefore, it is unclear how Fry derived the data shown in his Figure 3.

Fry (2004) also stated that it has been theorized that his training philosophy (heavier resistance produces better results) is more important for advanced trainees. The four references he cited to support his claim are books—not resistance training studies. The misapplication of the size principle in the books by Fleck and Kraemer (1997) and Stone and O'Bryant (1984) has been previously discussed. In their book entitled *Periodization Breakthrough!*, Fleck and Kraemer (1996) claimed that to increase maximal strength and power, 1–6 repetitions are required. They specifically noted that training with a 5 RM load produces mostly gains in maximal strength and power and some muscular size, while training with a 7 RM load elicits smaller gains in strength and power and greater muscular hypertrophy. They did not cite any training studies to support their opinion that training with 5 repetitions per set versus 7 repetitions per set would produce differential outcomes—either statistically or clinically significant—in muscular strength, power or hypertrophy.

In the book by Zatsiorsky (1995), the author reported his direct observations of the USSR weightlifting team during the year prior to the 1988 Olympic Games. Only 7% of all the lifts employed loads heavier than 90% maximum. These elite competitive athletes performed as many lifts (8%) with loads lighter than 60% of maximum. The majority of all the lifts (85%) were with loads between 60% and 90% maximum (Figure 4.4, p. 97). Zatsiorsky noted that the largest proportion of weights lifted was between 70% and 80% maximum resistance, and that these levels should be "thoughtfully implemented" (p. 107). Fry's heavier-is-better training philosophy (Fry 2004) is not supported by Zatsiorsky's observations.

Fry (2004) concluded: "The bottom line is that relatively heavy loads must be utilized if maximal strength is to be increased and/or maintained" (p. 671). However, neither the size principle nor the references (Green et al. 1998; Fleck & Kraemer 1997; Fleck & Kraemer 1996; Zatsiorsky 1995; Hakkinen & Pakarinen 1993; Hakkinen et al. 1990; Stone & O'Bryant 1984; Thorstensson et al. 1976) cited by Fry supports his conclusion.

Several other claims related to the size principle and motor unit recruitment in the aforementioned book by Zatsiorsky (1995), which was cited by Fry (2004) and also cited five times in the American College of Sports Medicine's Position Stand (2002) on resistance training, warrant examination. After he described the size principle, Zatsiorsky expressed opinions that lack any scientific support. For example, Zatsiorsky claimed in his Figure 4.7 (p. 103) that a 1 RM recruits all the motor units within the pool, with slower and intermediate motor units recruited but not exhausted; and the larger motor units recruited and exhausted (he did not define exhausted). He claimed in his narrative that these larger exhausted motor units are the only motor units subjected to a training stimulus. However, there is no neurophysiological evidence to suggest that during a maximal effort (e.g., 1 RM, 5 RM or 10 RM), an optimal stimulus requires exhaustion of the motor units. Furthermore, he did not cite studies that support any of his speculations.

Zatsiorsky (1995) noted that maximal muscular tension is achieved by lifting a maximal resistance (1 RM) or lifting a submaximal resistance to failure (e.g., 5 RM). Although a 1 RM could elicit high muscular tension, this is not the case with the submaximal resistance. The effort is the same (maximal), but as previously discussed, the tension created within the muscle is less with the submaximal load (assuming similar repetition duration). The tension remains at that level throughout a set of repetitions until fatigue causes a reduction in the ability to generate tension.

Zatsiorsky (1995) stated: "If an athlete can lift a barbell 12 times but lifts only 10, the exercise set is worthless" (p. 105). He noted that the smaller motor units are recruited but not exhausted, and the larger motor units are not recruited at all (Figure 4.7, p. 103). He claimed that if motor units are not fatigued (he did not define fatigued), then they are not trained. Because there is no universally accepted definition for the concept of exhausted or fatigued muscles, these words are extremely ambiguous unless specifically defined by the author. Zatsiorsky did not cite any references to support his opinion that not training to failure is worthless or to substantiate his speculation on exhausted or fatigued motor units.

