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# Manipulating Resistance Training Program Variables to Optimize Maximum Strength in Men: A Review

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## ABSTRACT

Maximum strength is the capacity to generate force within an isometric contraction. It is a valuable attribute to most athletes because it acts as a general base that supports specific training in other spheres of conditioning. Resistance training program variables can be manipulated to specifically optimize maximum strength. After deciding on the exercises appropriate for the sport, the main variables to consider are training intensity (load) and volume. The other factors that are related to intensity are loading form, training to failure, speed of contraction, psychological factors, interset recovery, order of exercise, and number of sessions per day. Repetitions per set, sets per session, and training frequency together constitute training volume. In general, maximum strength is best developed with 1–6 repetition maximum loads, a combination of concentric and eccentric muscle actions, 3–6 maximal sets per session, training to failure for limited periods, long interset recovery time, 3–5 days of training per week, and dividing the day's training into 2 sessions. Variation of the volume and intensity in the course of a training cycle will further enhance strength gains. The increase in maximum strength is effected by neural, hormonal, and muscular adaptations. Concurrent strength and endurance training, as well as combination strength and power training, will also be discussed.

***Key Words:*** maximal strength, training intensity, training volume, rest interval, periodization, concurrent training

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## Introduction

Man has sought strength since antiquity. A 315-lb block of red sandstone found in Olympia had a 6th-century inscription stating that a Bybon, using only 1 hand, threw it over his head (33). Even then, the sport of weightlifting was approached systematically: Milo of Croton lifted a bull-calf daily until it was fully grown, and was eventually able to carry the bull around the stadium. Records indicated that Galen (A.D. 129–199), the most outstanding physician of ancient times since Hippocrates, classified exercises into those that exercised the muscles without violent movement (e.g., digging, weightlifting), quick exercises that promote activity (e.g., ball play, rolling on the ground), and violent exercises. In the 1950s, research into the field of strength training picked up, with investigators experimenting with more precise training prescriptions.

Traditionally, resistance training was limited to sports like wrestling, powerlifting, bodybuilding, and Olympic weightlifting. More recently, however, sports that do not utilize resistance training have become the exception rather than the rule. Athletes share many attributes such as strength, power, endurance, and flexibility. Of these, maximum strength is one of the most fundamental (141).

Maximum strength can be developed through a carefully designed resistance training program. In the past, training programs were based almost entirely on the experiences of the coach or athlete, and there was a proliferation of scientifically unsupported resistance training programs that confused not only the novice athlete, but also the experienced ones. Indeed, science has been slow to validate the anecdotal evidence that is still often used to underpin current resistance training practices. This slow pace of research has been due not only to the time and costs involved in conducting controlled studies, but also to various errors in methodology such as failing to control variances and confounding factors such as the effect of learning when testing for strength (111, 113).

A resistance training program can be described by many variables, with training intensity and volume being the principal variables. This review examines the scientific literature currently available to determine how training intensity, training volume, and other variables can be manipulated to specifically optimize maximum strength for the adult male athlete. As aerobic capacity and power are also important for most athletes, the effect of concurrent strength and endurance training, as well as combined strength and power training, will also be examined. Finally, physiological adaptations to strength training will be discussed to elucidate the link between resistance training program variables and maximum strength. To limit the already wide scope of this review, other factors such as diet, supplements, and adjuvant modalities, namely transcutaneous electromyostimulation (112, 135) and vibratory stimulation (56), will not be discussed. It is also beyond the scope of this review to discuss strength development in women, adolescents, and the elderly.

## Maximum Strength

There are several categories of strength, namely maximum strength, speed strength (power), explosive strength (maximum rate of force development), starting strength (force achieved 30 milliseconds after the start of contraction), and reactive strength capacity (ability to switch from eccentric to concentric contraction) (129). Maximum strength represents the highest tension possible within a sustained (isometric) muscle action. It is noteworthy that, in recording maximum strength (as opposed to the other types of strength), the muscle is allowed as much time as it needs to reach its peak force. Maximum strength is reflected by the maximum voluntary contraction (MVC) and is also termed peak isometric force. The 1 repetition maximum (1RM), which is the heaviest load that can be lifted once during a traditional weightlifting-type task, is an isoinertial measure that gives an estimate of maximum strength. Tending to be more sensitive to the effects of training compared to the MVC (3), the 1RM is frequently used to estimate maximum strength.

Maximum strength is obviously desirable in sports such as Olympic weightlifting and power lifting. A sprinter, on the other hand, would strive for speed strength, whereas a long jumper or basketball player would aim to optimize reactive strength capacity. Regardless of which aspect of strength the coach or athlete decides is appropriate for a given sport, maximum strength should first be developed (57, 63, 105, 141) because it acts as a general base that supports specific training in other spheres of conditioning.

As the athlete enhances his maximum strength, he also benefits from improvements in other performance characteristics of neuromuscular function such as power (43, 46, 61, 70, 74, 90, 98, 101, 124, 133, 138, 141) and endurance time (time to exhaustion) (49, 121). Strength training prescriptions involving large muscle groups and very high volumes may also improve maximal oxygen uptake ($VO_2max$) and reduce the resting systolic blood pressure (121). The associated increases in lean mass (47, 49, 55, 99, 101, 104, 121) will be advantageous for sports such as rugby and the shot put.

## Resistance Training Program Variables

Coaches and athletes are well aware that the system of resistance training they select will influence strength, power, endurance, weight, and a host of other parameters to different degrees (57, 63). Different training methods will induce different adaptations (37, 43, 44, 47, 61, 70, 71, 78, 138). As an illustration of training specificity, Häkkinen and Keskinen (41), despite using small sample sizes, convincingly showed that among 3 groups of athletes that had undergone different types of training, the strength-trained athletes (elite competitive powerlifters) had the greatest maximum strength; the speed-trained athletes (elite sprinters and jumpers) had the greatest rate of force development (explosive strength); the endurance-trained athletes (elite distance swimmers), however, had the least maximum strength and the lowest rate of force development. Even among strength-trained athletes, the manipulation of a few training variables will produce vastly different results, demonstrating the importance of carefully designing the resistance training program to achieve the desired training targets.

