TAKE QUIZ

Training Principles for Power

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SUMMARY

THE ABILITY TO EXPRESS HIGH POWER OUTPUTS IS CONSIDERED TO BE ONE OF THE FOUNDATIONAL CHARACTERISTICS UNDERLYING SUCCESSFUL PERFORMANCE IN A VARIETY OF SPORTING ACTIVITIES, INCLUDING JUMPING, THROWING, AND CHANGING DIRECTION. NUMEROUS TRAINING INTERVENTIONS HAVE BEEN RECOMMENDED TO ENHANCE THE ATHLETE'S ABILITY TO EXPRESS HIGH POWER OUTPUTS AND IMPROVE THEIR OVERALL SPORTS PERFORMANCE CAPACITY. THIS BRIEF REVIEW EXAMINES THE FACTORS THAT UNDERLIE THE EXPRESSION OF POWER AND VARIOUS METHODS THAT CAN BE USED TO MAXIMIZE POWER DEVELOPMENT.

INTRODUCTION

Many sports require the ability to generate high amounts of force in relatively short periods of time (42,58). The ability to express high rates of force development is often related to an athlete's overall strength levels (71) and ability to express high power outputs (27,30). Stone et al. (71) suggested that the ability to express high rates of force development and high power outputs are critical performance characteristics central to success in most sporting events. These abilities are considered to be among the most important sports performance characteristics, especially in activities that rely on jumping, change of direction, and/or sprinting performance (31,53,71).

The overall relationship between sport-specific movements and the ability to generate high power outputs is well documented in the scientific literature (4,5,8,60). For example, Hansen et al. (33) reported that peak power outputs are significantly ($p < 0.001$) higher in Elite Rugby Union players compared with their junior counterparts. Similarly, Baker (4) suggested that professional Rugby League players (National Rugby League) produce significantly higher power outputs in both upper- and lower-body movements compared with college-aged players (Student Rugby League). Additionally, Fry and Kraemer (25) demonstrated that in American Collegiate Football, strength and power characteristics differentiate between level of play, with stronger more powerful athletes being more prevalent on higher division teams. Similarly, Barker et al. (6) reported that maximal strength and power-generating capacity is able to differentiate between starters and nonstarters. When examining other sports such as women's basketball, volleyball, and softball, significant correlations have been found between maximal strength and peak power output ($r = 0.719$) and agility T test time ($r = -0.408$) (61). When both men (basketball, volleyball) and women (basketball, volleyball, and softball) from a variety of sports were collapsed into one group, back squat strength was highly correlated with peak power ($r = 0.917$) and agility T test time ($r = -0.784$). Based upon the contemporary body of scientific knowledge, it is evident that maximal strength, the rate of force development, and peak power generating capacity are all important attributes that need to be developed when implementing strength and conditioning programs.

There is considerable debate concerning which of these characteristics should be the primary training targets when attempting to optimize power output with resistance training interventions. For example, some authors argue that once adequate strength levels are developed continuing to develop this attribute results in diminishing returns (17), whereas others argue that maximal strength impacts power generating capacity in a hierarchical manner in which its influence on power production diminishes as the external load decreases (65,66). Conceptually, it is often believed that as the external load diminishes the influence of maximal strength decreases and a greater reliance on the rate of force development occurs. This relationship is often used as the central argument for developing power outputs with explosive exercises that are performed at what has been termed the "optimal load" (20,42).

Generally, there seem to be 3 main schools of thought when attempting to maximize power output (20). The first school suggests that using lower-intensity efforts (<50% of 1 repetition maximum [RM]) are optimal for the development of power generating capacity (44,54), whereas the second school proposes that higher loads (50–70% 1RM) are required (63,70,81). The third school of thought suggests a mixed methods approach in which a variety of loads and exercise types are used in

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a periodized fashion to optimize power output (9,20,42,58).

Although each school of thought offers compelling rationales for using low-load, high-load, or mixed load training methods, it is often difficult for the strength and conditioning professional to determine which methods are the best approach for optimizing maximal strength, rate of force development, and power generating capacity. Therefore, the current brief review is designed to explain how power is calculated and which key training outcome factors are critical for the optimization of power generating capacity. In the context of this discussion, specific methods of elevating power and how they may be incorporated into a periodized training plan will be addressed.

MECHANICAL POWER

To understand the main training attributes that contribute to maximal power output, it is important to understand the basic definition of power and how it is mathematically calculated. Mechanical power is often referred to as the rate of doing work (45) and is calculated by multiplying force by velocity (58)

$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

$$= \frac{\text{Force} \times \text{Distance}}{\text{Time}}$$

$$= \text{Force} \times \text{Velocity}.$$

Based upon these mathematical equations, it is evident that the 2 central components that impact the athlete's ability to generate high power outputs are the ability to apply high levels of force rapidly and express high contraction velocities (42). The basic inverse relationship between the force a muscle can generate and the velocity at which it contracts is often depicted by a characteristic curve (Figure 1) (18,42) in which the amount of force that can be generated by a concentric muscle action decreases as the velocity of movement increases. When related to the maximal power output, it is evident that force and velocity are interdependent and that maximal power output occurs at compromised levels of maximal force and velocity (Figure 2) (42,68). This relationship is clearly depicted in a traditional vertical jump force, velocity, and power tracing, where peak power does not occur at either the points of maximal force or velocity (Figure 3). Ultimately, as the athlete tries to accelerate during the jumping motion, the time frame for the application of force becomes shorter, which highlights the importance of the rate of force development in the expression of power (58).

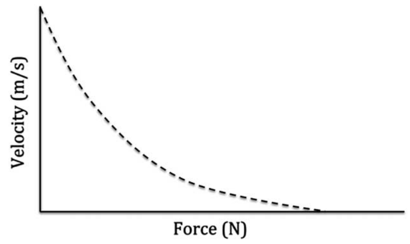

Figure 1. The basic force-velocity relationship. Adapted from Kawamori and Haff (42).

Ultimately, 3 key elements must be considered when attempting to increase power output. First, it is essential that overall muscular strength is maximized because of its direct relationship with the ability to express high rates of force development and power outputs. Second, it is important to develop the ability to express high forces in very short periods of time, which are reflected by the rate of force development. Finally, it is important to develop an ability to express high forces as the velocity of shortening increases. Careful inspection of each of these elements reveals that there is a strong interplay between each element with overall strength levels serving as the main driver for the ability to express high power outputs (42,58). Support for the interrelationship between maximal strength, the rate of force development, and maximal power output is clearly seen in the scientific literature where significant correlations have been found between these variables (27,30).