Bird and colleagues (2005) recommended 8–12 RM for maximal strength gains and their only reference to support that protocol was a meta-analysis by Rhea and colleagues (2003). Rhea and colleagues claimed that previously untrained individuals experience maximal strength gains training with a 12 RM and that training with an 8 RM produces the greatest strength gains in previously trained (not defined) individuals. However, there are a few very important examples to show that the meta-analysis by Rhea and colleagues is illogical and impractical. In their Table 1 (p. 458), they reported an effect size of 2.8 as a result of training with an average 60% 1 RM and an effect size of 1.2 as a result of 70% 1 RM training. Assuming that the effort at the end of each set in the previously untrained subjects was similar in both situations, the effect size as a result of training with 60% 1 RM was 2.3 times greater than training with 70% 1 RM (a difference of 1.6 standard deviations). There is no known physiological mechanism that would explain their reported pattern of outcomes.

Rhea and colleagues' (2003) data for advanced trainees are also illogical from a practical aspect. They claimed that training with an average 80% 1 RM resulted in an effect size (1.8) that was almost three times greater than using 85% 1 RM (0.65). In other words, their data suggest that if the average 1 RM is 100 kg for a specific exercise, and training involves an 8 RM with 80 kg, which was estimated by Rhea and colleagues to be 80% 1 RM (e.g., with a variation of 70–90% 1 RM), the effect on strength gains is 2.8 times greater (more than 1 standard deviation difference) than performing that specific exercise with an average of 85 kg (85% 1 RM or approximately 6–7 RM). There is no known physiological mechanism that would explain this large difference in outcomes as a result of a relatively small change (5%) in resistance. In addition, the practical application of an average percent 1 RM is also questionable and was not addressed by Rhea and colleagues. For example, training three times a week with an average 80% 1 RM could refer to 1 set for a specific muscle group at each of the three sessions using 75%, 80% and 85% 1 RM (average = 80% 1 RM); or 3 sets for the muscle group with 65%, 80% and 95% 1 RM (average = 80% 1 RM); or some combination of these examples. They did not explain how they determined the average percent 1 RM or its practical application to resistance training. The conclusions regarding training intensity (percent 1 RM) reported by Rhea and colleagues are illogical, without foundation, and have no reasonable practical application to resistance training. Their own data do not support their own claims (Rhea et al. 2003) or the training protocol recommended by Bird and colleagues (2005).

In a lengthy review of adaptations to resistance training, Crewther and colleagues (2005) stated: "Heavy loads would seem fundamental to strength development, as high forces are associated with maximal motor unit recruitment according to the 'size principle', with these units also firing at higher frequencies" (p. 975). They also noted: "Given the relative importance of high forces for adaptation, the use of heavy training loads would appear to provide the superior stimulus for maximal strength development" (p. 975). Crewther and colleagues did not cite any references to support either of their apparent misapplications of the size principle.

Crewther and colleagues (2005) stated that because of the maximal efficiency of eccentric muscle actions, supramaximal loads (> 100% concentric 1 RM) may facilitate the development of "high-load forces" (p. 977). They claimed that a study by Murphy and colleagues (1994) supported the use of supramaximal eccentric loading to increase force production. However, Murphy and colleagues merely attempted to develop a so-called iso-inertial force-mass relationship with loads ranging from 30% to 150% concentric 1 RM bench press, determine its relationship to dynamic physical performance and isometric tests, and report the reliability of isometric and iso-inertial tests. This was not a training study. Furthermore, Murphy and colleagues did not suggest that training with higher supramaximal loads would elicit superior outcomes. Actually, they reported (Figure 2, p. 253) no significant difference in force measurements (~1150, 1160, 1170 and 1190 N, respectively) with loads (mass) of 100% concentric 1 RM (concentric-only muscle action), 100%, 130% and 150% concentric 1 RM (eccentric-only muscle action). This was antithetical to the claim by Crewther and colleagues that the force output increased "… with the heavier masses in the eccentric conditions" (p. 977).

