Medicina Sportiva
Med Sport 13 (4): 203-209, 2009
DOI: 10.2478/v10036-009-0033-2

THE CORRECT INTERPRETATION OF THE SIZE PRINCIPLE AND ITS PRACTICAL APPLICATION TO RESISTANCE TRAINING

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Abstract

Many resistance training experts claim that a very heavy resistance is required to produce optimal strength gains. However, the size principle, motor unit activation studies, and the overwhelming majority of resistance training studies refute that claim. In fact, these studies support the premise that a moderate amount of resistance will produce similar strength gains.

Key words: *motor units, effort, recruitment, activation, strength gains*

Introduction

A recently published comprehensive review meticulously described the origin and practical significance of the size principle of motor unit recruitment (1). That review revealed how the size principle has been incorrectly applied to resistance training. The accurate interpretation of that landmark scholarly review is a prerequisite for establishing scientifically based guidelines for resistance training. Therefore, the purpose of this brief review is to summarize that lengthy document with a fundamental definition of the size principle and motor unit activation, and specifically explain the correct practical application of these neuromuscular concepts to safe, effective resistance training.

Motor unit activation

A motor unit consists of a neuron, its axon and all the individual muscle fibers innervated by that specific neuron. The size principle states that when the central nervous system recruits motor units for a specific activity, it begins with the smaller, easily excited motor units and progresses to the larger, more difficult to excite motor units (2). An increase in force production is a result of the orderly activation of a greater number of motor units (recruitment) and an increase in their frequency of activation (rate coding). Most of the peer-reviewed evidence strongly suggests that there are no functionally meaningful violations of the size principle (3).

The interpolated twitch technique is a measure of the level of motor unit activation during a maximal voluntary effort. An electrical stimulus is applied with surface electrodes onto a muscle or its nerve and fully activates all the motor units available for that specific activity. If all the available motor units are voluntarily recruited and firing at optimal frequencies, no additional force will be detected when the electrical stimulus is applied. However, if some available motor units are not recruited or they are not firing at their optimal frequency, the electrical stimulus will produce a twitch (force) in addition to the voluntary force. A small or nonexistent interpolated twitch suggests near-maximal or truly maximal voluntary motor unit activation (4-5).

Motor unit activation studies, which compared extremely divergent age groups (e.g., 20-year old and 80-year old participants) of males and females, showed that the difference in the ability to generate force, which was significantly lower in older subjects, does not affect voluntary activation of specific motor units (see reference 1 for a review of 11 interpolated twitch studies). All the cited motor unit activation studies strongly support the concept of a direct relationship between effort – that is, the degree of difficulty in performing the exercise – and motor unit activation. It is the degree of the effort that determines the activation level of motor units and the resultant force output. A maximal effort elicits maximal or near maximal activation of motor units (1).

Although it was not a training study, the motor unit activation study with a profound practical application to resistance training was conducted by Behm and colleagues (6). They recruited 14 young males who were performing resistance training a minimum of three times a week for at least one year. The participants were tested for voluntary and electrically stimulated motor unit activation (interpolated twitch technique) before and after performing 5RM, 10RM and 20RM dumbbell curls (RM = repetition maximum). Repetition duration was 3 seconds concentric, 1 second isometric, and

3 seconds eccentric, with a total time-under-load of 35, 70 and 140 seconds for the 5RM, 10RM and 20RM, respectively. There was no significant difference in voluntary motor unit activation following the three protocols. The three different amounts of resistance used in the 5RM, 10RM and 20RM protocols (and the different time-under-load) elicited similar activation levels of motor units (93.5 to 95.5%) because there was a maximal effort (RM) on the last repetition of each protocol. Behm and colleagues concluded that the popular opinion that a resistance heavier than a 6RM would produce greater increases in neural drive was not substantiated in their study. In fact, their study showed that it was the degree of effort in performing the final repetitions that determined motor unit activation and not the amount of resistance or time-under-load.

