Roles of Maximal Strength and Rate of Force Development in Maximizing Muscular Power

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ABSTRACT

THIS BRIEF REVIEW ENCOMPASSES THE ROLE OF MAXIMAL STRENGTH AND RATE OF FORCE DEVELOPMENT IN THE PRODUCTION OF MUSCULAR POWER. IT BEGINS WITH THE INVESTIGATION OF POWER OUTPUT AND ITS IMPORTANCE FOR SPORT. AFTER THIS BASIS FOR POWER PRODUCTION, THIS REVIEW EXAMINES BOTH MAXIMAL STRENGTH AND RATE OF FORCE DEVELOPMENT EFFECTS ON THE DEVELOPMENT OF OPTIMAL POWER OUTPUT. FINALLY, A RATIONAL WHY MAXIMIZING RATE OF FORCE DEVELOPMENT DURING THE COMPETITION SEASON TO ACHIEVE SUCCESS IN SPORT IS PROVIDED.

INTRODUCTION

WHY IS POWER IMPORTANT?

It has been previously suggested that power outputs are perhaps the most important characteristic impacting sport success (54). The reasoning behind this concept is that power outputs have demonstrated a strong relationship with improved performance of various sport tasks such as sprinting (65,66), jumping (20,34,38,40), change of direction (41,48,52), throwing (36,37), and weightlifting movements (11,26). Optimization of power outputs at specific times of the training year is often a primary goal when using periodization strategies (32,55,59). Therefore, enhancing these sport skills through the augmentation of peak power at particular times of the competitive season may increase an athlete's preparedness, thus giving them a greater probability of winning an event.

A counterargument to this concept is often made with respect to endurance events, as peak power may not be a vital performance characteristic in tasks such as running, cycling, or swimming. However, multiple studies have shown that the average power output for the duration of a distance event, and even peak power during the final sprint, may play a critical role in determining the outcome of a race (42,44,58). Additionally, literature exists suggesting that levels of peak power outputs can differentiate athletic performance (4,6,7,9,21,25,30). As such, the development of muscular power is critical across the spectrum of sport from aerobic to anaerobic sports.

WHAT IS POWER?

Power is a work rate expressed by the equation,

$$Power = Force \times Velocity.$$

The power equation reflects the 2 components that must be considered when attempting to maximize total power output. The first component is velocity, which is directly related to momentum. The second component is force, which is associated with momentum through impulse.

$$Power = Force\ x\ Velocity$$

$$\underbrace{Force\ x\ \Delta Time}_{\text{(Impulse)}} = \underbrace{Mass\ x\ \Delta Velocity}_{\text{(Momentum)}}$$

Velocity. The concept of examining changes in momentum to understand the velocity component of the power equation is used because most sport activities involve accelerating a mass. When the mass in question is an

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external load that is being acted on, alterations in the mass can lead to changes in velocity, when the impulse is held constant. When these concepts are applied to sport-related movements in which an athlete is accelerating their own mass, any desired change in momentum must be obtained by altering the velocity, requiring a change in the impulse.

Force. The force being applied during most actions in sport is not constant across the duration of time; therefore, integration must be performed to calculate the impulse,

$$Impulse = \int Force \ dt.$$

This allows for the force applied to be represented as the area under the force time curve. Research has shown that the duration of time in which forces are applied in various sports skills is only negligibly modifiable, particularly at the highest levels (Table). This leads to the idea that in order for the impulse to be increased, the total force applied during the action must be increased.

Maximal strength. A growing body of evidence has been presented showing that maximal strength has a strong correlation with rate of force development (RFD) and power (5,6,8,38,39). The ability to generate maximal force is limited by time constraints of sport specific tasks. This concept illuminates the importance of RFD within the confines of those time demands. Maximal strength represents the upper limit of the ability to produce force. Increases in maximum strength increase the ability to generate higher forces through a spectrum of velocities.

Rate of force development. The previously laid out concepts lead to a paradigm in which RFD is the underpinning mechanism behind the expression of power in sport. If the goal is to increase the rate at which velocities change (accelerate), and both the mass of the athlete and period over which force can be applied are not readily modifiable, the rate at which force is generated must be increased. The purpose of this article is to further elucidate the underlying mechanisms of maximal strength and RFD in the optimization of muscular power.