There are some studies that have failed to demonstrate appreciable differences in performance characteristics of neuromuscular function despite using different training prescriptions (101, 130, 133). However, most of these studies have tended to adopt small sample sizes and short training periods, or have failed to control for confounding factors such as concurrent training.

Once the choice of resistance exercise has been made on the basis of the sport, the primary training variables are training intensity (load or resistance) and training volume. Other training variables or factors such as loading form, training to failure, speed of contraction, psychological factors, interset recovery, order of exercise, and number of sessions per day are related to the training intensity. Training volume is determined by the number of repetitions per set, number of sets, and the training frequency.

## Training Intensity

Training intensity is one of the most important variables to consider when designing a resistance training program to target maximum strength. It is reflected by the load or resistance used. Absolute intensity is the load lifted per repetition (expressed in kilograms) whereas relative intensity is the percentage of the 1RM lifted (98, 122).

The role of a high training intensity is to increase neural activation; peak electromyographic activity in muscles, which reflects the level of neural activity, increases with increasing load (97). Likewise, the integrated electromyographic activity has been shown to increase during high-intensity training (>80% of 1RM and eccentric contractions at 100–120% of 1RM) and decrease during low-intensity training and detraining (45). Neural activation serves not only as a stimulus for strength gains, but it is also an adaptation to strength training (41). As a stimulus, increased neural activation contributes to strength gains during the first 4 weeks of the training period, whereas muscle hypertrophy plays a bigger role during the later part of the training period (43).

High training intensities evoke a postexercise increase in testosterone release as well as an increase in human growth hormone (69, 70, 78, 107). The elevation of these 2 anabolic hormones in the serum, coupled with a decrease in serum cortisol levels, brings about an anabolic environment that encourages hypertrophy and strength gains (70).

### *Ways to Prescribe Intensity: RM vs. Percentage of 1RM*

The training load can be prescribed as a specified number of RMs or as a specified percentage of the 1RM. A RM is the heaviest load or resistance that can be lifted a specified number of times.

If the athlete is prescribed a load that is expressed as a percentage of his 1RM, then the 1RM must first be determined. This is easy for the experienced athlete, but for the novice lifter or the adolescent, the risk of injury may be reduced by predicting the 1RM from the number of repetitions completed at lesser loads with the aid of a formula or conversion table (4, 75, 77). To avoid using the formula, the 3RM can be determined, and the load can then simply be prescribed directly as a percentage of the 3RM.

Prescribing the RM (i.e., using the actual repetitions performed to dictate the load and not vice versa) is thought to be superior to using a percentage of the 1RM for the following reasons: (a) Strength varies by 10–20% over the course of a single day, resulting in a variable number of repetitions if a fixed percentage of the 1RM is prescribed (105). With RM loading, the load is increased when the athlete is stronger so that the number of repetitions completed is unchanged. This results in more control over the number of repetitions performed, reducing the chance of ''over-'' or ''undershooting'' the desired training zone (50). (b) Interindividual differences in the number of repetitions attainable for a fixed percentage of 1RM exist (50). For example, at 70% of 1RM, one individual might perform 12 repetitions, whereas another might perform 24 (105), resulting in the latter athlete training at an unintentionally low intensity. (c) The number of repetitions attainable for a specified percentage of 1RM varies from one muscle to another as well (105), with smaller muscles tending to perform fewer repetitions (50). Hence, if the percentage of 1RM is prescribed, a large muscle will tend to perform more than the intended number of repetitions, whereas the reverse is true for the smaller muscles. (d) If the percentage of 1RM is used, then there is a need to frequently monitor the 1RM strength, especially for untrained individuals who tend to make rapid gains. On the other hand, when the RMs are prescribed, athletes simply increase the load whenever they exceed the prescribed RM.

### *Loading Form*

Muscular action during exercise can be concentric, eccentric, or isometric.

*Isometric contractions.* These contractions are specific to sports such as wrestling and gymnastics and are not commonly used in resistance training programs.

*Eccentric contractions.* These contractions (load > 100% of 1RM) generate the highest muscular tension, as much as twice that of isometric contractions (141). As a result, they are associated with a higher incidence of microscopic injury and delayed-onset muscular soreness (21, 29, 73, 94); after 5 sets of 10 repetitions of elbow flexion at 110% of 1RM, the elbow flexors have been shown on magnetic resonance imaging to swell to 40% above the preexercise volume by day 2–4, recovering by week 2 to a volume 10% smaller than that before exercise (28).

*Concentric contractions.* These contractions (load ≤ 100% of 1RM) feature prominently in most resistance training programs. They are thought to recruit more motor units and stimulate more hypertrophy of type II fibers compared to eccentric contractions when exercising at the same relative power level (88).

Some coaches advocate the concurrent use of the different loading forms instead of only one (105). Indeed, studies have demonstrated that the addition of eccentric contractions (100–200% of 1RM) to concentric contraction exercises was associated with an increase in the IEMG as well as greater improvements in maximal force (42, 45).

### *Optimal Load*

Studies to identify the optimal range of training intensities for developing maximum strength are complicated by the interplay between intensity (load) and volume (total number of repetitions). Manipulating the intensity in isolation will yield misleading results. For example, Berger (13) compared the effect of 1 set of 2-, 4-, 6-, 8-, 10-, and 12RM bench press 3 times per week on maximum strength and concluded that the optimal load is between 3 and 9 RMs. Evidently, each group experienced different training volumes, with the 2RM group doing a total of only 6 repetitions per week. Such a low volume barely provides an appreciable stimulus to the muscle and may mask the efficacy of the load being tested. Equated or partially equated

**Table 1.** RM loading in the wave program used by elite rowers.*

| Exercise | Session 1 | Session 2 | Session 3 |
|---|---|---|---|
| Bench press | 6→4→2→6→4→2 | 8→6→4→8→8 | 6→4→6→4→6→4 |
| Squat | 5→5→3→5→5→3 | | 5→3→3→5→3→3 |

* Modified from Wardle and Wilson (131).

training volumes between groups would provide a more accurate reflection of the influence of various training loads on strength gain.

Although not all of the more recent studies equated training volume while investigating the intensity, the volumes used by the various experimental groups were not on either extreme, making the results slightly more reliable. These studies demonstrate convincingly that heavy loads of 70–120% of 1RM, or 1–6 RMs, are the most effective in enhancing maximum strength (12, 43, 61, 90, 114, 120, 123). This is also true in the maintenance of maximum strength (89).