Two noteworthy resistance training studies (7-8) underscore the importance of effort as the stimulus for strength gains—rather than the actual amount or modality of resistance used for training. Tanimoto and colleagues (7) randomly assigned 36 previously untrained young males to one of two resistance training protocols or a control group (no training). The trainees performed one warm-up set and three regular sets for each of five machine exercises (squat, chest press, pull-down, abdominal crunch, and back extension) two times per week for 13 weeks. The resistance was progressively adjusted to evoke volitional exhaustion on the eighth repetition (~8RM), which guaranteed a similar effort (maximal) for both training groups. With the use of a metronome, one group performed all the exercises with repetition durations of 1-second concentric and 1-second eccentric muscle action using approximately 85-90% 1RM. The other group used a 3-second concentric and 3-second eccentric repetition duration with approximately 55-60% 1RM. The longer duration repetitions were more difficult than the shorter duration repetitions and therefore required a lighter resistance (percent of the 1RM) to elicit volitional exhaustion around the eighth repetition. The trainees rested 60 seconds between sets and three minutes between exercises. The authors noted that almost all of the motor units were recruited on the final repetition of all the sets (electromyographic signals of the vastus lateralis during the squat exercise) in both groups because all the subjects performed the sets to exhaustion. There was a significant increase in total 1RM strength (five exercises) and muscle thickness (B-mode ultrasound measurement) in both training groups, with no significant difference between groups. The large difference in the amount of resistance used for training did not produce a significant difference in strength gains or muscle thickness between the training groups because the effort at the end of each set was similar (maximal).

Dorgo and colleagues (8) randomly assigned 84 healthy college students (46 males and 38 females) to either a traditional weight resistance training group (WRT) or a manual resistance training group (MRT). Thirty-eight of these subjects were previously engaged in resistance training for a minimum of two hours per week. The amount of resistance can be quantified in WRT by the amount of weight lifted; however, the resistance is not quantifiable with MRT because the resistance for every exercise is provided manually by another person (a spotter) and traditional weight training equipment such as barbells, dumbbells and machines are not used. By targeting comparable muscle groups and exercise movements as closely as possible, the MRT exercises were similar to the WRT exercises in this study. All subjects in the WRT and MRT groups performed 2-4 sets of 8-12RM for 6-9 large muscle group exercises three times per week for 14 weeks, with identical rest intervals between sets and exercises. The same strength measure (free-weight 1RM bench press and squat exercises) was used for both groups. The authors noted: "The WRT group had an apparent advantage in the free weight 1RM testing because the same equipment was used for training and assessment, whereas the MRT group did not use any free weights or exercise machines during the 14 week program" (p. 302). Nevertheless, both groups showed similar significant increases in muscular strength (absolute and relative) and muscular endurance, with no significant difference between groups for either exercise. Because the amount of resistance applied by the spotters during the training was not known in the MRT group, and may have been quite different from the resistance used in the WRT group, the stimulus for similar strength gains in both groups was most likely the same degree of effort – maximal.

Although the relationship between effort and motor unit activity has been misunderstood—or ignored—by many resistance training experts, this important neuromuscular concept is not new. A half-century ago, Henneman (9) published his research on the size principle and explained that increasingly larger motor units require progressively greater increases in the intensity of the stimulus. In a lengthy review of motor unit activation and its practical application to resistance training more than 20 years ago, Sale (10) stated that to attain full motor unit activation the trainee may execute a single maximal repetition (1RM); or as he stated in his narrative and displayed graphically, the trainee could perform repetitions to muscular fatigue with five repetitions (5RM) or 10 repetitions (10RM). Sale noted that motor unit activation would not be maximal at the beginning of the 5RM or 10RM sets but would be maximal at the termination of either set and similar to the 1RM motor unit activation.

It is important to recognize that none of the motor unit activation studies speculated on a minimal activation threshold required for optimal strength gains. The activation level required to increase muscular strength is unknown, and may be considerably less than the activation levels reported in the interpolated twitch studies. Therefore, a maximal or near maximal effort simply ensures maximal or near maximal voluntary motor unit activation.

Contrary to the strongly supported aforementioned neuromuscular concepts, numerous resistance training experts (at least 47 authors specifically identified in reference 1) have incorrectly claimed that in order to recruit the larger motor units and to maximize strength gains, a very high resistive force (load) is required. Because greater motor unit activation produces a greater force output, it is mistakenly believed that a greater force (heavy resistance) is required for maximal motor unit activation. That erroneous belief is an invalid reverse inference of the size principle (1).