MAXIMAL STRENGTH

Strength is a trainable skill that can be expressed during competition. Strength is not only the ability to generate force but also a vehicle that carries with it other abilities such as RFD, impulse, momentum, velocity, and power. Different levels of strength exist ranging from submaximal to maximal, with maximal strength being a major factor influencing performance (57). Research has shown that stronger athletes are found at higher levels of competition in a variety of sports compared with weaker athletes (4,9,25,27,30). This information begins to illuminate the importance of maximal strength in sports competition. However, the exact relationship between maximum strength and peak power is context dependent and not completely clear (54,56).

FORCE-VELOCITY RELATIONSHIP

Strength can be expressed over a range of speeds and loads, but with increasing load an inverse relationship exists between force and velocity. Force and velocity exists on a continuum, with which maximal force and maximal velocity are located at polar ends. In a practical application, the heavier the load the slower the velocity and the lighter the load the higher the velocity. This relationship is important because located in the middle of the force-velocity curve is maximal power output (61,63). Studies have shown that human muscle velocity of shortening is limited (43,49), so to improve the force-velocity curve increases in strength must be achieved.

WHY IS SHORTENING VELOCITY LIMITED?

Studies by Nyitrai et al. (43) and Sargeant (49) have shown that shortening velocity of muscle is limited because of the enzyme kinetics of skeletal muscle. Human muscle cannot dissociate myosin heavy chains from actin filaments faster than what is performed by myosin ATPase. Therefore, additional consideration should be given to the fiber type in question because of type II fibers' cross-bridge dissociation occurring 4–9 times faster than type I fibers (15,16). Because shortening velocity is limited, maximal force becomes increasingly important to provide a window in which greater increases in power can be achieved (13,14,16,17).

EFFECT OF INCREASED STRENGTH ON THE FORCE-VELOCITY CURVE

To cause a shift in the force-velocity curve, strength training alone provides an adequate stimulus to alter the relationship in untrained individuals (28). However for those with advanced training age and increased strength, a mixed-methods approach should be implemented to achieve continual increases in performance (67). As training age advances, a mixed-methods approach, in which both maximal force and maximal velocity are addressed, should be used to achieve increases in both maximal strength and power. More specifically without a mixed-methods approach, the force-velocity curve will be asymmetrically developed. Thus, the desired training effect is to shift the curve up and to the right. This shift represents increases in both maximal strength and maximal velocity, thus increasing maximal power output (Figures 1–4).

This force-velocity relationship is also important because it serves as a basis for the development of power and provides a theoretical basis for the structure and implementation of training. Protocols containing both high velocity and high force training produce better results than training each aspect alone, but a proper sequencing must be used to maximize mixed training stimuli (46,47). Harris et al. (31) have shown that training maximal strength

Table Time for Force Application		
Sources	**Task**	**Time (s)**
Zatsiorsky and Kraemer (68)	Sprinting ground contact time	0.08–0.10
Zatsiorsky and Kraemer (68)	Long jump take-off time	0.11–0.12
Zatsiorsky and Kraemer (68)	High jump take-off time	0.17–0.18
Zatsiorsky and Kraemer (68)	Javelin delivery	0.16–0.18
Zatsiorsky and Kraemer (68)	Shot put delivery	0.15–0.18
Zatsiorsky and Kraemer (68)	Hand take-off (horse vaulting)	0.18–0.21
Schmidtbleicher (50)	Vertical jump	~0.3
Stodden et al. (53)	Baseball pitch	0.145
Koenig et al. (35)	Baseball/softball swing	0.22–31

before maximal velocity provides the most beneficial adaptations and this may be due in part to delayed gains in performance and shortening velocity limitations of skeletal muscle.

Training for maximal strength was thought only to affect power output at corresponding heavy loads (31,39). Stone et al. (55) have shown that training with heavy loads had an effect on power outputs at light loads. For example, Stone et al. (54) have also shown that the association between maximal strength with power output may account for up to 50% of the variance. This association between maximal strength and power output indicates that maximal strength should be a focus in training even if the loads used are higher than encountered in competition. For example, putting in golf is a low force activity that can be positivity altered with increased strength; also, driving distance can be positively impacted by increases in strength and power ultimately improving club head speed (23,24). An athlete encounters a variety of forces during competition. As you raise maximal strength, the submaximal effort that is expressed occurs at a higher absolute value (50).

MAXIMUM STRENGTH RELATIONSHIP WITH POWER OUTPUTS AND PERFORMANCE

Studies have shown that a high correlation exists between maximal strength and power output. Maximum strength has been shown to establish the upper limit of power production (22,54,61–63). Accordingly, stronger athletes have been shown to have an advantage in gaining power (20,31). In weaker athletes, increasing maximum strength has been show to produce greater increases in RFD and power than does power training alone (19,20,31,46). Ultimately, an intimate relationship exists between maximal strength and power. The RFD can be perceived as the bridge between these 2 entities, as most sport skills are not performed within a timeframe that permits the expression of maximal force production (1,3,68). Furthermore, maximal strength is a critical factor in the development of this crucial training variable, whereas RFD is the conduit through which high forces can be expressed in athletic competition.

