

Power and Maximum Strength Relationships During Performance of Dynamic and Static Weighted Jumps

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ABSTRACT

The purpose of this study was to investigate the relationship of the 1 repetition maximum (1RM) squat to power output during countermovement and static weighted vertical squat jumps. The training experience of subjects ($N = 22$, 87.0 ± 15.3 kg, $14.1 \pm 7.1\%$ fat, 22.2 ± 3.8 years) ranged from 7 weeks to 15+ years. Based on the 1RM squat, subjects were further divided into the 5 strongest and 5 weakest subjects ($p \leq 0.05$). Squat jumps were performed with a countermovement or statically at 2 different sessions spaced 1 week apart. Jumps were performed with weights ranging from 10 to 100% of the 1RM squat. A maximum effort was made for each trial; subjects performed jumps (feet left the floor) with weights up to approximately 90% of 1RM. Squat-jump power was determined using the V-scope 120. Results indicate strong correlations ($r = 0.77$ – 0.94) between the 1RM squat and both countermovement and static jump power up to 90% of 1RM. The highest power outputs for both jump conditions occurred at 10% of the 1RM and decreased as the relative intensity increased. Comparisons of weak and strong subjects indicate that as maximum strength increases the percentage of 1RM at which peak power occurs also increases (40 vs. 10% of 1RM). From a practical aspect, to improve jumping power output, these results suggest that improving maximum strength should be a primary component of training programs and that strength training should shift from lighter (10% 1RM) to heavier (40% 1RM) loads.

Key Words: power, strength, vertical jump

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Introduction

Power can be defined as work/time or force \times velocity. Power generation during sports performance

is generally considered to be the major factor for separating participants. Although force production tends to increase as resistance increases, velocity tends to fall. Peak (instantaneous) power (PP) is the highest power generated during a particular movement and is produced when both force and velocity are at optimum values (not necessarily maximum values). The highest values for PP have been found previously to occur at approximately 30% of peak isometric force during isolated movements (16, 22) and at approximately 30–50% of the 1 repetition maximum (1RM) (12, 21). Furthermore, differences in PP may be at least partially associated with the type of training undertaken or with sport performance. For example, PP production during unweighted and weighted jumps have been related to differences in sports training background (18).

Strength can be defined as the ability to produce force (26). Thus, strength can have a magnitude ranging from zero force production to maximum. Because power is the product of force and velocity, it is obvious that appropriate increases in force can increase power production. It is the authors' opinion that many and perhaps most coaches and athletes involved in "strength-power" sports currently believe that maximum strength is related to power production and that increases in maximum strength can cause increases in power production. This belief has a long history of theoretical support (13, 14, 17). Several possible reasons as to why maximum strength may affect PP output—(a) A given weight would represent a smaller percentage of maximum strength for a stronger person; thus, this weight would be easier to accelerate. (b) A person with greater maximum strength might have larger or a greater percentage of type II fibers. Type II fibers are the primary motor units that contribute to high power output. (c) As a result of strength training

Table 1. Squat test protocol.**Warm-up**

Five minutes of mobility exercises (i.e., jumping jacks, body mass squats)
Five squats with the bar (20 kg)

Test

Each bar mass of up to 130 kg was tested twice. Thereafter, only 1 squat-jump was performed to limit fatigue until maximum (1 repetition maximum [1RM]) was reached. If the subject believed that a test was not valid or did not represent a maximum effort, a repeat trial was performed
The test (jumping) began at 0 kg (213 cm length of PVC pipe)
The subjects then performed jumps at 30, 40, 50, 60, 70, 80, 90, 110, and 130 kg. (group N only increased to 80 kg). The bar was then increased by 10–20 kg until the 1RM was approached (90% of 1RM), thereafter smaller increments of 5 or 2.5 kg were used until the 1RM was achieved.

(i.e., greater maximum strength), additional alterations can occur simultaneously, which would affect power. These alterations could include hypertrophy of type II fibers, increases in the Type II/I cross-sectional area ratio, or alterations in motor unit activation (11). Adaptations such as these would affect higher power outputs.