MAXIMAL STRENGTH

Strength should be considered one of the foundational elements required for the development of power (4,9,55,87) based upon the contemporary literature where stronger athletes are reported to express higher power outputs (4,71). One explanation for this relationship relates to the fact that stronger individuals are able to generate forces significantly faster than their weaker counterparts (2,30).

Typically, both weaker and younger athletes do not possess the requisite strength levels for the expression of high power outputs. Therefore, in these instances, simply increasing strength levels can stimulate a resultant increase in power output (4,16) and overall performance capacity (16,17,32,71) without using classic power development exercises. Häkkinen and Komi (32) offered evidence to support this contention in that after 24 weeks of intense strength training with loads between 70 and 120% of 1RM, a 7% increase in vertical jump performance, which is representative of an increase in power generating capacity, was noted. Additional support for these findings can be seen in the work of Cormie et al. (16) where the development of maximal strength was shown to be a more effective training modality for increasing power output during unloaded and loaded jumps with weaker individuals. Taken collectively, these data clearly indicate that with weaker athletes, strength training that targets the maximization of overall strength levels results in significant improvements in muscular power (4,16) and more importantly overall athletic performance (16,71).

However, once athletes have established adequate strength levels, they are then able to maximize the benefits of incorporating specific training activities (i.e., plyometrics, ballistic exercises, and complex or contrast training) designed to optimize power development. In fact,

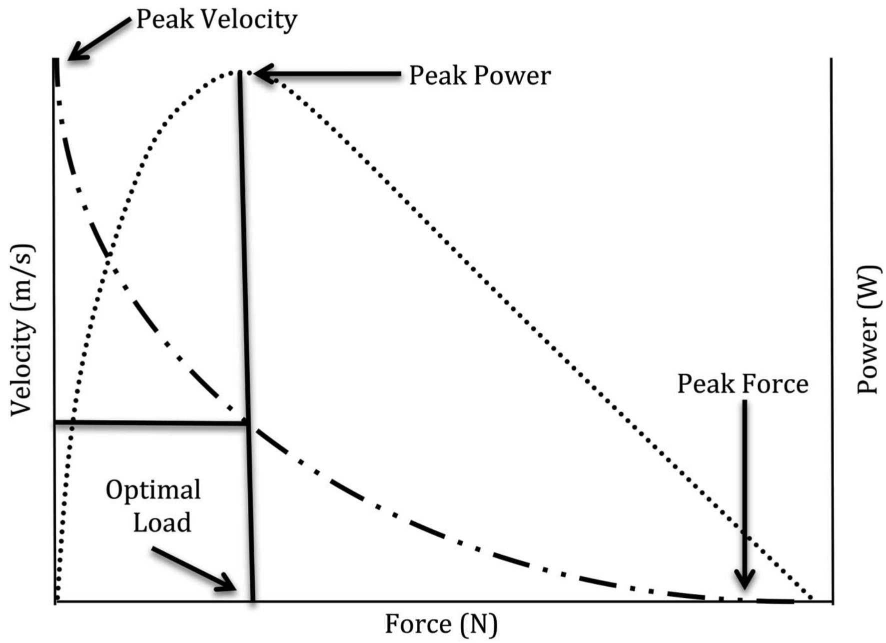

Figure 2. Force-velocity, force-power, velocity power, and optimal load relationship. Adapted from Newton and Kraemer (58) and Kawamori and Haff (42).

stronger athletes generally demonstrate a greater responsiveness to targeted power-based training methods such as plyometric or explosive exercise training (17).

It is clear that the maximization of muscular strength is a key component of all training programs that are designed to maximize power development capacity. However, it is often difficult to determine when an adequate strength level has actually been achieved and when a shift in training emphasis to include more specialized power development strategies can be used. Careful inspection of the literature suggests that athletes who squat a minimum of 2× body mass can express higher power outputs than their weaker counter parts (1.7 or 1.4×x body mass) in vertical (6,71) and horizontal jumping activities (64). Additionally, Wisløff et al. (86) suggests that soccer players who can squat >2.0× body mass are significantly faster and able to jump higher than those who squat <2.0× body mass. Recent work by Keiner et al. (43) reports that youth

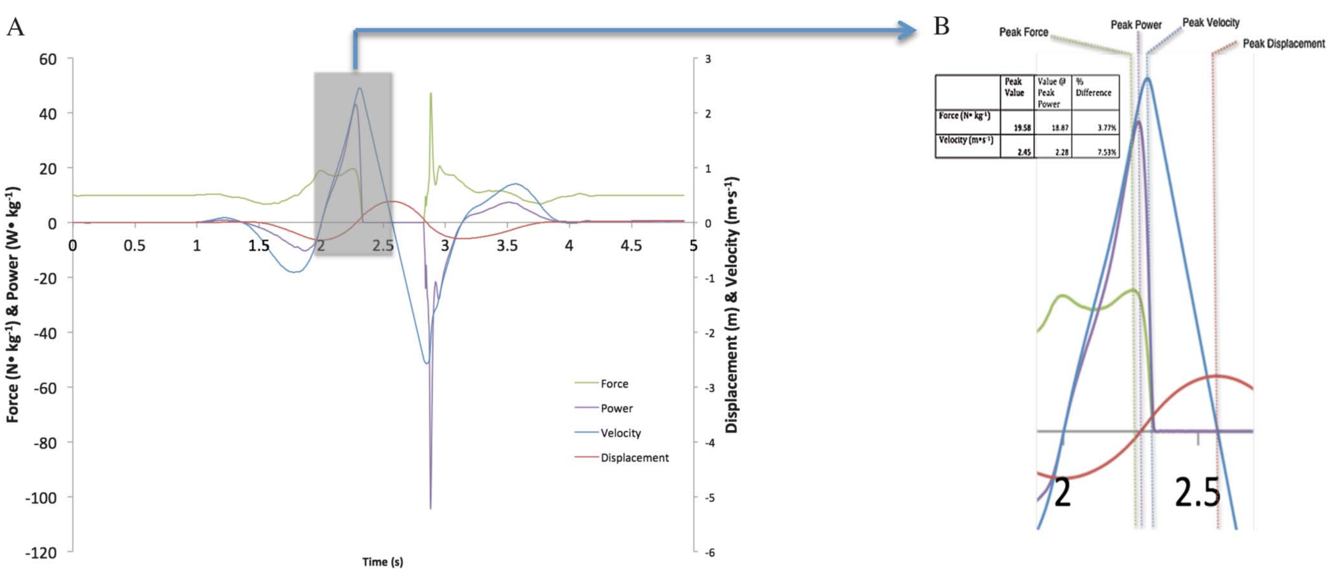

Figure 3. Force, velocity, and power output during a vertical jump. (A) Force, velocity, power output during a vertical jump, (B) Peak Force, Peak Velocity, Peak Power, and Peak Displacement during a vertical jump.