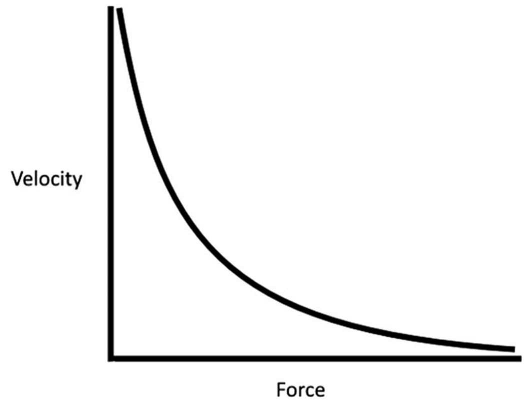

Figure 1. Force velocity curve.

RATE OF FORCE DEVELOPMENT

Maximal strength is a vital component in producing the high levels of force needed in sport (54,59,68). However, the time required to complete many sport specific skills is shorter than that needed to express maximal strength (59,68). More specifically, a minimum window of approximately 300 milliseconds is necessary to produce maximal muscle force (1,2,59,68); however, force application during skills such as sprinting, jumping, throwing, and kicking lasts approximately 30–200 milliseconds (Table). Accordingly, the rate at which force is developed within those short periods dictates the gross amount of force applied during the skill. As previously noted, a greater force applied over a given period creates a greater impulse, thus facilitating greater momentum and, subsequently, a higher power output. Interestingly enough, muscular power has been repeatedly shown to be a differentiating factor in athletic success (4,6,12,33,41,51). Although many studies have attributed improvements in performance to enhanced power production, it may be more accurate to ascribe this development to greater RFD, as it can be viewed as the underpinning mechanism in producing greater power outputs. Therefore, as noted by Stone et al. (54), RFD is

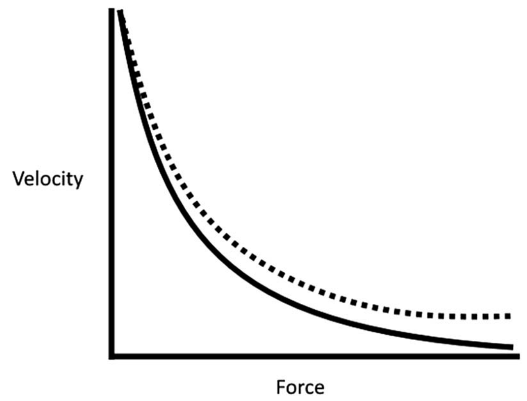

Figure 2. Effect of heavy load training.

perhaps the most central factor to sport success across a wide spectrum of events. This concept has been supported in a number of different studies with respect to both general and specific sport skills such as sprinting (65,66), jumping (20,34,38,40), change of direction ability (CODA) (41,48,52), throwing (36,37), weightlifting movements (11,26), and endurance-based activities (44,45,58).

GENERAL SPORT SKILLS

Sprinting, for example, is perhaps the most universal of sport skills in the realm of athletics. In a pioneering study by Weyand et al. (66), the investigators found that faster runners possessed significantly greater force application, stride length, and shorter ground contact time (GCT) in comparison to slower runners. However, the time required to reposition the leg before the next step, referred to as "swing time," was not significantly different between groups. In other words, the faster subjects covered a greater distance per stride with less time spent on the ground, but did not swing their legs into position before the next step significantly faster than slower subjects. In fact, the authors noted that the slowest subject was able to reposition her leg between strides in nearly the same time as the fastest 100-m sprinter in the world. Accordingly, the authors attributed the greater sprint velocities achieved by faster runners to greater ground force application, rather than the sprinters' ability to quickly reposition their limbs during the flight time between strides. However, since the faster subjects displayed higher ground reaction forces over shorter ground contact times, it can be inferred that the primary mechanism underpinning these high forces is the rate at which they are produced. This notion was confirmed by Weyand et al. (65) in which the authors determined that sprint performance is not limited by an athlete's ability to apply force, but rather their ability to produce a high RFD over the brief contact times exhibited during sprinting.