Crewther and colleagues (2005) also stated that larger high-threshold motor units may be preferentially recruited during lengthening muscle actions with resistance greater than 100% concentric 1 RM, and that this supramaximal loading would seem ideal for maximal strength development. They cited a review by Behm (1995). In fact, Behm merely stated that Nardone and colleagues (1989) reported some alterations in motor unit recruitment during lengthening muscle actions, with some high-threshold motor units firing prior to low-threshold motor units. However, Nardone and colleagues reported electromyographic activity in five subjects who performed concentric, isometric and eccentric plantar flexion muscle actions with a torque that corresponded to 15–20% of the torque produced during a maximal voluntary muscle action. Neither the review by Behm nor the study by Nardone and colleagues supports the claim by Crewther and colleagues because the forces were less than 20% maximal and not supramaximal, as mistakenly reported by Crewther and colleagues.

Furthermore, Crewther and colleagues (2005) noted that ballistic training (described by them as throwing and catching the resistance) may enhance the training stimulus. They speculated that near maximal forces are required to elicit maximal strength gains. They did not cite any references to support their recommendation for throwing and catching the resistance.

Crewther and colleagues (2005) claimed that another benefit of supramaximal loading is the higher incidence of microscopic muscle injury, which provides an ideal stimulus for morphological adaptation to occur according to the protein degradation-synthesis response of muscle. However, the studies they cited (Nosaka & Newton 2002; Jamurtas et al. 2000) did not measure or report microscopic muscle injury. Nosaka and Newton reported the acute effects of performing 3 sets of 10 maximal eccentric arm curl muscle actions in one limb compared with 3 sets of 10 submaximal (50% maximal isometric force at 90 degrees) eccentric muscle actions in the contralateral limb of eight previously untrained males. Plasma creatine kinase concentration significantly increased after both sessions, with peak levels occurring 4–5 days post-exercise. These changes in creatine kinase were significantly greater following the session of maximal eccentric loading compared with submaximal loading, and the differences became greater after 3–5 days. The authors suggested that the difference in load affected the recovery process several days after the exercise session, which was significantly more than the changes immediately post-exercise. Nosaka and Newton specifically noted: "… CK [creatine kinase] activity may not be a quantitative reflection of muscle damage" (p. 207). However, they did advise against using maximal or near-maximal resistance for eccentric muscle actions in potential non-compliant trainees, and recommended the use of submaximal resistance and machines with eccentrically shaped cams (e.g., Nautilus machines) that vary the external torque. Contrary to the statement by Crewther and colleagues, Nosaka and Newton did not measure microscopic muscle damage. More importantly, they did not suggest that greater muscle damage would produce an ideal stimulus, nor did they speculate on how muscle damage would stimulate any strength-related adaptations.

In the other reference cited by Crewther and colleagues (2005), Jamurtas and colleagues (2000) reported the acute responses to 6 sets of knee extension and calf raise exercises performed to volitional exhaustion in 24 previously untrained males. Two sessions were separated by 6 weeks. The three groups of participants performed the exercises using 70% of their 1 RM concentric-only machine exercise, eccentric-only machine exercise, or plyometric jumps (concentric and eccentric muscle actions). Creatine kinase concentration significantly increased post-exercise, peaked at 24 hours, and remained elevated for 72 hours. The changes were not significantly different among the groups (concentric, eccentric and plyometric) at any time (24, 48 and 72 hours post-exercise). Muscle soreness was significantly lower in the concentric group compared with the other two groups. Jamurtas and colleagues speculated that the eccentric phase of the plyometric exercises may have produced more microscopic damage to the muscle fibers, as indicated by the greater degree of soreness. Because of the reported tenderness around the musculotendinus junction, they hypothesized that damage to connective tissue may have contributed to the perceived soreness. They did not measure microscopic muscle damage, nor did they speculate on the effect of muscle damage as a stimulus for adaptation, as erroneously reported by Crewther and colleagues.