athletes between the ages of 16 and 19 should be able to easily achieve a minimum back squat of 2.0× body mass if training interventions are structured correctly.

Additionally, if using strength-power-potentiation complexes athletes who can squat >2× body mass demonstrate the greatest expressions of potentiation (64). It is important to note that the 2× body mass marker is only a recommended minimum strength level that should be targeted for both male and female athletes. It does not mean that athletes who have not met this minimum should not perform jumping activities, sprinting, or strength training. Additionally, it does not mean that once this level of strength is achieved that additional strength development is not warranted or desired. In fact, when stronger athletes remove the emphasis on developing strength they rapidly lose strength (17) that ultimately can have negative implications for the ability to express high power outputs, sprint, or change direction rapidly. When athletes do achieve the 2× body mass minimum strength level, they are then able to achieve better training benefits from power-specific training activities such as strength-power-potentiation complexes (64) and ballistic exercises such as jump squats (17). Overall, it is apparent that a minimum back squat of 2.0× body mass is at best a minimum strength requirement before specialized training for the optimization of lower-body power development should occur.

Overall, the relationship between maximal strength and power should always be considered when designing performance-based resistance training programs. Specifically, strength and conditioning professionals should be cognizant of the fact that the development of maximal strength should never be neglected and should always be part of the training process because maximal strength is the critical quality that underpins the ability to develop high power outputs in a variety of sporting movements (4).

RATE OF FORCE DEVELOPMENT

The rate of force development or "explosive muscle strength" describes the rate at which force is expressed during a sporting movement (1,53). Typically, the rate of force development is determined from the slope of the force time curve (Δforce/Δtime) (84) (Figure 4). This slope can be determined in several ways such as the peak rate of force development in a 20-millisecond sampling window or between specified time bands such as the slope between 0 and 200 milliseconds. Regardless of how the rate of force development is calculated, it exhibits a significant functional importance in fast and forceful muscle contractions (1). For example, contraction times of 50–250 milliseconds are often associated with fast movements such as jumping, sprinting, or changing of direction. In these situations, the short contraction times make it unlikely that maximal forces can be applied as it can take >300 milliseconds to generate maximal force (1,74,75). Because of these occurrences, some authors have recommended that the lifting of light loads in a ballistic fashion should be used to optimize the rate of force development and overall power output (19,58).

When examining various training interventions, it is clear that heavy load resistance exercise results in an increase in the isometric peak force (19,58) and the rate of force development in weaker and untrained individuals (51). Although heavy resistance training can increase the athlete's strength reserve and positively impact the rate of force development, it is likely that with stronger more experienced athletes, the optimization of the rate of force development and subsequent power development is better achieved with the incorporation of explosive or ballistic exercises (19,31). Therefore, various training foci have the potential to impact different parts of the force-time (Figure 5) and force-velocity curves (Figure 6).

For example, heavy resistance training can significantly increase the ability to generate peak force and the rate of force development when compared with untrained individuals (Figure 5) (51). Conversely, ballistic or explosive training can result in increases in the overall rate of force development that is greater than what can occur with heavy resistance training or during an untrained state. However, ballistic training cannot increase the overall maximal strength levels to the same extent as heavy resistance training. Therefore, a mixed training approach is often recommended when

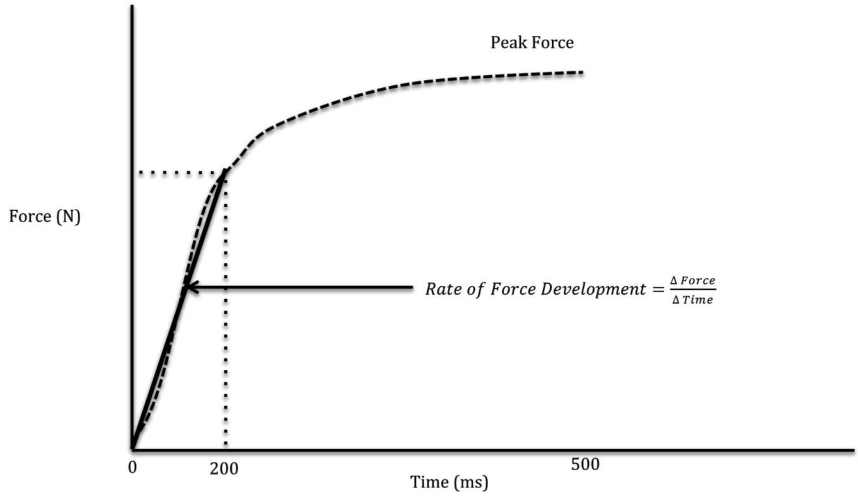

Figure 4. Isometric force-time curve. Adapted from Haff et al. (30).