However, the exact relation of maximum strength (as measured by a 1RM) to power production is not clear. Schmidtbleicher (25) indicates that maximum strength is the basic quality affecting power output. He suggests that maximum strength affects power in a hierarchical manner with diminishing influence as the external load decreases to a point at which other factors such as rate of force development become more important. This argument indicates that maximum strength should have its greatest influence on power output at heavy loads and that light loads should be influenced to a smaller degree by maximum strength levels. However, some evidence indicates that maximum strength may have a greater influence on power output over a wider range of loads than might be expected (20). Studies (5, 6, 19) using the unweighted standing long jump and vertical jump indicate that the shared variance between power and measures of maximum strength is approximately 50%. However, Whitely and Smith (32) and Eckert (10) found that by adding additional resistance to a movement the relationship between maximum strength and power and strength and speed tended to increase with the added resistance, a finding supported by Schmidtbleicher (25). More recently, Moss et al. (20) investigated the relationship between the 1RM and PP at various percentages of the 1RM using flexion at the elbow. They (20) found strong correlations between the 1RM and maximum PP output ($r = 0.93$) but also showed a strong correlation between the PP output at 2.5 kg and the 1RM ($r = 0.73$). These studies indicate that the relationship between the power production during a specific movement and the 1RM for this movement should account for 50% or more of the variance and should tend to increase as the weight lifted increases.

Another factor considered is the type of muscle actions involved in the movement. Previous investigations considering the relationship of power to 1RM focused on countermovements (stretch-shortening cycle) or made no comparison between static and countermovement performances. For example, Cronin et al. (8) found that 1RM strength, measured with a countermovement, was strongly associated with the PP developed during the first 200 ms of the concentric portion of a countermovement bench press at varying weights. However, the authors (8) did not note an association with a concentric-only bench press. Considering the findings of Cronin et al. (8), it is possible that the relationship between maximum strength and other variables such as power is different when comparing countermovements to static performances.

Because the degree to which maximum strength influences power production, particularly over a wide range of loads, is unclear, study of the relationship of maximum strength with measures of power is warranted. Furthermore, a better understanding of this relationship can provide a basis for improving the design of resistance training programs with the intent of improving maximum power.

The primary purpose of this study was to examine the relationships (correlations) between the 1RM squat and PP production during countermovement and static unweighted and weighted squat jumps. In addition, the load (% 1RM) providing the highest PP was investigated.

Methods

Experimental Approach to the Problem

Squat jumps were performed with or without a countermovement at 2 different sessions spaced 1 week apart. During the first session, subjects performed countermovement squat jumps with incremental weight increases, as described in Table 1. Squat-jump depth was determined by the anterior surface of the thigh, with a line between the inguinal fold and the top of the patella parallel to the floor. Proper depth

was determined visually and measured to assure consistent squatting depth. A rubber stretch cord was placed across the power rack to assure proper squatting depth for all subjects and each trial. Bar placement on the shoulders was between C7 and the superior aspect of the scapula; all subjects were accustomed to using this "high bar" placement. Subjects used their normal foot placement. Each subject had sufficient experience or had been tested previously so that a reasonable idea of the 1RM was known before beginning the data collection. Jumps began at 0 weight (subjects held a plastic pipe on their shoulders weighing less than 0.25 kg) and were incrementally increased until approximately 80% of the 1RM was reached. Two trials were given for each weight up to the 80% value. Thereafter, single attempts were made, to minimize fatigue, until the 1RM was reached (approximately 2–4 additional attempts). On being questioned, subjects believed that this method resulted in a true 1RM and was not unduly fatiguing. Data were recorded for each submaximal weight and at maximum (1RM). Subjects were instructed to perform a maximal effort for each trial; as a result, subjects were able to perform jumps (feet left the floor) with weights up to approximately 90% of 1RM. If the subjects felt that their effort was less than maximal, the trial was repeated. Subjects were allowed to take as much recovery time as necessary (typically 2–5 minutes). At the second session, subjects performed squat jumps in the static condition with the same incremental weight increases as those in the dynamic condition (Table 1). The squat depth used was the same as that used in the countermovement trials. The subjects held the static position for 3 seconds before initiating a maximal upward effort. Subjects were able to jump (feet left the floor) at all weights up to approximately 90% of the maximum. A pilot study ($N = 4$) was performed to ensure that the squat-jump-testing procedure was viable. All squats were performed inside a specially designed power rack (Sorinex, Orange, SC) for spotting assistance and safety.