Interestingly, four training studies compared conventional concentric/eccentric training with concentric/accentuated-eccentric training (also known as negative accentuated training). Brandenburg and Docherty (2002) randomly assigned 23 young males to one of two training groups: 4 sets of ~ 10 concentric/eccentric repetitions to concentric failure with ~ 75% of the concentric 1 RM, or 3 sets of ~ 10 concentric/accentuated-eccentric repetitions to concentric failure using ~ 75% of the 1 RM for the concentric muscle actions and 110–120% of the concentric 1 RM for the eccentric muscle actions. Both groups followed a 2-second concentric 2-second eccentric protocol for elbow flexion and elbow extension exercises for 9 weeks. They reported a significant increase in elbow flexor 1 RM (11% and 15%), elbow extensor 1 RM (9% and 24%), and specific tension (concentric 1 RM divided by the cross-sectional area) for the biceps (9% and 9%) and triceps (13% and 22%) in the traditional concentric/eccentric and concentric/accentuated-eccentric groups, respectively. There was no significant difference between groups except for

1 RM triceps strength, which was significantly greater in the accentuated-eccentric group. Muscle cross-sectional area of the biceps and the triceps as measured with magnetic resonance imaging did not significantly increase in either group. Out of the six reported dependent variables, only one (triceps 1 RM) showed a significant advantage to supramaximal loading. Notably, one third (4 of 12) of the subjects in the accentuated-eccentric (supramaximal) group withdrew from the study; two because of injury and two for non-compliance (Brandenburg & Docherty 2002).

Barstow and colleagues (2003) randomly assigned 39 previously trained males and females to perform traditional resistance elbow flexor exercise (60% 1 RM for concentric and eccentric muscle actions) or negative accentuated exercise (60% 1 RM concentric and 100% 1 RM eccentric muscle actions) for 3 sets of 6–10 repetitions two times a week for 12 weeks. The traditional group significantly increased strength (concentric 1 RM) by 13.8% and the negative accentuated group increased 15.5%, with no significant difference between groups. Barstow and colleagues concluded: "The results of this study suggest that although dynamic training load increased approximately 27% for both training groups, the C1RM [concentric 1 RM] analysis did not support the superiority of enhanced-eccentric training for improving isotonic elbow flexor strength in a group of trained subjects" (p. 66).

Two other studies reported no significant difference in strength gains or anthropometric outcomes (Godard et al. 1998; Ben-Siri et al. 1995), which strongly suggested that there was no additional benefit to training with supramaximal loads (refer to Carpinelli et al. 2004 for details). These four studies (Barstow et al. 2003; Brandenburg & Docherty 2002; Godard et al. 1998; Ben-Siri et al. 1995) are curiously missing from the review by Crewther and colleagues (2005). Moreover, Crewther and colleagues did not cite a single study to support their claim that there are superior outcomes as a result of training with supramaximal eccentric loads compared with concentric and eccentric training with a similar moderate resistance.

Crewther and colleagues (2005) stated: "… near maximal forces are necessary to induce maximal strength through neural mediated adaptation" (p. 984–5). One of the two references cited (Bloomer & Ives 2000; Schmidtbleicher 1992) is a chapter in a book. Schmidtbleicher (1992) claimed that compared with the requirement for the initial rate of force development for very light loads and maximal rate of force development for moderate loads, "maximal strength predominates" (p. 381) with very heavy loads. Schmidtbleicher did not cite any reference to support his opinion, which was reported by Crewther and colleagues. The other reference cited by Crewther and colleagues is a review by Bloomer and Ives (2000) who described the size principle, but then noted: "… if muscle fibers are recruited but not fatigued, they are not trained" (p. 31). One of the two references cited by Bloomer and Ives is the previously discussed book by Zatsiorsky (1995). The other reference is a review by Sale (1987). However, Sale noted: "… adaptations are induced only in those MUs [motor units] that are active in the training exercise" (p. 141). Sale specifically referred to the activation of motor units. He did not claim that motor units had to be fatigued. These references (Bloomer & Ives 2000; Zatsiorsky 1995; Schmidtbleicher 1992; Sale 1987) do not support the heavier-is-better claims by Crewther and colleagues (2005).