Consequently, many experts claim that if a person trains with a resistance lighter than 80-90% of the 1RM (1RM = the maximal resistance used for only one repetition in good form) or lighter than a 6RM (6RM = a resistance that allows the completion of only six repetitions in good form), strength gains would be less than those produced with a heavier resistance. That widely accepted opinion is not supported in the scientific literature and has resulted in misleading recommendations for resistance training.

Resistance training studies

There are eight studies (11-18) that reported greater strength gains after training with a heavier resistance compared with a much lighter resistance. Researchers compared protocols such as 10RM and 10 1RM repetitions (11), 3-5RM, 9-11RM and 20-28RM (12), 50-55% 1RM and 80-85% 1RM (13), 40-60% 1RM and 70-90% 1RM (14), 60% 1RM and 80% 1RM (15), 50% 1RM and 80% 1RM (16), 4-6RM and 14-16RM (17), and 6-10RM and 20-30RM (18). In each of these studies there were small but statistically significant greater strength gains for some exercises in the groups that trained with the heavier resistance. However, seven (11-13, 15-18) of these eight studies employed previously untrained subjects.

The study by Jones and colleagues (14) was the only study that did not recruit previously untrained participants. They randomly assigned 30 young, moderately resistance-trained, male collegiate baseball players to a high-resistance (70-90% 1RM) group or low-resistance (40-60% 1RM) group. The authors did not describe the participants' previous resistance training. Both groups performed 3-4 sets of four free-weight lower-body exercises two times per week for 10 weeks. There was no significant difference between groups in 11 out of 12 performance measures, which included multiple tests for peak force, peak velocity and peak power production. The only significant difference between groups was a greater increase in 1RM squat for the high-resistance group (16.3%) compared with the low-resistance group (11.5%). Both groups performed what the authors described as intended maximal concentric acceleration (IMCA) for each repetition, which actually caused some subjects' feet to leave the floor during the squat exercise. The authors concluded: "Since both groups used IMCA [intended maximal concentric acceleration] lifting techniques in their training, these results only are applicable to athletes who attempt maximum acceleration with each repetition" (p. 356).

Many resistance training experts (19-25) claim that a very heavy resistance is required for optimal strength gains especially in experienced strength athletes. One of these authors (21) claimed that very heavy loads approaching maximal capacity (100% 1RM) must be used to produce maximal strength gains and that these very heavy loads are most important for advanced trainees. Interestingly, there is a study by Fry and colleagues (26) that was published several years prior to his review. They used a time-series design for six males who had 2-12 years of resistance training experience and were capable of performing the free-weight squat with at least 1.5 times their body mass. All subjects performed three sets of 10RM squats on Mondays and three sets of 5RM squats on Thursdays for four weeks (the so-called *normal* training phase). This was followed by two sets of one repetition with 95% 1RM and three sets of one repetition with 90% 1RM three times a week for three weeks (the so-called *high-intensity* phase). During the *high-intensity* phase there were significant decrements in 9.1 meter sprint time and peak isokinetic squat force at 0.20 $m \cdot s^{-1}$, with no significant changes in body composition, flexibility, lower-body reaction time, vertical jump, 36.6 meter sprints, lateral agility, isokinetic squat force at 0.82 and 1.43 $m \cdot s^{-1}$, or isokinetic back extension at 0.17 and 1.05 $rads \cdot s^{-1}$. The 1RM squat significantly increased during the *normal* training phase but there was no significant change in 1RM during the *high-intensity* phase. Fry and colleagues noted: "In essence, a plateau in 1RM performance was observed during the phase of training emphasizing heavy, near-maximal lifts" (p. 57). Curiously, Fry neglected to cite his own study (26) that contradicts the claim in his review (21).

There are no training studies—just opinions—to support the claim that very heavy resistance is required for optimal strength gains in experienced resistance trainees.