Training intensity is seldom kept constant. It is usually varied not only over the course of the training period (this is called periodization, a principle that will be discussed later), but also from set to set within each training session in accordance to specified patterns (26). In the light-to-heavy system, the load is progressively increased from set to set while the repetitions are reduced. In the heavy-to-light system, the load is progressively decreased from set to set. In the triangle or pyramid program, the load is progressively increased over several sets until only 1RM is performed, and it is then decreased over the next few sets. This is a combination of the previous 2 systems. In the wave pattern (131), the load is varied in an undulating manner over several sets (Table 1).

When training for maximum strength, the loading should vary within the 1–6RM zone. Although the efficacy of variations in intensity and volume over training periods (periodization) has been investigated, there is little conclusive evidence to indicate if the variation of loads from set to set as described above is effective or necessary.

### *Training to Failure*

To enhance maximum strength, it is important that all sets be maximal (27) to ensure that a high level of neural activation or drive is used to stimulate the muscles. This means that for the chosen weight, the athlete should attempt to complete as many repetitions as possible, using the proper technique.

Some coaches prescribe both the load and the repetition at the same time (63). For example, ${}^{70\%}/_{12}\,{}^{75\%}/_{10}\,{}^{78\%}/_{8}\,{}^{70\%}/_{12}$ is a 4-set exercise prescription in which the numerator is the load and the denominator is the repetition. Because the effort should be maximal, it is unnecessary to prescribe both the load and repetition at the same time; either the load alone should be specified (i.e., percentage of 1RM), whereby the athlete will then do as many repetitions as possible with that load, or the repetition alone should be prescribed (i.e., RM), whereby the athlete will then use the heaviest load that will allow him to just manage to complete the prescribed number of repetitions using strict form. The only time when a submaximal effort is appropriate in a program targeted at maximum strength is during the warm-up set, where it is typical to do 10 repetitions at 50% of 1RM (i.e., ${}^{50\%}/_{10}$) (79).

After the last repetition is completed using strict form, does it help to ''squeeze'' out an additional repetition or two? The additional repetitions can be accomplished by getting a spotter to partially assist in completing the repetition (forced repetition system), by doing half-lifts (burn system), or by breaking strict form (cheat system, e.g., swinging the body at the beginning of a barbell arm curl) (26). Training to muscular failure (defined for discussion here as the inability to maintain a proper technique or to complete a muscular contraction because of fatigue) in this way may increase the risk of acute injuries (122). If training to failure is practiced over a prolonged period (>7 weeks), it may also lead to overuse injuries and overtraining (122). Yet another consideration is that sets to failure might psychologically condition the athlete to fail and habitually perform incomplete sets (122).

Despite the risks of overtraining and injury, Rooney et al. (110) demonstrated that when a 6RM load is lifted repeatedly 6 times without resting between repetitions, the strength gains are significantly greater than when the same load is lifted an equal number of times with a 30-second interval between each lift to avoid fatigue. He suggested that when the athlete is fatigued, additional motor units are recruited in an attempt to continue the muscular activity, and this is thought to provide an additional stimulus for strength gains and hypertrophy. Other studies have shown, on the contrary, that training to failure may not be necessary for optimal gains, but they were not controlled for volume and intensity (72, 124).

Considering that evidence supporting the long-term benefits of training to failure is still equivocal, training to failure should be limited to short periods only to reduce the risk of overtraining, overuse injuries, and possibly negative psychological conditioning.

Athletes should note that there is a tendency to train to failure when the RM training zone is prescribed, as opposed to the percentage of 1RM; an athlete who has been prescribed a load of 3–5RM will tend to accomplish 5 repetitions using a weight that is more appropriate for 3 or 4 repetitions with strict form (122).

### *Speed of the Contraction*

For a given resistance, a high speed of contraction will necessitate a higher degree of motor unit recruitment, resulting in greater strength gains (96). A study comprising 2 groups of untrained men, one performing the contractions as fast as possible (i.e., making a maximal effort) to lift the bar during a half-squat, and the other lifting the barbell in a slow and controlled manner, showed that both groups had significant but similar gains in 1RM squat after 8 weeks of training (140). Unfortunately, the IEMG was not measured during the study to confirm if the neural activation was indeed different for both groups. The authors suggested that perhaps the slow-contracting group made up for the lower neural activation with a more prolonged period of muscle tension (and hence a longer stimulus).

### *Psychological Factors*

If the athlete believes that the weight is lighter than it actually is and expects to be able to lift it, he will make a greater effort and hence will be more likely to succeed (92). Behm and Sale (10) showed that intended rather than actual movement velocity determines the velocity-specific training response, further demonstrating the importance of neural factors in strength training.

### *Interset Recovery*

Bodybuilders tend to use very short interset recovery periods (rest intervals between sets) of 30–60 seconds, whereas powerlifters and weightlifters tend to use longer intervals (2–5 minutes for weightlifters) (67, 76). How long should the interset recovery be for developing maximum strength? Prolonging the interset recovery attenuates the exercise-induced rise of serum creatine kinase and of the catabolic hormone cortisol (68) and will also ensure that the neuromuscular system has enough time to recover and make another maximal effort. Indeed, Robinson et al. (109) showed that for the lower body, a 3-minute rest interval resulted in greater gains in maximum strength than a half-minute rest interval. However, after a successful 1RM attempt in the bench press, a rest interval of 1 minute has been shown to be as adequate as a 10-minute rest interval in ensuring a second successful attempt (132). Hence, the optimal rest interval should be longer (e.g., 3–5 minutes) if the athlete is exercising bigger muscle groups (as in squats, snatches, power cleans) (109), if he is using sets with higher repetitions (e.g., a 10RM set) (64), or if he is proceeding beyond his second set. Unfortunately, precise rest intervals for different situations cannot be recommended because of a paucity of research in that area.

Although the longer interset recovery used by powerlifters and weightlifters will lead to greater maximum strength gains, a shorter interset recovery coupled with a moderate training intensity and high training volume (as of that practiced by bodybuilders) may stimulate a greater testosterone response and consequently greater hypertrophy (69, 78).