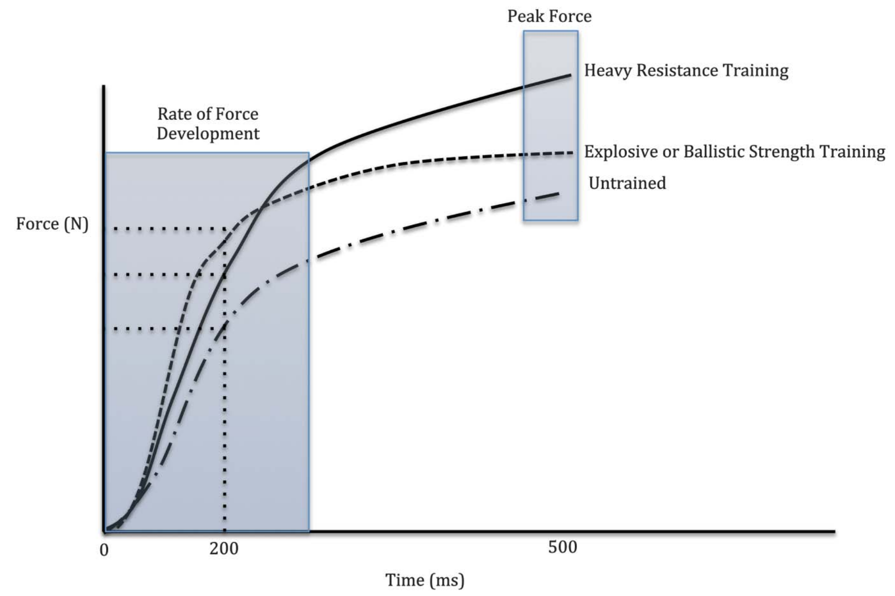

Figure 5. Isometric force-time curve depicting the rate of force development and maximal force generating capacity. Adapted from Newton and Kraemer (58).

attempting to maximize the rate of force development and power output (31).

THE OPTIMAL LOAD AND THE DEVELOPMENT OF STRENGTH AND POWER

The optimal load is the load that elicits the maximal power output for a specific movement (19,42). It is suggested that the optimal load is an effective stimulus for improvements in power output (19,40,54,56,76,77,85). However, there are very few studies that have supported this contention (40,54,56,85). Conversely, several other studies suggest that training at the optimal load is not more effective than training with heavy loads (16,35) or with mixed-load models (76,77) when trying to maximize power development.

Theoretically, training at or around the optimal load may seem to be a better way to train for sports performance; the current body of knowledge does not convincingly justify this belief because many athletes require the ability to produce high power outputs under loaded conditions (4,5). For example, in Rugby League, one of the key differentiators between levels of play is the athlete's overall strength and their ability to generate high power outputs under loaded conditions (4,5). Therefore, in these types of athletes, it is important to develop the ability to not only express high forces but also generate high power outputs under loaded conditions. Using loads that are higher than the optimal load increases the athlete's ability to express high power outputs under loaded conditions (56). For example, Moss et al. (56) report training with higher loads seems (>80% 1RM) to result in superior power outputs under loaded conditions (>60% of 1RM) compared with training with moderate to low-load interventions (<30% of 1RM) (56). Because stronger athletes are better able to express higher power outputs under loaded conditions, it is evident that focusing on strength development is a key component of any strength training interventions that are preparing athletes in sports such as Rugby League, Rugby Union, and American Football.

When considering overall maximal strength development, the use of the optimal load for power development results in a muted ability to improve strength levels (16,35,54,76,77), which can have significant ramifications when working with athletes who must express high power outputs under loaded conditions. Furthermore, training at the optimal load has the inherent limitation of only maximizing power output at or near the load that is being trained (40,54). This may impact sports performance capacity by limiting the ability of an athlete to maximize power output under a variety of loaded conditions (56). This is a limitation because many athletes require the ability to produce power under both "unloaded" and "loaded" conditions. An unloaded condition involves activities such as sprinting or the squat jump, where an athlete primarily overcomes the inertia of their body mass (67). In comparison, a loaded condition may involve activities such as a collision in contact sports such as American football, rugby, and wrestling or an athlete changing direction where they must apply even greater forces to change the momentum of the system (mass × velocity). The scenarios of unloaded versus loaded demonstrate why power (force × velocity) is important to develop at many loads on the force-velocity spectrum.

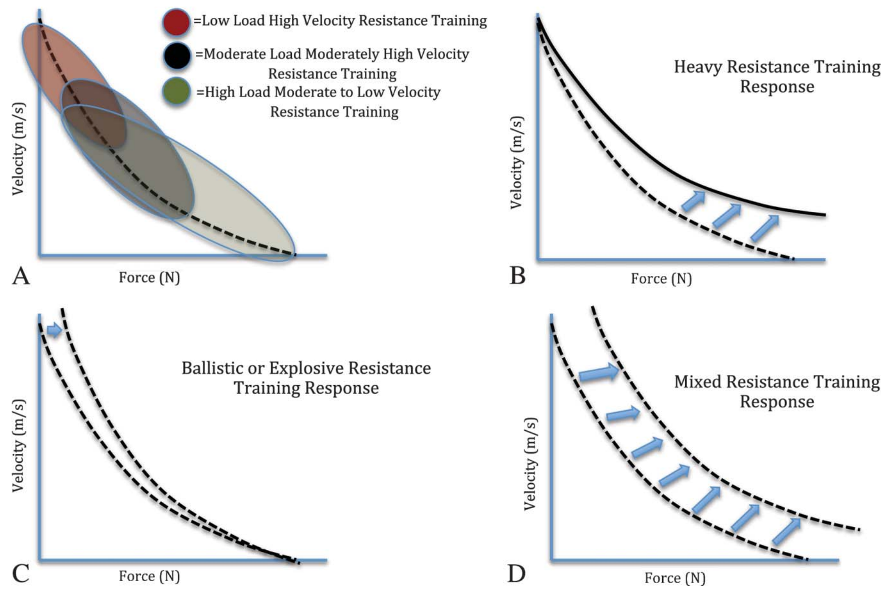

Figure 6. Potential training interventions which impact the force-velocity curve.

Although velocity will be compromised at higher loads (those above an individual's optimal load), the goal is always to produce the highest velocity (and therefore power) at any given load during competition or training. Ultimately, for many athletes, a continuum of loads are encountered during sporting play making it far more beneficial to develop the ability to maximize power output across a variety of loads. These loads should range from unloaded to load conditions in order to develop the entire force-velocity profile (39,67). One key area to accomplish this goal is with appropriate sequential periodization models as well as using warm-up sets that are performed at a variety of submaximal loads.

MIXED METHODS FOR THE OPTIMIZATION OF POWER OUTPUT

When examining the literature, unidimensional training approaches that only focuses on the development of strength or power do not maximize the development of power, strength (14,76,78), and overall sports performance capacity. Therefore, a mixed methods approach is recommended when attempting to maximize power output (19,58) (Figure 7).