In a lengthy review of molecular and cellular adaptations to resistance training, Toigo and Boutellier (2006) expressed conflicting opinions. They noted that the size principle predicts that motor unit recruitment is determined by the force requirement and larger motor units are recruited only when the force requirement is high. However, their proposed model of motor unit recruitment states that as long as an exercise is performed to volitional muscular fatigue, different load magnitudes such as 60%, 75% and 90% 1 RM will result in similar complete motor unit recruitment. Obviously, their misapplication of the size principle and their proposed model of recruitment are antithetical.

In addition to the infiltration of the heavier-is-better training philosophy in resistance training guidelines, reviews and books, it has also affected the reporting of resistance training studies. For example, Hatfield and colleagues (2006) recently reported the acute responses in nine resistance-trained males to two different repetition durations (incorrectly noted by Hatfield and colleagues as speed of movement and movement velocity) after performing as many repetitions as possible with 60% and 80% 1 RM for the squat and shoulder press exercises. The longer repetition duration protocol (10 seconds concentric, 10 seconds eccentric muscle actions) resulted in significantly fewer repetitions, lower force levels, power and volume of work for both exercises compared with the self-selected repetition duration (not specified). There was no significant difference in the rating of perceived exertion between protocols or exercises (15.8 and 16.2 for the shoulder press using 60% 1 RM, 15.0 and 15.4 with 80% 1 RM, 15.4 and 16.6% for the squat at 60% 1 RM, and 15.9 and 14.0% at 80% 1 RM, longer and self-selected repetition durations, respectively). Their data showed that there was a similar effort at the termination of each of the eight exercise protocols. According to the size principle, a similar number of motor units were activated at the end of each exercise—regardless of the amount of resistance, number of repetitions, or repetition duration. This important point was apparently missed by Hatfield and colleagues.

Hatfield and colleagues (2006) stated in their Discussion section that the longer repetition duration would not allow one to train with an appropriate amount of resistance, and that maximum or near maximum force is required for optimal increases in muscular strength and hypertrophy. In an attempt to support their conclusion, they cited four studies (Shoepe et al. 2003; Siegel et al. 2002; Schlumberger et al. 2001; Sogaard et al. 1996). Schlumberger and colleagues compared single-set and multiple-set protocols in females who used similar amounts of resistance (6–9 RM). Shoepe and colleagues compared functional properties of muscle fibers in two groups of males (sedentary versus resistance trained). Siegel and colleagues simply reported the acute response (power output) to exercise with 30%, 40%, 50%, 60%, 70%, 80% and 90% 1 RM. Sogaard and colleagues reported motor unit recruitment patterns in six females during concentric and eccentric muscle actions of the elbow flexors with a 2 kg load. None of these studies (Shoepe et al. 2003; Siegel et al. 2002; Schlumberger et al. 2001; Sogaard et al. 1996) claimed or even suggested that high forces are required for optimal strength gains. Nor did any of them support Hatfield and colleagues' (2006) apparently incorrect application of the size principle.

Hatfield and colleagues (2006) also concluded that the highest possible force was required to optimize muscular performance and tissue adaptations. They cited only one reference to support that claim, which they noted as reference number 32. However, because they listed only 31 references, their statement remains unsubstantiated.