Larson and Potteiger (76) recently compared 3 different types of rest intervals: a fixed 3-minute rest interval, an interval equivalent to the time it takes the heart rate to drop to 60% of age-predicted maximum, and an interval equivalent to 3 times the exercise duration. All 3 were found to be equally effective methods of estimating the time needed for adequate recovery.

### *Order of Exercise*

Traditionally, exercises involving large muscles (multijointed movements) are done first, followed by the exercises involving smaller muscles (single-jointed movements). By exercising the large muscles first, it is thought that at the end of the session, the work done by the various muscle groups would be proportionate to their size (26). In the preexhaustion method, the reverse order is followed: the objective here is to fatigue the smaller assisting (synergistic) muscles so that when the larger muscles are exercised, they will have to generate greater forces to compensate for the fatigued smaller muscles. There is little objective research to compare the 2.

What has been shown is that when 2 exercises using similar muscles are done one after another (e.g., bench press, inclined bench press), the performance in the second exercise will be diminished (115). Because sport-specific movements are more important to the athlete, perhaps exercises more specific to the sport should be performed first.

### *Dividing the Daily Volume Into 2 Sessions*

Dividing the daily training volume into 2 sessions helps recovery and encourages a greater effort to be made. Häkkinen and Kallinen (40) studied a group of strength-trained women who had stopped making gains on their maximal isometric force with a once-per-day intensive strength training program. When the same daily training volume was divided into 2 sessions, they saw significant improvements in maximum strength after only 2 weeks.

## Training Volume

The training volume is the total work performed within a specified time. It can be determined precisely by calculating the work done in joules (i.e., force × distance), but total repetitions and volume load (or total load) are simple estimations for training volume that

**Table 2.** Summary of studies looking into optimal training frequency.

| Study | Frequencies compared ($d \cdot wk^{-1}$) | Controlled for volume | Previous training status | Body part | Frequency with highest strength gains | Limitations of study* |
|---|---|---|---|---|---|---|
| Gillam 1981 (36) | 1, 2, 3, 4, 5 | No | Untrained | Upper body | 5 $d \cdot wk^{-1}$ | ● Study not controlled for volume<br>● Unrealistic prescription (18 sets of 1RM) |
| Gregory 1981 (39) | 2, 3 | No | Untrained | Upper body<br>Lower body | Both equal<br>3 $d \cdot wk^{-1}$ | ● Study not controlled for volume |
| Graves et al. 1988 (38) | 2, 3 | No | Untrained | Lower body | 3 $d \cdot wk^{-1}$ | ● Study not controlled for volume<br>● Nautilus machine used in study |
| Hoffman et al. 1990 (53) | 3, 4, 5, 6 | Yes | Trained | Upper body<br>Lower body | 5 $d \cdot wk^{-1}$<br>4 $d \cdot wk^{-1}$ | ● Frequencies self-selected by subjects |

* 1RM = 1 repetition maximum.

are used more commonly: (a) total repetitions = sets × repetitions (7, 26, 105); (b) volume load = sets × repetitions × weight used (26, 98, 114).

As with intensity, training volume is an important stimulus for strength gains. It has been suggested that to develop maximum strength, training volume is perhaps more important than intensity during the initial phase of strength training (72).

To avoid overtraining and the detrimental rise in serum cortisol (70), excessively high training volumes should be avoided during periods when high intensities are used. Fry et al. (31) induced overtraining (decrement in 1RM performance) using 10 single-repetition sets daily (70 repetitions per week) at 100% of 1RM squats, whereas a lower-volume protocol (32) using 8 single-repetition sets (40 repetitions per week) at almost the same intensity (95% of 1RM) 5 days a week resulted in 1RM strength increments instead.

The training volume is prescribed in terms of the number of repetitions per set, number of sets per session, and the number of sessions per week (frequency). For maximal sets, the number of repetitions per set is dictated by the load, as described earlier.

### *Number of Sets per Session*

To save time, some athletes perform only 1 set to failure. However, multiple sets have been shown to be superior to single sets in achieving gains in maximum strength (64, 72). Most coaches and athletes use 3–6 sets of repetitions (105, 120, 131). When programs with 1, 2, or 3 sets were compared by Berger (12), it was concluded that the programs with 3 sets produced the greatest strength gains. Unfortunately, the efficacy of programs using more than 3 sets was not assessed in this study.

Recently, Ostrowski et al. (101) compared 3-, 6-, and 12-set protocols ($n = 9$ per group, all using the same RM load) and found that all 3 volumes resulted in increases in 1RM strength that were not significantly different between groups after 10 weeks of training. The results seem surprising considering the large difference in volumes between groups. However, it should be noted that each muscle group was exercised only once per week (for logistical reasons), although the subjects trained 4 $d \cdot wk^{-1}$. Physiological changes after a single bout of exercise return to baseline levels after a certain time, so if the exercise sessions are spaced too far apart, cumulative adaptations such as strength gains will fail to surface. In this study, perhaps it is the long interval between training sessions for each muscle group and the resultant loss of the intended additive effect, together with the relatively short study period and the use of trained subjects, that have made the between-group difference in strength gains harder to detect.

### *Training Frequency*

After a single bout of heavy resistance exercise, an immediate decrement in strength occurs, and complete recovery of both the MVC and 1RM requires approximately 3 days for experienced lifters (80). Although this indicates that an intersession recovery of 3 days is desirable to invoke maximum tensions during training, most studies (1, 36, 38, 39, 53) have found that increases in strength occur with shorter intervals between sessions (Table 2). Increased stimulation of the muscles in the high-frequency programs probably more than compensates for the slightly reduced muscular tension.

It is evident from Table 2 that the optimal frequency is 3–5 $d \cdot wk^{-1}$. Also, it seems that the upper body tends to respond better with a higher training frequency of 5 $d \cdot wk^{-1}$ (with the exception of Gregory's [39] study) compared with the lower body, where 3–4 $d \cdot wk^{-1}$ was found to be optimal. A possible explanation for this is that the smaller muscles will produce smaller gains and may need more stimulus or prolonged training before strength gains become statistically significant (51, 124). Another point to note from Table 2 is that previously trained athletes are closer to their strength potential and may require higher frequencies compared with untrained athletes.