The use of a mixed methods approach to optimize power-generating capacity allows for a superior increase in maximal power output and a greater transfer of training effect because of a more well-rounded development of the force-velocity relationship (20,76,77). Theoretically, the use of low-load high-velocity movements can impact the high-velocity area of the force-velocity relationship, while heavier

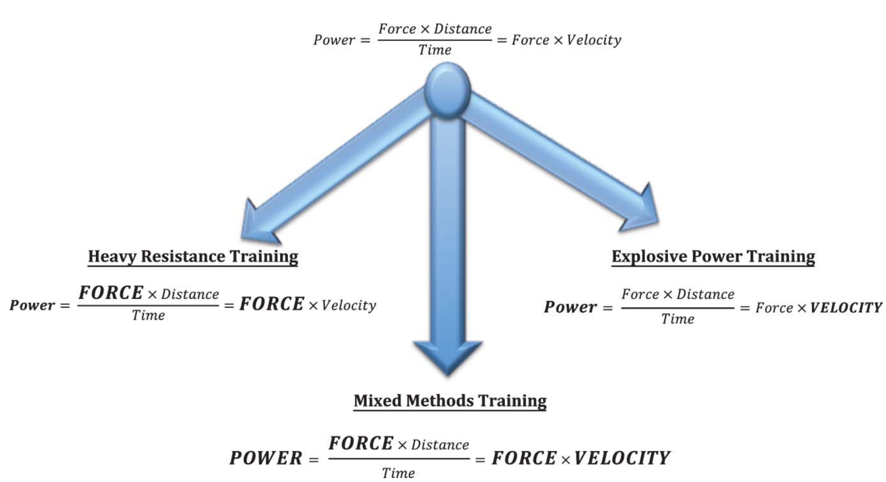

Figure 7. Training method relationship to the development of power, strength, and movement velocity.

Figure 8. Relationship of power zones and various exercises. Data obtained from Kawamori et al. (41), Kirby et al. (44), and Cormie et al. (13).

loads enhance the high-force portion of this relationship. Thus, using combined methods of training allows for a more complete adaptation to occur across the entire force-velocity curve (19,20,76,77). Significant scientific support for the use of mixed methods is present in the contemporary literature (3,34,50,52,57,59,76,77), where superior enhancements in maximal power output and various markers of athletic performance are associated with mixed method training interventions. For example, Cormie et al. (14) reported that combined training results in improvements in power across a greater range of loaded activities and increased maximal strength to a greater degree compared with power or strength only training.

One strategy for employing a mixed training approach is to use a variety of training loads. For example, in the back squat, power development can occur between loads of 30–70% of 1RM, whereas higher loads (>75% of 1RM) would typically be employed for strength development (Figure 8) (15,44).

So, if athletes were performing sets at 80–85% of 1RM for the development of strength, they would perform submaximal back squats as part of their warm-up, which would effectively serve to develop power generating capacity if performed "explosively" (44). In this scenario, it is imperative that the athlete has the intent to move with high velocities (7). By lifting these submaximal warm-up loads "explosively" with the intent to move as quickly as possible, a greater potential for developing power across a variety of loads can be accomplished (21). Thus, with exercises that are used to target strength development, the warm-up sets actually become effective power training activities.

A second power development strategy is to use a mixed methods approach in which various portions of the force-velocity curve are targeted with the use of a variety of training exercises

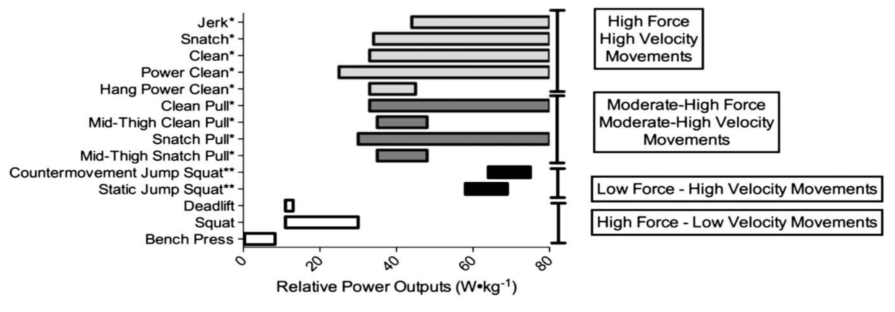

Figure 9. Relative power outputs for various exercises. The relative power outputs noted will vary depending upon the load lifted, the level of athletes, athletes level of strength, and the technique used in the lift. *Loads of between 75 and 85% of 1repetition maximum produce the highest power outputs; **loads of 0–30% produce the highest power outputs.

Table 1
Example mixed methods approach for developing power

Exercise	Sets × reps	Load (%, 1RM)	Type of exercise
Power clean	3 × 5	75–85	High force, high velocity
Back squat	3 × 5	80–85	High force, low velocity
Jump squat	3 × 5	0–30	Low force, high velocity
Depth jump	3 × 5	0	High force, high velocity

performed at different loading intensities. For example, unloaded jump squats, which are effectively plyometric exercises, would target power development of the low-force high-velocity portion of the force-velocity relationship when performed with loads between 0 and 30% of 1RM (Figure 9). Conversely, using moderate to high loads (70–90%) in the squat would target the development of power in the high-force portion of the force-velocity curve. While performing power cleans, either from the floor or hang, loads between 70 and 90% of 1RM have the potential to develop the wide range of force and velocity parameters.

A third power development strategy is to consider the various lifting activities available, such as strength training movements and their derivatives, jump squats, and traditional strength building exercises, and each of these exercise types have the ability to target the development of power under differing conditions. Each of these types of exercise can be related to portions of the force-velocity curve, thus allowing the strength and conditioning professional the ability to sequence various exercises into a mixed methods training session. For example, a variety of training methods could be used in the training program to capitalize on each type of exercises' ability to develop power (Table 1). The back squat could be used to develop strength and the high-force low-velocity portion of the force-velocity relationship, whereas the power clean could be used to develop the high-force high-velocity portion of the curve. Incorporating the jump squat in the program could serve to maximize the low-force high-velocity portion of the curve.