In another study, Shimano and colleagues (2006) concluded that performing as many repetitions as possible in the free weight squat, bench press and arm curl exercises using 60%, 80% and 90% 1 RM resulted in similar levels of perceived exertion in previously untrained males and resistance trained males. The practical application of these results and those of the aforementioned study by Hatfield and colleagues (2006) is that the perceived effort and therefore the recruitment of available motor units is similar when a set of repetitions is continued to the point of maximal effort (RM)—regardless of the number of repetitions, repetition duration, or amount of resistance. However, Shimano and colleagues apparently did not recognize the implication of their results and claimed that a resistance load of at least 90% 1 RM should be used for optimal strength gains in previously untrained and resistance trained individuals. They cited no evidence to support that claim or their misapplication of the size principle.

Minimal Support for Heavier-is-Better

Although not cited by any of the aforementioned authors who endorsed the heavier-is-better training philosophy, there is one study by Campos and colleagues (2002) who reported some advantage to a lower repetition protocol. They randomly assigned 32 previously untrained males (age, ~22 years) to one of three training groups (4 sets of 3–5 RM, 3 sets of 9–11 RM, or 2 sets of 20–28 RM) or a control group. The three training groups performed the leg press, squat and knee extension exercises 2 days a week for the first 4 weeks and three times a week for the next 4 weeks. Although the authors stated that they selected three practical ranges of repetitions, 20–28 RM is not commonly employed in most resistance training protocols. Therefore, comparisons are justified only between the 3–5 RM and 9–11 RM groups. The strength gain (1 RM) for the squat (~61%) and leg press (~100%) was significantly greater in the 3–5 RM group compared with the 9–11 RM group (~31% and ~80%, squat and leg press, respectively). There was no significant difference between the groups for the gains in knee extension strength (~67% and ~56%, 3–5 RM and 9–11 RM groups, respectively). Exercise-induced fiber transformation (from Type IIB to IIA) was similar for both groups, and muscle hypertrophy of the three fiber types (Types I, IIA and IIB) significantly increased in both groups, with no significant difference between groups. The authors did not speculate on why the heavier resistance (3–5 RM) produced more favorable strength gains in the leg press and squat exercises and not in the knee extension exercise, and their only comment regarding the similar hypertrophic responses in the 3–5 RM and 9–11 RM groups was that it was interesting. Campos and colleagues (2002) concluded: "It has often been accepted that improved strength/power results from high intensity/low volume training, whereas low intensity/high volume training maximizes muscle hypertrophy. Based on data from the present investigation, this may not be entirely true. Indeed, data from the present investigation suggest low and intermediate RM training induces

Table 1. Summary of authors who recommended heavier-is-better resistance training based on an incorrect application of the size principle

Brown et al. 2007
Kraemer & Vingren 2007
Kraemer et al. 2007
Hatfield et al. 2006
Kraemer & Fragala 2006
Shimano et al. 2006
Toigo & Boutellier 2006
Bird et al. 2005
Crewther et al. 2005
Fry 2004
Kraemer & Ratamess 2004
Peterson et al. 2004
Kraemer 2003
Rhea et al. 2003
Fleck 2002
Hasegawa et al. 2002
Hoffman 2002
Kraemer 2002
Haff & Potteiger 2001
Kraemer & Gomez 2001
Kraemer & Newton 2000
Kraemer & Bush 1998
Kraemer et al. 1998
Fleck & Kraemer 1997
Fleck & Kraemer 1996
Zatsiorsky 1995
Stone 1993
Schmidtbleicher 1992
Fleck & Kraemer 1988
Kraemer et al. 1988
Fleck & Kraemer 1987
Garhammer 1987
Stone & O'Bryant 1984
Kraemer 1983
Palmieri 1983
Berger 1982
Stone 1982
Atha 1981

similar muscular adaptations, at least after short-term training in previously untrained subjects" (p. 58).

Authors who have asserted that very heavy or near-maximal resistance is required for optimal strength gains did not cite any training studies that actually support their apparent incorrect application of the size principle (Table 1).