It must be clarified that the recommended frequency of 3–5 d·wk$^{-1}$ refers to the optimal frequency for each body part. Many athletes weight train more frequently than this but do not exercise the whole body on each occasion. For example, the back and shoulder muscles might be exercised on Mondays, Wednesdays, and Fridays, whereas the chest and lower-limb muscles are exercised on Tuesdays, Thursdays, and Saturdays, to achieve an average of 3 sessions per week for each muscle group. This is called a split routine. Other variations include the blitz program (performing several exercises involving only 1 body part per session) and the isolated exercise system (devoting an entire training session to a single exercise) (26). Volume-controlled studies have not been carried out to study the split routine, the blitz program, nor the isolated exercise system.

### *Maintenance Frequency*

Strength training may need to be curtailed for various reasons such as injury, progression into a phase of more sport-specific training, going into a tapering or transition phase, in-season time constraints, or reducing the risk of overtraining during the in-season. With detraining, strength athletes will exhibit a significant reduction in strength because initial strength levels are high above the baseline. Endurance athletes such as swimmers, on the other hand, will experience little (if any) drop in maximum strength (93). In basketball players who had undergone a preseason resistance training program but not an in-season program, it was shown that there was a significant drop in 1RM squat performance 10 weeks into the season (compared to the preseason performance) (51). As much as 68% of the initial isometric strength gains could be lost after 12 weeks of detraining (38), and such losses are accompanied by decreases in maximum IEMG and fiber sizes (45), as well as a fiber type transition from type IIA to type IIB (119).

Table 3 summarizes the results of selected studies aimed at identifying the minimum number of sessions required weekly to maintain initial strength gains. Early studies (14, 89, 111) found frequencies of once every 2 weeks and less to be adequate, but there were faults in the study design during the training phase. For example, Rose et al. (111) recorded strength increases at the end of the training phase that were probably due to learning. Hence, the subjects did not experience any strength decrements while training once every 4 weeks over a year because they were maintaining learning rather than genuine strength gains.

The later studies were better designed and concluded that 1–2 sessions per week were sufficient for maintaining strength gains (22, 38, 52). Higher frequencies may be more appropriate for athletes with higher strength levels, whereas lower frequencies may be adequate if the particular body part is actively used during competition or sport-specific training (22).

## Periodization

Coaches and athletes rarely keep the training volume and intensity constant throughout the year—instead, volume and intensity are varied cyclically within training cycles (16). This is called periodization.

### *Structure of the Training Cycle*

The overall training program is divided into macrocycles (usually spanning over a year), which are further subdivided into mesocycles (2–3 months long) and microcycles in an attempt to achieve optimal performance through the preparation, competition, and transition periods (16, 85, 86). Within each cycle, the training volume and intensity is varied so that the athlete uses high volumes and low intensities at the start of the cycle. In the course of the cycle, volume is reduced while intensity is increased. The construction of training cycles should be individualized according to the athlete's sport, age, experience level, injuries, adaptation capacity, and competition dates among other things (15, 16, 58, 63, 85–87).

### *Cyclical Nature of Performance and Rationale for Periodization*

An athlete's form or readiness for high-level performances undulates in a cyclical manner (Figure 1)—it is impossible for an athlete to repeatedly record his personal best time in every race of the season without any variation in the recorded times (84). Matveyev (84) suggested that this cyclical behavior of form is a consequence of the interplay between stabilizing factors (namely specific endurance, initial training level, and specific skill level) and changing factors (work capacity, motivation, and ability to mobilize).

With this in mind, the theoretical benefits of periodization can be better understood along the following lines. (a) Periodization serves to modify the training intensity and volume so that the training conforms to the athlete's innate cycle (84). Hence the training is light during a period when the athlete is at risk of fatigue; training is heavy when he is fresh; and training tapers off to allow him to recover in time for a major competition. (b) The high-volume, low-intensity phase at the beginning of each cycle is thought to be a major contributing factor to the success of the periodized model because it prepares the athlete to better tolerate the higher intensities later in the cycle, increas-

**Table 3.** Summary of studies looking into the minimal training frequency needed to maintain strength gains.*

| Study | Training phase | Maintenance frequencies studied | Minimum frequency for maintenance | Duration of maintenance phase | Remarks |
|---|---|---|---|---|---|
| Rose et al. 1957 (111) | 1 set of 1RM 5 d·wk$^{-1}$ | 1 session·wk$^{-1}$<br>1 session·2 wk$^{-1}$<br>1 session·4 wk$^{-1}$ | 1 session·4 wk$^{-1}$ | ≈1 y | ● Increases in the 1RM during the training phase was probably due to learning rather than actual strength gain; hence the subjects were maintaining learning rather than true strength gains. |
| Berger 1965 (14) | 1 set of 6RM squats 3 d·wk$^{-1}$ × 3 wks | 0 session·wk$^{-1}$<br>1 session·wk$^{-1}$<br>2 session·wk$^{-1}$<br>3 session·wk$^{-1}$ | 0 session·wk$^{-1}$ | 6 wk | ● Berger concluded that ''dynamic strength will not be reduced in 6 wk of no training.'' Possible explanations could be that the maintenance phase was too short; that the sample size was too small ($n$ = 9); or that the strength gains from the training phase was too small to assess maintenance frequency. |
| Morehouse 1966 (89) | 1 set of 1–10 MVC 4 d·wk$^{-1}$ × 9 wk | 2 sessions·wk$^{-1}$<br>1 session·wk$^{-1}$<br>1 session·2 wk$^{-1}$ | 1 session·2 wk$^{-1}$ | 8 wk | ● Because of the low-volume prescription used during the training phase, strength gains were minimal such that the low frequency was adequate for maintenance.<br>● The study found that for strength maintenance, intensity is more important than frequency. |
| Graves et al. 1988 (38) | 1 set of 7–10RM on Nautilus machine | 0 session·wk$^{-1}$<br>1 session·wk$^{-1}$<br>2 session·wk$^{-1}$ | 1 session·wk$^{-1}$ | 12 wk | |
| Hoffman et al. 1991 (52) | Preseason resistance training program | 2 sessions·wk$^{-1}$ | 2 sessions·wk$^{-1}$ | 6 mo | ● Subjects were basketball players and maintenance phase was during the in-season.<br>● Previously untrained subjects increased strength.<br>● Previously trained subjects maintained strength. |
| DeRenne et al. 1996 (22) | 12-wk preseason progressive strength program | 0 session·wk$^{-1}$<br>1 session·wk$^{-1}$<br>2 session·wk$^{-1}$ | 1 session·wk$^{-1}$ | 12 wk | ● Subjects were pubescent baseball players (mean age 13.25 ± 1.26 y) and maintenance phase was during the in-season.<br>● Although a minimum of 1 session·wk$^{-1}$ was necessary for maintenance of upper-body strength, lower-body strength could be maintained without a strength program. |

* RM = repetition maximum; MVC = maximum voluntary contraction.