Subjects

Twenty-two male subjects between 17 and 30 years participated in this study. All subjects signed informed consents in accordance with American College of Sports Medicine guidelines. Subjects completed a training history questionnaire before initiation of the study. A 7-site skinfold was used to determine approximate body fat percentages (15), and body mass (BdM) was obtained using an electronic scale. Squat training histories of the subjects showed experience ranged from 7 weeks to 15+ years. A large range in squatting experience (and 1RM) was purposely chosen to highlight the potential association between maximum strength and power. To further aid in understanding the relationship of maximum strength to

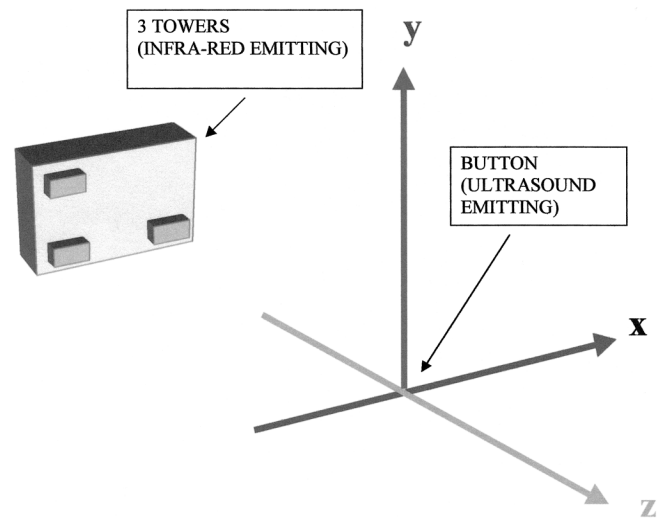


Figure 1. V-scope tracking: resolving a point in dimensional space.

power, subjects were divided into 2 groups containing the 5 strongest and 5 weakest subjects based on the 1RM squat.

Instrumentation

V-scope. Squat-jump power was determined using V-scope 120 (Lipman Electronic Engineering Ltd., Ramat Hahayal, Israel). The V-scope is a movement analysis device using infrared and ultrasound technology to track an ultrasound-emitting button attached at the end of the bar during weightlifting (30). Briefly, the V-scope tracks the movement of the ultrasound-emitting button from 3 towers housed in a large briefcase (Figure 1), placed approximately 1 m above the floor and 4–5 m from the button. Trigonometric algorithms (triangulation) are used to characterize the position of the button in 3-dimensional space. The V-scope sampled data using a frequency of 66 Hz. Displacement reliability and validity were checked by moving the ultrasound-emitting button both vertically and horizontally through known distances (trials = 100×2 for each condition). Test-retest reliability was estimated using intraclass correlations (ICC). Movement-displacement reliability was consistently above $ICC = 0.99$. Total displacement difference between trials ($N = 100$) was less than 1 cm (<1%). Peak power (instantaneous) for the squat jumps was calculated using Newton's second law (V-scope software) as (a) force = mass \times acceleration + W , where mass = bar mass + BdM and W = mass of the weight lifted in the jump \times 9.8. and (b) power = force \times velocity.

Comparison of force data (V-scope vs. force plate) resulted in a correlation of $ICC = 0.94$, $N = 100$ trials. In addition, squat-jump reliability for PP was examined through test-retest trials ($N = 220 \times 2$ conditions). Reliabilities for countermovement squat-jump

Table 2. Physical characteristics of the subjects (mean \pm SD): $N = 22$.

Age (y)	Height (cm)	BdM*	LBM (kg)	Percent fat
22.2 \pm 3.8	177.9 \pm 6.4	87.0 \pm 15.3	74.1 \pm 8.7	14.1 \pm 7.1

Table 3. Countermovement and static 1 repetition maximum performance (mean \pm SD): $N = 22$.

CMSq (kg)*	CMSq/BdM	SSq (kg)	SSq/BdM
148.5 \pm 44.9	1.66 \pm 0.42	137.8 \pm 40.5	1.55 \pm 0.37

* CMSq = countermovement squat-jump; SSq = static

PP and static squat-jump power were ICC = 0.88 and 0.92, respectively.

Statistical Analyses

Calculation of the relative intensity (% 1RM) was bar mass/1RM \times 100. By converting the mass lifted to a relative intensity, data were normalized according to maximum strength levels. Correlations between variables were calculated using the Pearson product moment method. The strength of the correlations was based on the findings of Cohen (7), where $r = 0.0$ – 0.1 = trivial, 0.1 – 0.3 = moderate, and 0.3 – 0.5 = large effect.