Compared with only eight studies (11-18) that showed some advantage to training with a heavier resistance, this comprehensive review of published

Table 1. *82 Resistance training studies reported no significant difference in strength gains as a result of training with a heavier resistance*

Ahtiainen et al.	*J Strength Cond Res* 2005; 19: 572-82.
Baker et al.	*J Strength Cond Res* 1994; 8: 235-42.
Barney & Bangerter	*Res Q* 1961; 32: 138-46.
Barstow et al.	*J Sport Sci Med* 2003; 2: 62-9.
Bemben et al. *	*Med Sci Sports Exerc* 2000; 32: 1949-57.
Bemben et al.	*Med Sci Sports Exerc* 2002; 34: S288.
Ben-Siri et al.	*J Strength Cond Res* 1995; 9: 143-8.
Berger *	*Res Q* 1962; 33: 168-81.
Berger *	*Res Q* 1962; 33: 334-8.
Berger *	*Res Q* 1963; 34: 396-8.
Berger & Harris	*J Assoc Phys Mental Rehabil* 1966; 20: 205-7.
Blazevich & Jenkins	*J Sports Sci* 2002; 20: 981-90.
Brandenburg & Docherty	*J Strength Cond Res* 2002; 16: 25-32.
Brentano et al.	*J Strength Cond Res* 2008; 22: 1816-25.
Campagna et al.	*J Appl Sport Sci Res* 1989; 3: 78.
Capen	*Res Q* 1956; 27: 132-42.
Chestnut & Docherty *	*J Strength Cond Res* 1999; 13: 353-9.
DeLateur et al.	*Arch Phys Med Rehabil* 1968; 49: 245-8.
Delecluse et al.	*Prev Med* 2004; 39: 823-33.
Drinkwater et al.	*J Strength Cond Res* 2007; 21: 841-7.
Faigenbaum et al.*	*Pediatrics* 1999; 104 e5: 1-7.
Faigenbaum et al.	*Pediatr Exerc Sci* 2005; 17: 237-48.
Fry et al.	*J Strength Cond Res* 2000; 14: 54-61.
Godard et al.	*J Strength Cond Res* 1998; 12: 26-9.
Graves et al. *	*Med Sci Sports Exerc* 1999; 26: S74.
Guglielmo et al.	*Int J Sports Med* 2009; 30: 27-32.
Harris et al. *	*J Strength Cond Res* 2004; 18: 833-8.
Harris et al.	*J Strength Cond Res* 2008; 22: 1742-9.
Herrick & Stone	*J Strength Cond Res* 1996; 10: 72-6.
Hisaeda et al. *	*Ergonomics* 1996; 39: 842-52.
Hoffman et al.	*J Strength Cond Res* 2009; 23: 11-9.
Hortobagyi et al. *	*Ergonomics* 2001; 39: 842-52.
Hunter et al.	*Med Sci Sports Exerc* 2001; 33: 1759-64.
Jackson et al.	*J Strength Cond Res* 2007; 21: 289-95.
Jan et al.	*Phys Ther* 2008; 88: 427-36.
Johnson et al.	*Med Sci Sports* 1976; 8: 35-8.
Jones & Rutherford	*J Physiol* 1987; 391: 1-11.
Kerr et al. *	*J Bone Min Res* 1996; 11: 218-25.
Komi & Buskirk	*Ergonomics* 1972; 15: 417-34.
Kramer	*J Strength Cond Res* 1997; 11: 143-7.
Krusen	*Arch Phys Med* 1949; 30: 271-7.
Laurentino et al.	*Inr J Sports Med* 2008; 29: 664-7.
Lyttle et al.	*J Strength Cond Res* 1996; 10: 173-9.
Maddalozzo & Snow	*Calcified Tissue Int* 2000; 66: 399-404.
Massey et al.	*J Strength Cond Res* 2004; 18: 518-21.
Masuda et al. *	*Eur J Appl Physiol* 1999; 79: 347-52.