Studies That Do Not Support Heavier-is-Better

Studies that reported the effects of training with different amounts of resistance (Harris et al. 2004; Vincent et al. 2002; Hortobagyi et al. 2001; Bemben et al. 2000; Chestnut & Docherty 1999; Faigenbaum et al. 1999; Graves et al. 1999; Masuda et al. 1999; Weiss et al. 1999; Hisaeda et al. 1996; Kerr et al. 1996; Taaffe et al. 1996; Pruitt et al. 1995; Stone & Coulter 1994; Schmidtbleicher & Haralambie 1981; Withers 1970; O'Shea 1966; Berger 1963, 1962a, 1962b) strongly support the previously discussed acute neurophysiological responses reported by Behm and colleagues (2002).

For example, there are studies that compared 2 RM, 6 RM and 10 RM free-weight bench press (Berger 1963), 2 RM, 10 RM and 12 RM bench press (Berger 1962a), 2 RM and 10 RM bench press (Berger 1962b), 2–3 RM, 5–6 RM and 9–10 RM free-weight squats (O'Shea 1966), 3–5 RM and 13–15 RM barbell squats (Weiss 1999), 4 RM and 10 RM for seven upper-body exercises (Bemben et al. 2000), 7–10 RM and 15–20 RM knee extension exercise (Graves et al. 1999), 4–6 RM and 15–20 RM knee extension (Hisaeda et al. 1996), 3 RM, 5 RM and 7 RM for three upper- and lower-body free-weight exercises (Withers 1970), and 6 RM, 9 RM and 15 RM upper-body and lower-body free-weight and machine exercises (Harris et al. 2004). They all reported no significant difference in the strength gains among the various groups using different amounts of resistance (RMs) for training (Table 2).

Table 2. Summary of studies that reported resistance training protocols using different amounts of resistance and showed no significant difference in strength gains

Reference	Training protocol
Harris et al. 2004	6 RM, 9 RM and 15 RM
Vincent et al. 2002	50% 1 RM and 80% 1 RM
Hortobagyi et al. 2001	40% 1 RM and 80% 1 RM
Bemben et al. 2000	40% 1 RM and 80% 1 RM
Chestnut & Docherty 1999	4 RM and 10 RM
Faigenbaum et al. 1999	6–8 RM and 13–15 RM
Graves et al. 1999	7–10 RM and 15–20 RM
Masuda et al. 1999	40–80% 1 RM and 90% 1 RM
Weiss et al. 1999	3–5 RM and 13–15 RM
Hisaeda et al. 1996	4–6 RM and 15–20 RM
Kerr et al. 1996	8–10 RM and 20–25 RM
Taaffe et al. 1996	40% 1 RM and 80% 1 RM
Pruitt et al. 1995	40% 1 RM and 80% 1 RM
Stone & Coulter 1994	6–8 RM, 15–20 RM and 30–40 RM
Schmidtbleicher & Haralambie 1981	30% 1 RM and 90–100% 1 RM
Withers 1970	3 RM, 5 RM and 7 RM
O'Shea 1966	2–3 RM, 5–6 RM and 9–10 RM
Berger 1963	2 RM, 6 RM and 10 RM
Berger 1962a	2 RM, 10 RM and 12 RM
Berger 1962b	2 RM and 10 RM

The study by Graves and colleagues (1999) is noteworthy because the 10 pairs of identical twins were the quintessentially matched groups. After training two times a week for 10 weeks, increases in isometric strength (averaged for the eight positions tested) were significant in both groups. However, there was no significant difference in the strength gains as a result of training with 7–10 RM (13.2%) or 15–20 RM (12.8%).

Conclusions

The misapplication of the size principle is an error in reasoning. Recommendations to train with very heavy resistance (loads heavier than 6 RM), because they purportedly result in superior strength gains, are based on a faulty premise (an invalid reverse inference of the size principle) and have very little supporting evidence. The question is whether the incorrect application was unintentionally created and perpetuated because of a misunderstanding, or whether it was intentionally created and perpetrated in order to support a preconceived opinion. Whatever the reason, the grossly distorted heavier-is-better training philosophy has deeply infiltrated the resistance training literature.