Differences in group maximum strength and power were assessed using Student's t -tests. The magnitude of the differences in means (5 strong vs. 5 weak) was shown as effect size (change in means/SD) and interpreted according to the criteria of Cohen (7): <0.2 = trivial, 0.2 – 0.4 = small, 0.5 – 0.7 = moderate, >0.7 = large. Precision of the estimate for power measures was shown as 95% confidence limits.

Results

Table 2 shows the physical characteristics of the 22 subjects, and Table 3 shows the 1RM squat variables. Correlations ($N = 22$) between BdM, lean body mass (LBM), and the countermovement 1RM squat (CMSq) indicate strong relations ($r = 0.73$ BdM vs. CMSq; $r = 0.79$ LBM vs. CMSq). Correlations between BdM, LBM, and the static 1RM squat (SSq) indicate moderate relationships ($r = 0.67$ BdM vs. SSq; $r = 0.71$ LBM vs. SSq). Height and percent fat did not show significant relations with the squat. Body mass and height were only moderately related ($r = 0.43$). The 1RM static squat represented approximately 93% of the countermovement squat ($N = 22$).

Table 4 shows the power (W) generated at 10–100% of the 1RM. Power decreased as the percentage of 1RM increased for both the countermovement and static

Table 4. Power output (W) as a function of relative intensity (% 1 repetition maximum) (mean \pm SD): $N = 22$.

	Countermovement squat jump	Static squat jump
10%	5,199.73 \pm 1,301.06	5,113.07 \pm 1,482.17
20%	5,194.89 \pm 1,359.08	5,046.11 \pm 1,433.12
30%	5,152.79 \pm 1,392.14	5,038.37 \pm 1,376.46
40%	4,987.51 \pm 1,452.10	4,993.40 \pm 1,391.84
50%	4,901.23 \pm 1,415.61	4,767.56 \pm 1,323.76
60%	4,881.14 \pm 1,464.05	4,628.04 \pm 1,316.06
70%	4,663.77 \pm 1,228.96	4,304.50 \pm 1,335.62
80%	4,458.59 \pm 1,078.80	4,194.37 \pm 1,300.06
90%	4,017.08 \pm 1,055.88	3,885.84 \pm 1,347.73
100%	3,030.79 \pm 1,185.31	3,137.26 \pm 1,294.54

conditions. No statistical differences in power were noted between static and dynamic conditions at any percentage of 1RM. Correlations between power and the 1RM values for each condition are shown in Table 5. The highest correlations between the 1RM and power were found at 50% of 1RM for both the countermovement and static conditions. Interestingly, the correlations for the static condition were somewhat higher than those for the countermovement condition.

Comparisons of maximum strength between the 5 strongest subjects and the 5 weakest subjects are shown in Table 6. All values for 1RM were greater in the strong group. Power output values are given in Table 7. Although the confidence limits were large (because of a small subject number), the effect size values consistently reflect moderate to large mean differences. The measures of jump power were in general agreement with power outputs from similar subject groups assessed with different methods (18). The strong group had higher values at all percentages of 1RM when compared with the weak group. The strong group had their highest power outputs at 40% of 1RM; the weak group had decreasing power outputs as the percentage of 1RM increased.

Discussion

The primary and unique finding of this study deals with the strong correlations between the 1RM countermovement parallel squat and power output generated during both countermovement and statically performed weighted jumps. These correlational findings suggest that jumping power may be increased with improvement of the 1RM squat. The fact that the 5 strongest subjects had markedly higher power outputs than the 5 weakest subjects strengthens this finding.

Although an increase in the resistance resulted in increased correlations between the 1RM and power, the change was not linear for either condition (static or countermovement). Increasing correlations occurred

Table 5. Relationships of maximum strength to power (W) at 10–100% of 1 repetition maximum (1RM) (N = 22).

	Correlations									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1RM countermovement squat and power	0.778824	0.839546	0.84874	0.877306	0.875232	0.852589	0.838003	0.797941	0.732311	0.595549
1RM static squat and power	0.84218	0.870468	0.902264	0.935779	0.938109	0.929605	0.9011	0.91079	0.859338	0.749635

only to a point (about 50% of 1RM) after which correlations decreased. The lowest correlations occurred at the 1RM value. One possibility for the lower correlation, as the bar mass approached the 1RM, is that after driving through the “sticking region,” maximum effort was no longer exerted. This reduction in force may have occurred as a result of trying to maintain control of the bar mass, or simply because so much energy was expended in the sticking region, further acceleration was difficult. However, the exact reason for low correlations between 1RM values and power at 1RM is unknown and will require further investigation.