McBride et al.	*J Strength Cond Res* 2002; 16: 75-82.
McCurdy et al.	*J Strength Cond Res* 2009; 23: 187-95.
Messier & Dill	*Res Q Exerc Sport* 1985; 56: 345-51.
Miller et al.	*Res Q Exerc Sport* 2006; 77: 58-63
Miszko et al.	*J Gerontol* 2003; 58A: 171-5.
Moss et al.	*Eur J Appl Physiol* 1997; 75: 193-9.
Neils et al.	*J Strength Cond Res* 2005; 19: 883-7.
O'Shea *	*Res Q* 1966; 37: 95-102.
Palmieri	*J Appl Sports Sci Res* 1987; 1: 36-8.
Pruitt et al. *	*J Bone Min Res* 1995; 10: 1788-95.
Reid et al.	*Brit J Sports Med* 1987; 21: 40-4.
Russo et al.	*Med Sci Sports Exerc* 2001; 33: S324.
Sale et al.	*Can J Appl Sports Sci* 1985; 10: 27P.
Sanborn et al.	*J Strength Cond Res* 2000; 14: 328-31.
Schiotz et al.	*J Strength Cond Res* 1998; 12: 173-8.
Schmidtbleicher & Buehrle	*Biomechanics X-B: 615-20, 1987.*
Schmidtbleicher & Haralambie *	*Eur J Appl Physiol* 1981; 46: 221-8.
Schroeder et al.	*J Strength Cond Res* 2004; 18: 227-35.
Seger & Thorstensson	*Int J Sports Med* 2005; 26: 45-52.
Seliger et al.	*Int Z Angew Physiol Einschl Arbeitsphysiol* 1968; 26: 227-34.
Silvester et al.	*NSCA J* 1982; 3: 30-3.
Smith & Rutherford	*Eur J Appl Physiol* 1995; 71: 332-6.
Stadler et al.	*Med Sci Sports Exerc* 1997; 20: S254.
Stone & Coulter *	*J Strength Cond Res* 1994; 8: 231-4.
Swanson & Moffatt	*NSCA J* 1986; 8: 71.
Taaffe et al. *	*Clin Physiol Funct I* 1996; 16: 381-92.
Takarada et al.	*J Appl Physiol* 2000; 88: 2097-106.
Tanimoto & Ishii	*J Appl Physiol* 2006; 100: 1150-7.
Tanimoto et al.	*J Strength Cond Res* 2008; 22: 1926-38.
Vikne et al.	*Med Sci Sports Exerc* 2006; 38: 1770-81.
Vincent et al. *	*J Am Geriatr Soc* 2002; 50: 1100-7.
Weiss et al. *	*J Strength Cond Res* 1999; 13: 236-41.
Westcott	*Am Fit Q* 1991; 10: 25-7.
Withers *	*Res Q* 1970; 41: 110-4.
Wong et al.	*J Athletic Training* 2009; 44: 264-71.
Wong & Ng	*J Electromyogr Kinesiol* 2009; (published ahead of print) doi: 10.1016/j.jelekin.2009.02.006

* Studies also cited in Reference 1

resistance training studies cites 82 other studies (including the 20 studies cited in reference 1) that reported no significant difference in strength gains as a result of training with different amounts of resistance (Table 1). In many of these studies the primary objective was not to compare strength gains between groups but to report on similarities or differences found in other physiological variables as a result of training with different amounts of resistance. Therefore, these serendipitous strength results enhance the validity of the strength gains by reducing potential inherent researcher bias, which may be based on a pre-conceived belief that a heavier resistance would produce greater strength gains.

The various studies included younger or older female or male participants whose resistance training experience ranged from novice to resistance trained athletes. Some studies used single set protocols while others employed multiple sets with various modalities such as free weights and machines. The researchers compared loads such as 2RM, 6RM and 10RM free-weight bench press (27); 2RM, 10RM and 12RM bench press (28);

2RM and 10RM bench press (29); 2-3RM, 5-6RM and 9-10RM free-weight squats (30); 3-5RM and 13-15RM barbell squats (31); 6RM, 9RM and 15 RM for three lower-body and five upper-body machine exercises (32); 4RM and 10RM for seven upper-body free-weight exercises (33); etc. All 82 resistance training studies in Table 1 reported no significant difference in strength gains between groups; that is, a heavier resistance did not produce significantly greater strength gains.