Another approach would be to use strength training exercises such as the clean and snatch and their derivatives such as the pulling motions to more evenly develop all portions of the force-velocity curve (Table 2). Strength training exercises and their derivatives are particularly important when attempting to develop strength and power attributes and have been consistently shown to produce superior performance gains compared with other methods of power development (36,78). It is important that any program designed to maximize power output contain strength training movements because these exercises are considered superior to other training methods for their ability to develop power and translate training gains to sports performance capacity (12).

Regardless of the methods used for power development, it is essential that they are logically incorporated into a periodized training plan.

Table 2
Strength training example of a mixed methods approach for developing power

Exercise	Sets × reps	Load (%, 1RM)	Type of exercise
Snatch	3 × 5	75–85	High force, high velocity
Snatch pull*	3 × 5	90–95	High force, moderate velocity
Snatch pull from blocks*	3 × 5	100–110	High force, moderate velocity
Romanian deadlift	3 × 5	70–75	Moderate force, low velocity

*Training load is a percentage off of the maximum snatch.

PERIODIZATION METHODS FOR THE DEVELOPMENT OF POWER

Periodization is the logical systematic structuring of training interventions in a sequential and integrative fashion to develop key attributes that results in the optimization of sports performance capacity at predetermined time points (10,11,29,37,38,62,79). To accomplish the primary goal of elevating performance, it is essential that the training program has structured variation that is designed to manage fatigue while stimulating physiological and performance adaptations. Typically, variation of training in the resistance training literature is considered in a very narrow scope with focus solely being on the loading paradigm used (22–24,46–48). A more comprehensive approach to variation must be used in which training foci, exercise selection, and density of training are considered in the context of the goals and structures contained in the periodized training plan (49,69,73,88). If variation is illogical, excessive, or unplanned, the overall effectiveness of the training plan will be limited and there will be an increased risk of overtraining responses.

Ultimately the training stimuli needs to be vertically integrated and horizontally sequenced to maximize the training-induced adaptations and performance outcomes (9,26). When training activities are vertically integrated, compatible training factors are paired allowing for the removal of interference effects (28,29). For example, if attempting to maximize the development of explosive strength and power one could vertically integrate the training plan by including activities to target maximal strength training, plyometric training, and sprint training (29). Additionally, from a power development perspective, vertical integration can allow for various parts of the force-velocity curve to be targeted through the selection of exercises and loads that target different parts of the curve (Figure 8).

The horizontal sequencing of training factors relates to the ordering of training foci (28,29,55,87). The sequential training approach can be applied to the development of power by initiating the training process with activities that target increases in muscle cross-sectional area followed by a period of training that maximizes muscular strength. Once muscular strength is developed, the training emphasis can then be shifted toward the maximization of power development (55,87) (Figure 9). Conceptually this type of training process is based upon the theory of phase potentiation, where the training adaptations stimulated by one period of training serve as the foundation for the subsequent phase (28,29). Support for this model of strength and power development can be found in the work of Harris et al. (34) where a sequenced training model in which combined training methods are employed resulted in greater improvements in back squat (11.6%⇑) and front squat (37.7%⇑) strength. Additionally, this model of training resulted in greater improvements in sprinting time across 9.14 m (2.3%⇓) and 30 m (1.4%⇓). Based upon the work of Minetti (55), Zamparo et al. (87), and Harris et al. (34) sequential periodization models are ideal for the optimal development of both strength and power.

While a complete discussion of the various periodization models needed for the development of power are out of the scope of this brief review, it is important to realize that there are a variety of programmatic models that can be used as part of a comprehensive periodized training plan. For further information on periodization, the reader is directed to the works of Stone et al. (72), Issurin (37,38), Bompa and Haff (9) and Verkoshansky (80,82,83).

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REFERENCES

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol* 93: 1318–1326, 2002.
2. Aagaard P, Simonsen EB, Trolle M, Bangsbo J, and Klausen K. Effects of different strength training regimes on moment and power generation during dynamic knee extensions. *Eur J Appl Physiol* 69: 382–386, 1994.
3. Adams K, O'Shea JP, O'Shea KL, and Climstein M. The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *J Appl Sport Sci Res* 6: 36–41, 1992.
4. Baker D. Comparison of upper-body strength and power between professional and college-aged rugby league players. *J Strength Cond Res* 15: 30–35, 2001.
5. Baker D. A series of studies on the training of high-intensity muscle power in rugby league football players. *J Strength Cond Res* 15: 198–209, 2001.
6. Barker M, Wyatt TJ, Johnson RL, Stone MH, O'Bryant HS, Poe C, and Kent M. Performance factors, physiological assessment, physical characteristic, and football playing ability. *J Strength Cond Res* 7: 224–233, 1993.
7. Behm DG and Sale DG. Intended rather than actual movement velocity determines velocity-specific training response. *J Appl Physiol* 74: 359–368, 1993.
8. Bevan HR, Bunce PJ, Owen NJ, Bennett MA, Cook CJ, Cunningham DJ, Newton RU, and Kilduff LP. Optimal loading for the development of peak power output in professional rugby players. *J Strength Cond Res* 24: 43–47, 2010.
9. Bompa TO and Haff GG. *Periodization: Theory and Methodology of Training.* Champaign, IL: Human Kinetics Publishers, 2009.
10. Bondarchuk A. Periodization of sports training. *Legkaya Atletika* 12: 8–9, 1986.
11. Bondarchuk AP. Constructing a training system. *Track Tech* 102: 254–269, 1988.
12. Chiu LZ and Schilling BK. A primer on weightlifting: from sport to sports training. *Strength and Cond* 27: 42–48, 2005.
13. Cormie P, McBride JM, and McCaulley GO. Validation of power measurement techniques in dynamic lower body resistance exercises. *J Appl Biomech* 23: 103–118, 2007.
14. Cormie P, McCaulley GO, and McBride JM. Power versus strength-power jump squat training: influence on the load-power relationship. *Med Sci Sports Exerc* 39: 996–1003, 2007.
15. Cormie P, McCaulley GO, Triplett NT, and McBride JM. Optimal loading for maximal power output during lower-body resistance exercises. *Med Sci Sports Exerc* 39: 340–349, 2007.
16. Cormie P, McGuigan MR, and Newton RU. Adaptations in athletic performance following ballistic power vs strength training. *Med Sci Sports Exerc* 42: 1582–1598, 2010.
17. Cormie P, McGuigan MR, and Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc* 42: 1566–1581, 2010.
18. Cormie P, McGuigan MR, and Newton RU. Developing maximal neuromuscular power: Part 1-biological basis of maximal power production. *Sports Med* 41: 17–38, 2011.
19. Cormie P, McGuigan MR, and Newton RU. Developing maximal neuromuscular power:

part 2-training considerations for improving maximal power production. *Sports Med* 41: 125–146, 2011.