Evidence (25, 31) indicates that power production for moving light loads also depends on other force-related components such as initial rate of force development (starting strength) and peak rate of force development (explosive strength). However, the present observation suggests that maximum strength is associated with high power outputs at light as well as heavy weights, supporting the findings of Moss et al. (20). For example, considering the 1RM values produced by the subjects, a value of 10% of the 1RM would represent a weight of approximately 8.5–22.5 kg for the countermovement conditions and 6.5–20 kg in the static conditions; the shared variance between the 1RM and the 10% value was approximately 61% ($r = 0.78$) for the countermovement condition and 70% ($r = 0.84$) for the static condition. Thus, data from the present study indicate that maximum strength plays a major role in power output in both static and countermovement jumps even at relatively light weights.

These results also indicate that both static and countermovement peak jumping power decrease with increasing percentages of maximum. Previous investigation indicates that PP occurs at about 30–50% of the 1RM (16, 21). The strength levels of the subjects in this study represented a much more heterogeneous group than those in previous studies. Our observation that the 5 strongest subjects produced their greatest power outputs at 40% of maximum agrees with previous observations. Furthermore, these results suggest that as maximum strength levels increase, there may be an upward shift in the percentage of maximum strength at which PP is produced.

Also of importance is the observation that power was equal or greater in the countermovement condition when compared with the static condition at all percentages of 1RM. This was also noted in the 1RM values for the squat. Several factors may have contributed to the augmentation of strength and power during the countermovement (6, 8). These factors include (a) a greater active state of the muscle as a result of the preceding eccentric phase, (b) storage and use of elastic energy, and (c) a stretch (myotonic) reflex occurring as a result of the eccentric action. Training-induced enhancement of these factors may also help

Table 6. Maximum squat—5 strongest vs. 5 weakest subjects.*

	Maximum squat (mean \pm SD)			
	CMSq	CMSq/BdM	SSq	SSq/BdM
Strongest†	212.5 \pm 8.4	2.00 \pm 0.24	190.5 \pm 9.4	1.79 \pm 0.19
Weakest	95 \pm 6.3	1.21 \pm 0.18	84.7 \pm 8.9	1.09 \pm 0.21

* CMSq = countermovement 1RM squat; SSq = static 1RM squat; BdM = body mass.

† Stronger subjects were significantly different from weaker subjects for all 1 repetition maximum (1RM) values ($p \leq 0.0125$).

Table 7. Maximum power output (mean \pm SD) at a percentage of 1 repetition maximum (1RM)—5 strongest vs. 5 weakest subjects.

% 1RM	5 Strong	5 Weak	95% Confidence limit	<i>p</i> Value	ES*
Countermovement					
10	5,079 \pm 2,363	3,785 \pm 376	877–1,711	0.001	0.55
20	5,321 \pm 2,497	3,751 \pm 534	1,063–2,075	0.001	0.61
30	5,331 \pm 2,539	3,650 \pm 366	956–2,406	0.003	0.66
40	5,391 \pm 2,566	3,296 \pm 310	1,285–2,907	0.002	0.80
50	5,206 \pm 2,525	3,129 \pm 343	1,108–3,045	0.004	0.81
60	5,303 \pm 2,700	3,167 \pm 488	886–3,386	0.009	0.78
70	4,887 \pm 2,407	3,256 \pm 419	760–2,902	0.009	0.75
80	4,567 \pm 2,245	3,364 \pm 322	457–1,949	0.11	0.53
90	4,106 \pm 2,072	3,025 \pm 392	212–1,950	0.026	0.51
100	3,349 \pm 1,708	2,033 \pm 829	405–2,227	0.016	0.69
Static					
10	5,464 \pm 2,507	3,482 \pm 443	1,648–2,318	0.00008	0.79
20	5,517 \pm 2,535	3,474 \pm 423	1,678–2,408	0.0001	0.80
30	5,502 \pm 2,492	3,431 \pm 404	1,823–2,317	0.00002	0.83
40	5,635 \pm 2,577	3,356 \pm 380	1,883–2,675	0.00009	0.87
50	5,377 \pm 2,474	3,246 \pm 348	1,628–2,634	0.0003	0.85
60	5,243 \pm 2,409	3,103 \pm 131	1,635–2,646	0.0003	0.88
70	5,042 \pm 2,312	2,908 \pm 290	1,559–2,709	0.0005	0.92
80	4,845 \pm 2,224	2,714 \pm 322	1,626–2,632	0.0003	0.84
90	4,605 \pm 2,129	2,484 \pm 411	1,618–2,620	0.0003	0.90
100	3,664 \pm 2,009	1,971 \pm 395	438–2,946	0.02	0.80