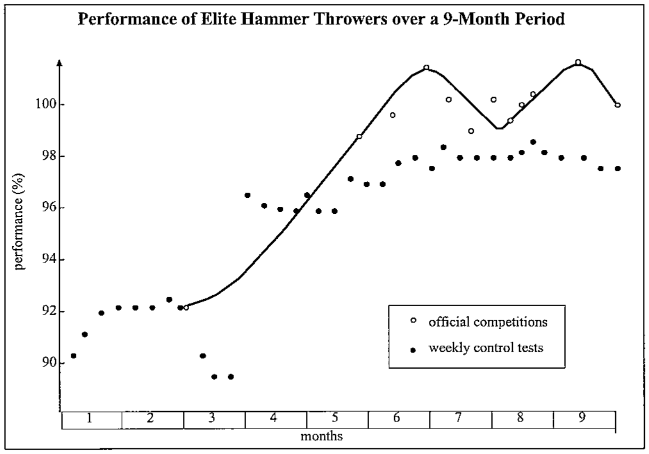

**Figure 1.** Chart showing the cyclical performance of elite hammer throwers in competitions and tests over a 9-month period (Figure modified from Matveyev [84]).

**Table 4.** Alternating accumulation and intensification phases for strength development (undulating periodization model).*

| Time (wk) | 1–2 | 3–4 | 5–6 | 7–8 | 9–10 | 11–12 |
|---|---|---|---|---|---|---|
| Repetitions (no.) | 10–12 | 4–6 | 8–10 | 3–5 | 5–7 | 2–3 |
| Sets (no.) | 3 | 5 | 4 | 5 | 4 | 6 |
| Intensity (%) | 70–75 | 82–88 | 75–78 | 85–90 | 80–85 | 90–95 |
| Volume (repetitions per session) | 30–36 | 20–30 | 32–40 | 15–25 | 20–28 | 12–18 |

* Modified from Poliquin (105).

es anaerobic capacity, and beneficially alters body composition (72, 98). (c) The low-volume, high-intensity phase towards the end of the cycle reduces the risk of overtraining. In noncyclical, monotonous programs, it is possible that the continuous use of the same set and repetition routine leads to overtraining (98). (d) The variations within the course of each cycle prevent the staleness that may be responsible for the differences in strength gains as well as differences in the final maximum power output between athletes (98). Varying the volume and intensity forces the neuromuscular system to adapt to the training load. Poliquin (105) believes that strength training programs lose their efficacy after only 2 weeks because of the body's rapid adaptation to a fixed training stimulus. Although it is true that adaptation to a fixed training stimulus can occur rapidly, a period of 2 weeks is probably an underestimation. Hickson (47) showed that with 5RM exercises for the lower body, progressive increments in the 1RM continued to the end of the study at 10 weeks; and Graves et al. (38) found that strength gains plateaued just before the 10th week in response to a low-volume, moderate-intensity program (1 set of 7- to 10RM leg extensions 2–3 times per week).

### *Supporting Evidence*

Because of the large number of permutations and the need to individualize cycles, it is difficult to design an effective periodized model to assess in an experiment. Negative results might simply be attributed to the faulty construction of the model rather than the inefficacy of periodization. Nevertheless, several investigators managed to demonstrate the superiority of periodized models over fixed models (64, 98, 120, 123, 124, 134). A crucial question in studies concerning the efficacy of periodization is whether the training volume should be equated when comparing the periodized and fixed models. Equating the volume might initially sound logical, but it is important to realize that the periodized model might owe its efficacy to the high overall volume made possible by the variations in volume and intensity; equating the volumes in this case will negate the advantage of the periodized model. In other words, the training volume should be treated as a study factor and not as a confounding factor; an experiment that controls for a study factor cannot be expected to show significance between groups. Indeed, a recent study failed to show any significant differences in maximum strength gains between a linear periodization model, an undulating periodization model, and a nonperiodized model when training volume and intensity were equated between the 3 groups (7). Investigators who did not control for volume (64, 98, 134) managed to elicit significantly greater strength gains in their periodized groups. Their results were all the more convincing because the superior strength gains in the periodized group occurred during the portion of the training period when the volume of the periodized group was lower than that of the fixed groups.

### *Linear and Undulating Periodization Models*

Although it is most common to use high volumes and low intensities at the beginning of the cycle and the reverse toward the end of the cycle (linear periodization model), coaches have described a variation that undulates the volume and intensity (undulating periodization model; Table 4) (105). Kraemer (64) compared an undulating model to a single-set protocol and found that in the undulating periodization model, 1RM strength continued to rise throughout the 24-week study period, whereas the 1RM strength of the subjects using the much-lower-volume, single-set protocol showed an early plateau. Direct comparisons between the undulating and linear models are currently lacking.

## Concurrent Training

Maximum strength is specific only to powerlifting and not to any other sport. Hence, single-mode training for maximum strength is rarely done. Training for maximum strength is usually combined with endurance training (in sports like wrestling, football, and basketball, for example) or power training (in sports like the long jump, sprinting, and the discus).

### *Concurrent Strength and Endurance Training*

For the strength athlete, adding an endurance program to his high resistance program will result in an attenuation of strength gains (24, 46, 47, 70) and power development (70). Of course, if the concurrent endurance program is relatively light (e.g., jogging 2 miles once per week), maximum strength will remain unaffected (91). When subjects who did only strength training were compared with subjects who did both strength and endurance training, it was found that strength gains from concurrent training initially matched that of isolated strength training for 7 weeks, after which it leveled off and dropped significantly on the 9th and 10th weeks (47). Hence, it seems that endurance training will cap the upper limits of strength gains. In another study (11), cortisol has been shown to be higher in men who did concurrent training compared to those who did strength training alone; however, the possibility of overtraining in the concurrent group was discounted by the fact that the group had a gradual increase in $\dot{V}O_2max$ throughout the 10 weeks. If endurance training is added to the dynamic strength program (e.g., maximal knee extensions on an isokinetic dynamometer at a velocity of $4.19\ rad \cdot s^{-1}$), maximum torque at fast, but not slow, velocities will be reduced (24).