20. Cronin J and Sleivert G. Challenges in understanding the influence of maximal power training on improving athletic performance. *Sports Med* 35: 213–234, 2005.
21. Cronin JB, McNair PJ, and Marshall RN. Is velocity-specific strength training important in improving functional performance? *J Sports Med Phys Fitness* 42: 267–273, 2002.
22. Fleck S and Kraemer WJ. *Designing Resistance Training Programs*. Champaign, IL: Human Kinetics, 2004.
23. Fleck SJ and Kraemer WJ. *The Ultimate Training System: Periodization Breakthrough*. New York, NY: Advanced Research Press, 1996.
24. Fleck SJ and Kraemer WJ. *Designing Resistance Training Programs*. Champaign, IL: Human Kinetics, 1997.
25. Fry AC and Kraemer WJ. Physical performance characteristics of american collegiate football players. *J Appl Sport Sci Res* 5: 126–138, 1991.
26. Haff GG. The essentials of periodization. In: *Strength and Conditioning for Sports Performance*. Jeffreys I and Moody J, eds. London, England: Routledge, Taylor & Frances Group, in press.
27. Haff GG, Carlock JM, Hartman MJ, Kilgore JL, Kawamori N, Jackson JR, Morris RT, Sands WA, and Stone MH. Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. *J Strength Cond Res* 19: 741–748, 2005.
28. Haff GG and Haff EE. Resistance training program design. In: *Essentials Of Periodization*. Malek MH and Coburn JW, eds. Champaign, IL: Human Kinetics, 2012. pp. 359–401.
29. Haff GG and Haff EE. Training integration and periodization. In: *Strength and Conditioning Program Design*. Hoffman J, ed. Champaign, IL: Human Kinetics, 2012. pp. 209–254.
30. Haff GG, Stone MH, O'Bryant HS, Harman E, Dinan CN, Johnson R, and Han KH. Force-time dependent characteristics of dynamic and isometric muscle actions. *J Strength Cond Res* 11: 269–272, 1997.
31. Haff GG, Whitley A, and Potteiger JA. A brief review: explosive exercises and sports performance. *Natl Strength Cond Assoc* 23: 13–20, 2001.
32. Häkkinen K and Komi PV. Changes in electrical and mechanical behavior of leg extensor muscles during heavy resistance strength training. *Scand J Sports Sci* 7: 55–64, 1985.
33. Hansen KT, Cronin JB, Pickering SL, and Douglas L. Do Force-Time and Power-Time Measures in a Loaded Jump Squat Differentiate between Speed Performance and Playing Level in Elite and Elite Junior Rugby Union Players? *J Strength Cond Res* 25: 2382–2391, 2011.
34. Harris GR, Stone MH, O'Bryant HS, Proulx CM, and Johnson RL. Short-term performance effects of high power, high force, or combined weight-training methods. *J Strength Cond Res* 14: 14–20, 2000.
35. Harris NK, Cronin JB, Hopkins WG, and Hansen KT. Squat Jump Training at Maximal Power Loads vs. Heavy Loads: Effect on Sprint Ability. *J Strength Cond Res* 22: 1742–1749, 2008.
36. Hoffman JR, Cooper J, Wendell M, and Kang J. Comparison of Olympic vs. traditional power lifting training programs in football players. *J Strength Cond Res* 18: 129–135, 2004.
37. Issurin V. Block periodization versus traditional training theory: a review. *J Sports Med Phys Fitness* 48: 65–75, 2008.
38. Issurin VB. New horizons for the methodology and physiology of training periodization. *Sports Med* 40: 189–206, 2010.
39. Jindrich DL, Besier TF, and Lloyd DG. A hypothesis for the function of braking forces during running turns. *J Biomech* 39: 1611–1620, 2006.
40. Kaneko M, Fuchimoto T, Toji H, and Suei K. Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scand J Sports Sci* 5: 50–55, 1983.
41. Kawamori N, Crum AJ, Blumert P, Kulik J, Childers J, Wood J, Stone MH, and Haff GG. Influence of different relative intensities on power output during the hang power clean: identification of the optimal load. *J Strength Cond Res* 19: 698–708, 2005.
42. Kawamori N and Haff GG. The optimal training load for the development of muscular power. *J Strength Cond Res* 18: 675–684, 2004.
43. Keiner M, Sander A, Wirth KPDP, Caruso O, Immesberger P, and Zawieja M. Trainability of Adolescents and Children in the Back and Front Squat. *J Strength Cond Res*, 2012.
44. Kirby TJ, Erickson T, and McBride JM. Model for Progression of Strength, Power, and Speed Training. *Strength Cond J* 32: 86–90, 2010.
45. Knudson DV. Correcting the use of the term "power" in the strength and conditioning literature. *J Strength Cond Res* 23: 1902–1908, 2009.
46. Kraemer WJ, Hatfield DL, and Fleck SJ. Types of muscle training. In: Strength Training. Brown LE, ed. Champaign, IL: Human Kinetics, 2007. pp. 45–72.
47. Kraemer WJ, Ratamess N, Fry AC, Triplett-McBride T, Koziris LP, Bauer JA, Lynch JM, and Fleck SJ. Influence of resistance training volume and periodization on physiological and performance adaptations in collegiate women tennis players. *Am J Sports Med* 28: 626–633, 2000.
48. Kraemer WJ, Vingren JL, Hatfield DL, Spiering BA, and Fragala MS. Resistance training programs. In: *ACSM's Resources for the Personal Trainer*. Thompson WR, Baldwin KE, Pire NI, and Niederpruem M, eds. Baltimore, MD: Lippincott, Williams, & Wilkins, 2007. pp. 372–403.
49. Kurz T. *Science of Sports Training*. Island Pond, VT: Stadion Publishing Company, Inc., 2001.
50. Kyrolainen H, Avela J, McBride JM, Koskinen S, Andersen JL, Sipila S, Takala TE, and Komi PV. Effects of power training on muscle structure and neuromuscular performance. *Scand J Med Sci Sports* 15: 58–64, 2005.
51. Lovell DI, Cuneo R, and Gass GC. The effect of strength training and short-term detraining on maximum force and the rate of force development of older men. *Eur J Appl Physiol* 109: 429–435, 2010.
52. Lyttle AD, Wilson GJ, and Ostrowski KJ. Enhancing performance: Maximal power versus combined weights and plyometrics training. *J Strength Cond Res* 10: 173–179, 1996.
53. McBride JM, Triplett-McBride T, Davie A, and Newton RU. A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *J Strength Cond Res* 13: 58–66, 1999.
54. McBride JM, Triplett-McBride T, Davie A, and Newton RU. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *J Strength Cond Res* 16: 75–82, 2002.
55. Minetti AE. On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. *Eur J Appl Physiol* 86: 363–369, 2002.