* ES = effect size.

to explain the difference in countermovement power output between the stronger and weaker subjects (Tables 6 and 7). However, static jump power values for the weak subjects represent a lower percentage of the power value for the strong subjects than do the countermovement jump power values. For example, on comparing the ratio of weak/strong, the average percentage of power output across 10–100% of 1RM for static squat jumps is 59% but is 67% for the countermovement condition. This difference in ratio values is amplified by the slightly larger static power outputs when compared with countermovement in the strong group. The smaller difference between power outputs (strong vs. weak) in the countermovement condition could indicate a greater reliance of the weak group on the rate of force development or factors associated

with stretch-shortening rather than maximum strength.

Practical Applications

Increasing power output (or work rate) is perhaps the most important aspect in improving the performance of a specific movement. Peak power represents the maximum power produced at a particular movement during a brief moment under a given set of conditions. The results of this study suggest that improving maximum strength could result in the improvement of PP output during jumping at percentages of maximum 1RM.

Importantly, the results of this study also suggest that maximum strength markedly contributes to pow-

er production during the movement of light resistances as well as heavy resistances. Thus, improving maximum strength could improve jumping with light (or zero) external loads. Although other factors may have contributed, McBride et al. (18) found that weightlifters (1RM = 244 ± 13 kg) tended to possess greater squatting strength compared with powerlifters (1RM = 226 ± 11 kg), sprinters (1RM = 204 ± 13 kg), and untrained subjects (1RM = 161 ± 11 kg). The weightlifters (18) showed higher power outputs during unweighted and weighted jumps when compared with groups with lower maximum strength levels, agreeing with the findings of the present study.

It should also be noted that jumping ability is associated with a variety of other athletic performances, such as sprinting, field events, and American football (4). Therefore, increasing maximum squat strength may enhance jumping activities as well as related sports performances.

These observations bring up several possibilities associated with strength training—(a) Increased maximum strength as a result of training can enhance power production. (b) Strength training results in changes in other factors (i.e., power, peak rate of force development) that may also accompany the increases in maximum strength; these factors also contribute to the observed improved sports performance. Using “explosive” training methods in which maximum efforts are made throughout the exercise (even though the mass lifted may be moving slowly because of its weight) can enhance these accompanying factors (30). (c) It should also be noted that in no study has strength training increased specific performance variables (i.e., sprinting, jumping, and throwing) to the same extent as the changes observed in maximum strength (i.e., the changes are not correlated perfectly); furthermore, the increases in strength may continue after power increases become asymptotic. It is possible that the lack of direct correspondence between increased strength and other types of performances is at least partially due to a lag time (1, 9, 28). Lag time is the period of time in which an athlete learns to use increased strength in various sports events. This lag time may extend for many months; if this is true, then this would be beyond the limited experimental bounds of most studies, which typically only last for a few weeks. Thus, gains in strength may not influence sporting performance variables for some time.

Caution should be exercised when completely depending on maximum strength to enhance power output. Although the correlations in this study were strong, none of the correlations accounted for all the variance in power output. Although untrained or novice trainees may show an increase in sport-related performance variables along with an initial increase in maximum strength (2, 23, 24, 27), making power and speed changes in advanced or elite athletes is much

more difficult (3, 29, 33) and requires more creative training programs. Although it appears that a key ingredient in these advanced programs is improvement of maximum strength, specialized work on speed and power is also necessary to achieve maximum adaptation (12). This would include the use of sequenced periodized programs, in which the initial emphasis is on gaining strength with later phases of the training program emphasizing on power and speed production (12, 30). Thus, appropriate longitudinal training should also be directed toward other factors such as rate of force development, acceleration (21, 26), and the proper sequencing of training variables (12, 28).

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