One criticism of the studies in Table 1, which reported the results of training with a heavier resistance compared with a moderate or lighter resistance, may be that many of those studies inherently contained one or more potential confounding variables such as a different number of sets or inter-set rest intervals, concentric-only versus eccentric-only training, concentric/eccentric training versus concentric/accentuated eccentric training, standard progressive resistance training versus periodization, different repetition durations, frequency of training, or time under load. However, that criticism ironically reveals—and unequivocally supports—the premise that despite all the manipulation of different potential confounding variables within a specific study, the overwhelming majority of resistance training studies (all 82 studies in Table 1) reported no significant difference in strength gains between groups.

Summary

Perhaps there would be much greater participation if potential trainees understood that resistance training does not require lifting very heavy weights. The majority of resistance training studies (82 out of 90) reported no significant difference in strength gains as a result of training with heavier loads (Fig. 1). In addition, greater adherence to resistance training programs could result in a larger segment of the population experiencing strength gains and many of the potential health-related outcomes (34). The concept of training with a moderate resistance—rather than a heavy resistance—is especially applicable to special populations such as the elderly or those with neuromuscular or orthopedic limitations, and those otherwise healthy people who wish to perform resistance training for a lifetime of benefits.

Conclusions and practical applications

- Recommendations to train with very heavy resistance (loads heavier than 6RM), because they purportedly result in superior strength gains, are based on a faulty premise and have very little supporting evidence.
- The size principle, motor unit activation studies and resistance training studies do not support the contention that individuals must train with maximal or near maximal resistance (load) to achieve optimal strength gains.
- Effective resistance training simply requires the selection of a reasonable range of repetitions (based on a personal preference) such as 4-6RM, 6-8RM, 8-10RM, 10-12RM, or 12-14RM, and a progression of the resistance to stay within the desired range of repetitions.

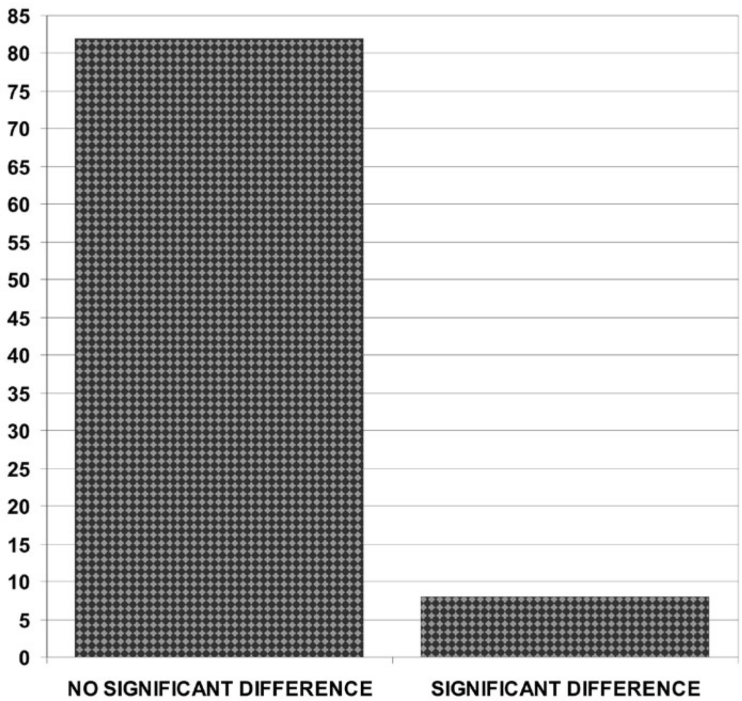

Fig.1. *82 resistance training studies showed that training with a heavier resistance did not result in significantly greater strength gains compared with using a lighter resistance. Only eight studies reported significantly greater strength gains for some exercises as a result of training with a heavier resistance*

- The level of motor unit activation required to stimulate strength gains is not known. Maximal or near maximal effort on the final repetitions of a set generates maximal or near maximal motor unit activation but may not be required for optimal strength gains.
- The preponderance of evidence strongly suggests that if a similar effort is applied on the final repetition of a set, the resulting strength gains are similar—regardless of the amount of resistance used for training.

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Received: August 14, 2009
Accepted: October 15 , 2009
Published: October 27, 2009

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