56. Moss BM, Refsnes PE, Abildgaard A, Nicolaysen K, and Jensen J. Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load-power and load-velocity relationships. *Eur J Appl Physiol* 75: 193–199, 1997.
57. Newton RU, Hakkinen K, Hakkinen A, McCormick M, Volek J, and Kraemer WJ. Mixed-methods resistance training increases power and strength of young and older men. *Med Sci Sports Exerc* 34: 1367–1375, 2002.
58. Newton RU and Kraemer WJ. Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength Cond J* 16: 20–31, 1994.
59. Newton RU, Kraemer WJ, and Hakkinen K. Effects of ballistic training on preseason preparation of elite volleyball players. *Med Sci Sports Exerc* 31: 323–330, 1999.
60. Nimphius S, McGuigan MR, and Newton RU. Relationship between strength, power, speed, and change of direction performance of female softball players. *J Strength Cond Res* 24: 885–895, 2010.
61. Peterson MD, Alvar BA, and Rhea MR. The contribution of maximal force production to explosive movement among young collegiate athletes. *J Strength Cond Res* 20: 867–873, 2006.
62. Plisk SS and Gambetta V. Tactical metabolic training: part 1. *Strength and Cond* 19: 44–53, 1997.
63. Poprawski B. TRACK and FIELD: Aspects of strength, power and speed in shot put training. *Strength Cond J* 9: 39–43, 1987.
64. Ruben RM, Molinari MA, Bibbee CA, Childress MA, Harman MS, Reed KP, and Haff GG. The acute effects of an ascending squat protocol on performance during horizontal plyometric jumps. *J Strength Cond Res* 24: 358–369, 2010.
65. Schmidtbleicher D. Training for power events. In: *Strength and Power in Sport*. Komi PV, ed. Oxford, England: Blackwell, 1992. pp. 381–385.
66. Schmidtbleicher D and Haralambie G. Changes in contractile properties of muscle after strength training in man. *Eur J Appl Physiol* 46: 221–228, 1981.
67. Sheppard JM and Young WB. Agility literature review: classifications, training and testing. *J Sports Sci* 24: 919–932, 2006.
68. Siegel JA, Gilders RM, Staron RS, and Hagerman FC. Human muscle power output during upper- and lower-body exercises. *J Strength Cond Res* 16: 173–178, 2002.
69. Siff MC. *Supertraining.* Denver, CO: Supertrainig Institute, 2003.
70. Spassov A. Special considerations when programming for strength and power for athletes: part I. *Natl Strength Cond Assoc J* 10: 58–61, 1988.
71. Stone MH, Moir G, Glaister M, and Sanders R. How much strength is necessary? *Phys Ther Sport* 3: 88–96, 2002.
72. Stone MH, O'Bryant H, and Garhammer J. A hypothetical model for strength training. *J Sports Med* 21: 342–351, 1981.
73. Stone MH, Stone ME, and Sands WA. *Principles and Practice of Resistance Training.* Champaign, IL: Human Kinetics Publishers, 2007.
74. Sukop J and Nelson R. Effect of isometric training on the force-time characteristics of muscle contraction. In: *Biomechanics IV*. Nelson RC and Morehouse CA, eds. Baltimore, MD: University Park Press, 1974. pp. 440–447.
75. Thorstensson A, Grimby G, and Karlsson J. Force-velocity relations and fiber composition in human knee extensor muscles. *J Appl Physiol* 40: 12–16, 1976.
76. Toji H and Kaneko M. Effect of multiple-load training on the force-velocity relationship. *J Strength Cond Res* 18: 792–795, 2004.
77. Toji H, Suei K, and Kaneko M. Effects of combined training programs on force-velocity relation and power output in human muscle. *Jpn J Phys Fitness Sports Med* 44: 439–445, 1995.
78. Tricoli V, Lamas L, Carnevale R, and Ugrinowitsch C. Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs. *J Strength Cond Res* 19: 433–437, 2005.
79. Verkhoshansky YU. How to set up a training program. *Sov Sports Rev* 16: 123–136, 1981.
80. Verkhoshansky YU and Verkhoshansky N. *Special Strength Training Manual for Coaches*. Rome, Italy: Verkhosansky STM, 2011.
81. Verkhoshansky YV and Lazarev VV. Principles of planning speed and strength/speed endurance training in sports. *Strength Cond J* 11: 58–61, 1989.
82. Verkoshansky Y. Main features of a modern scientific sports training theory. *New Studies in Athletics* 13: 9–20, 1998.
83. Verkoshansky Y. Organization of the training process. *New Studies in Athletics* 13: 21–31, 1998.
84. Viitasalo JT. Rate of force development, muscle structure and fatigue. In: *Biomechanics VII-A: Proceedings of the 7th International Congress of Biomechanics*. Morecki A, Kazimirz F, Kedzior K, and Wit A, eds. Baltimore, MD: University Park Press, 1981, pp. 136–141.
85. Wilson GJ, Newton RU, Murphy AJ, and Humphries BJ. The optimal training load for the development of dynamic athletic performance. *Med Sci Sports Exerc* 25: 1279–1286, 1993.
86. Wisløff U, Castagna C, Helgerud J, Jones R, and Hoff J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med* 38: 285–288, 2004.
87. Zamparo P, Minetti AE, and di Prampero PE. Interplay among the changes of muscle strength, cross-sectional area and maximal explosive power: theory and facts. *Eur J Appl Physiol* 88: 193–202, 2002.
88. Zatsiorsky VM. *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics, 1995.