How will strength training affect an endurance athlete? It has been shown that strength training leads to a dilution of the mitochondrial volume density through an increase in myofibrillar size with hypertrophy (83). However, despite the lowered mitochondrial volume density, endurance-trained athletes who added strength training to their program did not show any significant drop in their maximal oxygen consumption ($\dot{V}O_2max$) (48, 102). Furthermore, untrained subjects who embarked on a concurrent strength and endurance training program improved their $\dot{V}O_2max$ at the same rate as those who undertook endurance training alone (24, 46, 47, 70).

Strength training alone will not significantly improve an athlete's aerobic capacity (30, 55) unless extremely high volumes and large muscle groups are used (49, 121). Circuit weight training, a form of resistance training that is conducted almost continuously with moderate weight, using 10–15 repetitions per exercise with no more than 15–30 seconds of rest between bouts of activity (106), is seen by some as a means to improve both strength and endurance at the same time. Although it has some value in increasing muscular strength in untrained subjects, improvements in aerobic capacity are minimal, especially when corrected for increases in lean body mass. The reported increases in relative $\dot{V}O_2max$ of up to 7.8% (35, 62, 106, 137) is negligible when compared to improvements of approximately 12–20% reported for endurance programs such as running and walking (35). Unfortunately, despite the high rate of perceived exertion and high heart rates (secondary to reduced stroke volume) experienced during circuit weight training, the oxygen consumption ($\dot{V}O_2$) during the session is usually short of the minimum 50% $\dot{V}O_2max$ thought to be needed to achieve an endurance training effect (55, 106, 137). Although increases in $\dot{V}O_2max$ are difficult to achieve with strength training alone, improvements in short-term endurance (endurance time to exhaustion) are more attainable and more marked (49, 121).

Hence, it is apparent that, although aerobic endurance training inhibits strength development, strength training is not detrimental to the athlete's $\dot{V}O_2max$, and it can even improve the athlete's short-term endurance (20).

### *Combination Strength and Power Training*

For the majority of athletes, power is the primary objective. Single-mode training for power at sport-specific velocities usually involves training with lighter loads of about 30% of 1RM (95), using plyometric exercises such as depth jumps and countermovement jumps (34). At such low loading, maximum strength diminishes with time. But to enhance power, maximum strength is a prerequisite (power = force × velocity), and it has been shown repeatedly that strength training alone will lead to increases in power (43, 46, 61, 90, 98, 101, 124, 133, 138), especially at the low-velocity end of the force–velocity curve. For example, Wenzel and Perfetto (133) found that strength training was as effective as speed training in developing power in a group of 65 football players.

When a group of baseball throwers underwent an 8-week upper-body strength training program (using 10RM loads with forced repetitions) in addition to their throwing program (15 minutes of long toss, 3 times per week) during the fall portion of the preseason, their throwing velocity was found to be higher than the group that underwent the throwing program only (74). Combination strength and power training has also been shown to be superior to either strength training alone or plyometric training alone in improving vertical jump ability (6).

Another method of combining strength and power training is to alternate heavy and light loads to exercise a muscle in a single workout (contrast method). Young et al. (139) demonstrated that a loaded countermovement jump could be enhanced by a statistically significant 2.8% if preceded by 1 set of 5RM squats. Jumps enhanced in such a way may be expected to provide a superior training stimulus for developing muscular power.

## Physiological Adaptations to Strength Training

To formulate effective resistance training prescriptions, and to understand the relation between resistance training program variables and maximum strength, one should be familiar with the physiological adaptations following strength training. These include neural, hormonal, and muscular adaptations. The neural and endocrine adaptations have been briefly discussed earlier along with training volume and intensity. Muscular adaptations include hypertrophy, myosin heavy chain (MHC) isoform shifts, metabolic adaptations, possible changes in the neuromuscular junction, changes in capillary supply to muscles, and flexibility changes.

### *Hypertrophy*

A single bout of heavy resistance training has been shown to increase muscle protein synthesis via posttranscriptional events for up to 24 hours postexercise (19). Strength training leads to enlargement of the fast-twitch (type II) fibers, with hypertrophy of the slow-twitch (type I) fibers occurring to a lesser extent (45, 83, 118, 119). It is thought that the type I fibers partially resist the tendency to hypertrophy in response to strength training by down-regulating their testosterone receptors (78).

When Häkkinen et al. (45) put subjects through a 24-week high-intensity resistance training program, they noted that hypertrophy occurred during the first 12 weeks with no further increase in size thereafter. This lends support to the possibility of an optimal cross-sectional area for fibers undergoing hypertrophy. Once this optimal area is reached, hyperplasia of the muscle may occur, as described by MacDougall et al. (82), in bodybuilders and powerlifters. Whether or not hyperplasia truly occurs in humans is still a contentious issue (5, 81, 125, 127).