Practical Application

The correct interpretation of the size principle and its practical application should help dedicated trainees understand what constitutes a proper stimulus for resistance training and how to apply that stimulus. That is, the size principle does not support the popular resistance training recommendation to use a maximal or near maximal resistance. The size principle and interpolated twitch studies support the contention that if maximal motor unit activation is desired, a maximal or near maximal effort at the end of a set of repetitions—regardless of the amount of external resistance—will elicit maximal motor unit activity. Effective resistance training does not require the use of a maximal or near maximal force to stimulate the available motor units and produce significant increases in muscular strength.

The preponderance of studies strongly suggest that effective resistance training simply requires the selection of a desired range of repetitions (e.g., 3–5, 6–9, 10–12 RM), which is based on a personal preference rather than a specific goal, and a progression of the resistance to stay within the desired range of repetitions (Carpinelli et al. 2004). Very high RMs (e.g., loads lighter than 20 RM) or an extensive time under load (e.g., longer than 2–3 minutes) may involve mechanisms of fatigue that are not conducive to stimulate optimal increases in muscular strength. Despite the plethora of opinions in the resistance training literature, the specific mechanisms of fatigue and exactly what constitutes an optimal stimulus for strength gains are unknown. If a maximal—or near maximal—effort is applied at the end of a set of repetitions, the evidence strongly suggests that the different external forces produced with different amounts of resistance elicit similar outcomes.

If the heavier-is-better training philosophy is truly valid, as claimed by the majority of resistance training experts, the training studies would overwhelmingly support that concept. In fact, the preponderance of resistance studies reported no significant difference in strength gains as a result of training with heavier loads (Figure).

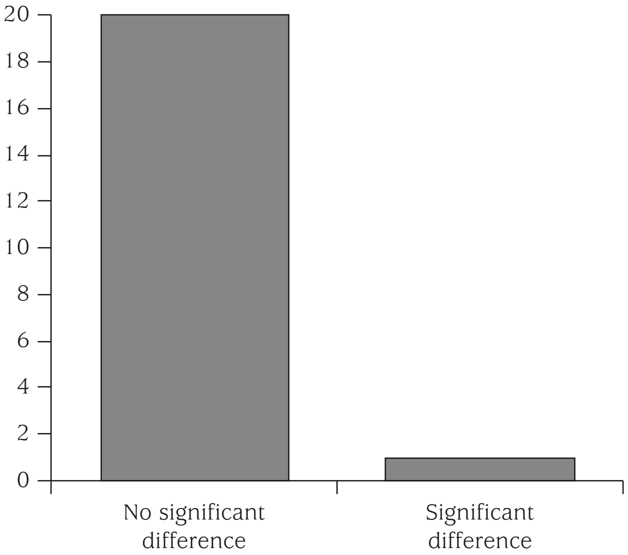

Fig. Twenty resistance training studies reported no significant difference in strength gains compared with only one study that reported a significant difference as a result of training with a heavier resistance.

If the size principle was correctly applied, effective resistance training may appeal to a larger proportion of the population. This would include competitive and recreational athletes as well as those in the general population who perceive resistance exercise as the lifting of very heavy weights and therefore potentially dangerous. Because some people may have a fear of injury—that need not exist—the heavier-is-better perception may actually be a deterrent to resistance training, which deprives those most in need of health-related benefits. These potential health-related benefits include the prevention of osteoporosis, falls, fractures and disability, changes in risk factors associated with cardiovascular disease, some cancers, diabetes (improvements in glucose tolerance and insulin resistance), enhanced lipid profiles, elevated resting metabolic rate, decreased resting blood pressure, reduced back pain and subsequent disabilities, and greater functional ability (Winett & Carpinelli 2001)—all in addition to muscular hypertrophy and strength gains.

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