Increased muscle bulk is advantageous to sports like rugby and the shot put, but it is understandably detrimental to most other sports, including sprinting and the long jump, where extra weight bearing may be a hindrance. Athletes in weight-limited sports (e.g., lightweight rowing) are also not keen on acquiring excessive muscle bulk. Can an athlete achieve strength gains without hypertrophy? Some coaches and investigators are of the opinion that training prescriptions can be altered to target strength gains plus hypertrophy or to target strength gains in isolation without hypertrophy (57, 58, 63, 65, 105, 131). Programs with high volumes and moderate intensities (e.g., 8–12 sets of 6–12RMs) with short rest intervals are thought to encourage hypertrophy, whereas those with low volumes and high intensities are expected to achieve strength gains without hypertrophy (9, 69, 100, 120, 123). Although high-intensity, low-volume protocols may produce relatively less hypertrophy, it seems difficult to eliminate hypertrophy completely. A low-volume protocol (1 set of 8–12RM exercises 3–4 times a week) was found to elicit a statistically significant 2.84% increase in lean body mass (55), whereas a much-higher-volume protocol elicited only a similar increase in lean body mass (121); O'Shea (99) compared a low-volume protocol (3 sets of 2–3RM squats) with a high-volume protocol (3 sets of 9–10RM squats) over 6 weeks and found significant increases in thigh girth in both groups, but there was no statistical difference between groups; yet another low-volume protocol using 3 sets per week per muscle group produced measurable hypertrophy on ultrasound after only 10 weeks of training (101); at the cellular level, Campos et al. (17) demonstrated that a low-volume, high-intensity protocol produced significantly greater muscle fiber hypertrophy compared to a high-volume, low-intensity protocol. Hence, most protocols (47, 49, 55, 99, 101, 104, 121), including low-volume ones aimed at maximizing strength, will induce some degree of hypertrophy. The claim that hypertrophy is avoidable with low-volume, high-intensity resistance training needs to be investigated using accurate imaging techniques such as magnetic resonance imaging (25) or ultrasound to assess increases in muscle cross-sectional area. Changes in the cross-sectional area of individual muscle fibers are hard to detect, so a failure to detect fiber hypertrophy cannot be taken as evidence that hypertrophy has not occurred.

Concurrent endurance training rather than low-volume resistance training may be the key to minimizing hypertrophy. When athletes who were already endurance trained were placed on a concurrent strength training program (3–5 sets of 5RM exercises 3 days a week for 10 weeks), they increased their leg strength by 30%, but there was no change in thigh girth nor vastus lateralis muscle fiber areas (48). Kraemer et al. (70) further demonstrated that strength training alone produced hypertrophy of types I, IIC, and IIA fibers, whereas concurrent strength and endurance training resulted in hypertrophy of only type IIA fibers. Although adding endurance training to strength training effectively attenuates hypertrophy, strength gains are unfortunately compromised as well (70).

### *Myosin Heavy Chain Isoform Shifts*

Human skeletal muscle is composed of a combination of different muscle fiber types. The various muscle fibers are classified into 7 fiber types on the basis of the pH sensitivity of myofibrillar adenosine triphosphatase types I, IC, IIC, IIAC, IIA, IIAB, and IIB (116). The type I fibers have the highest oxidative and lowest glycolytic capacity, whereas at the other end of the spectrum, the type IIB fibers have the lowest oxidative and highest glycolytic capacity (136). There are only 3 MHC isoforms: the slow MHCI and the fast MHCIIa and MHCIIb. Muscle fiber types I, IIA, and IIB express MHCI, MHCIIa, and MHCIIb, respectively. The type IIAB and C fibers, however, express 2 different MHCs; type IIAB fibers co-express MHCIIa and MHCIIb, whereas the C fibers (IC, IIC, IIAC) contain MHCI and MHCIIa in different proportions (116).

The training load selected will influence muscle fiber type utilization; type I and type IIA fibers are used for both light and heavy loads, whereas type IIAB and IIB fibers are activated for loads in excess of 60% of 1RM (128).

Elite sprinters, jumpers, and weightlifters have been found to have a high percentage of fast (type II) fibers in their thigh muscles (54), whereas bodybuilders have a comparatively higher proportion of slow (type I) fibers (5, 127). Heavy resistance training causes a drift in MHC isoforms from MHCIIb to MHCIIa within 4 weeks, and this transition may almost be complete at 12 weeks (59, 70, 108, 118, 119). This drift corresponds to a shift from type IIB to type IIA fibers. Such a drift facilitates fiber hypertrophy and is associated with strength gains and increased oxidative capacity of the muscle (2, 60, 66). Fiber type transition is thought to be restricted to neighboring subtypes, and there is very little evidence that, under physiological conditions in human muscle, a further drift from type II to type I fibers is at all possible with prolonged resistance training (60, 66, 117, 129).

### Metabolic Adaptations

The metabolic changes with strength training are manifested by reduced mitochondrial density, increased energy-rich phosphates, increased glycogen stores, increased splitting of energy-rich phosphates, increased citrate synthase activity, increased anaerobic glycogenolysis and glycolysis, increased oxidation of carbohydrates, and increased myoglobin (30, 54). The decrease in mitochondrial volume density is apparently the result of an increase in total contractile protein without a proportional increase in mitochondrial volume (83). An increase in citrate synthase activity (an oxidative enzyme) in fast-twitch fibers could possibly be induced by having shorter rest intervals between sets (126).

### Neuromuscular Junction

The neuromuscular junction serves as the interface between the nervous system and the muscle. Although changes have been demonstrated in the size and morphology of the synapses after exercise in animals, little is known about morphological adaptations to resistance training in humans (23, 66).

### Capillary Supply

A rich capillary supply to muscles will hasten muscle recovery after exercise and possibly allow the muscles to better tolerate anaerobic conditions during exercise. Heavy resistance training leads to an increase in the number of capillaries per unit area (30, 66). This ingrowth of capillaries may be enhanced using protocols that cause a greater lactate accumulation (e.g., short rest intervals between sets) as in that used by bodybuilders (66).

### Flexibility

Muscular stiffness has been anecdotally associated with resistance training (26). However, Olympic lifters, despite their strength, were found to be as flexible as controls because of the overhead lifting that they do (8). A recent cross-sectional study also failed to find a relation between muscle strength and flexibility (18). Furthermore, a prospective study found that 10 weeks of resistance training did not result in any decrease in flexibility in men; this study even found significant increases in flexibility in women (137). Hence, strength training does not have to be detrimental to the athlete's flexibility (103) as long as the athlete stretches appropriately and undergoes a full range of motion with each repetition.

## Practical Applications

Maximum strength acts as a general base that supports specific training in other spheres of conditioning. To optimally enhance maximum strength, the following are recommended: relatively high training intensities in the 1- to 6RM range, combining concentric and eccentric loading, training to failure for limited periods only, 3–6 maximal sets per session, allowing full recovery between sets, dividing the daily volume into 2 sessions, a training frequency of 3–5 days a week, and variation of the training volume and intensity (load) in the course of a training cycle. Training once per week with high training intensities will generally be adequate for maintaining strength gains.

Combining strength and endurance training will be detrimental to maximum strength gains, but aerobic capacity will generally be unaffected. Maximum strength and power are interrelated, so combining strength and power training is an effective way of increasing power.

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