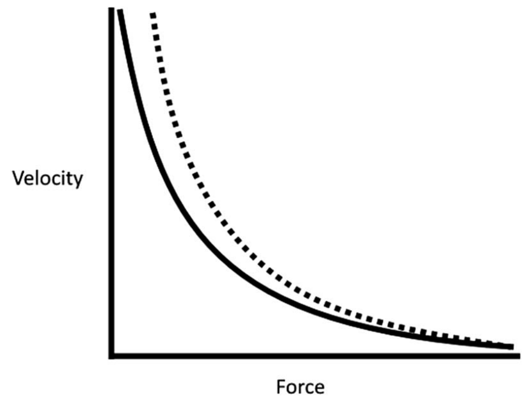

Figure 3. Effect of high-velocity training.

In addition to sprinting, jumping is another critical skill applied in a variety of sports such as basketball, volleyball, football, baseball, and soccer. As noted in the Table, take-off time during various jumping tasks ranges from approximately 100–300 milliseconds. This obviates the ability to express maximal forces within that limited period. Accordingly, multiple studies have shown RFD and its associates, such as impulse and power, to be primary contributors in jump performance (18–20,38,40,60).

In a study by Newton et al. (40), the investigators explored the effects of jump squats (JSs) versus back squats and leg presses over an 8-week period on vertical jump performance in collegiate male volleyball players. Although the groups did not display significant pre-to-posttest differences in 1RM squat strength, the JS group displayed significant increases in vertical jump performance and also significantly greater changes in comparison to the control group. The data analysis indicated that the primary mechanisms of the improved jump performance were an increase force production before take-off and a higher RFD. Therefore, the athletes who focused on ballistic exercise during the 8-week training period were better able to express a higher rate of force over the brief time of force application before take-off, which would explain the greater force outputs and subsequent increases in jump performance. Furthermore, jump performance has been related to other general sport skills, particularly CODA.

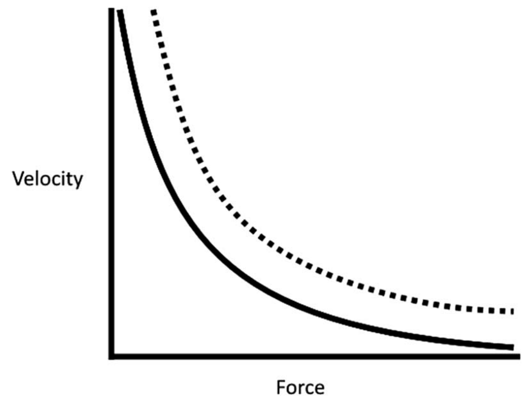

Figure 4. Effect of mixed-methods training.

To the authors' knowledge, only 1 study has directly investigated the association between RFD and CODA, which showed a favorable relationship between these variables (60). Despite this gap in the literature, a strong relationship between jump performance and CODA has been well established (10,34,41,48,52,64). With an understanding that RFD is a primary mechanism in determining vertical jump performance (40,60), it can be inferred that a relationship between RFD and CODA most likely exists.

SPECIFIC SPORT SKILLS

With respect to specific sport tasks, RFD also plays a key role in enhancing these skills as well. Increased pitching velocity in baseball, for instance, has been shown to accommodate training programs that include ballistic exercises such as JSs and bench press throws (37). In addition to the results of Newton et al. (40), a sound case can be made that these alterations may be underpinned by increases in RFD, as these exercises have been associated with increases with this training variable in other studies as well (19,29,40). In addition, a previous study by Marques et al. (36) explored the relationship between RFD and throwing velocity in elite handball players. The results of this investigation also indicated a significant association between these variables. In addition to pitching, batting in both baseball and softball is another skill that often falls below the time required to produce maximal force (35), which again highlights the importance of attaining a greater level of RFD to be able to make contact with the ball.

RFD AND ENDURANCE PERFORMANCE

Although the importance of strength and power development is often overlooked in endurance sports, there is evidence that the average power output may also be a key factor contributing to the outcome of the event (42,44,45,58). This was shown very clearly in a study by Paavolainen et al. (45) that explored the effects of explosive strength training on 5K performances in trained endurance athletes. During this investigation, the experimental group performed 9 weeks of extensive explosive strength training while the control group performed minimal explosive exercise. This training consisted of various sprinting and jumping exercises in addition to low-load, high-velocity strength training movements, such as a leg press and knee-flexor exercises. The training volume between the experimental group and control group was made equal, with 32% of total training time being dedicated to explosive strength training in the experimental group but only 3% of training time in the control group. After this protocol, the subjects in the experimental group significantly improved their 5K times whereas the control group did not. Pre-to-posttest differences were also seen in 20-meter fly-in times (V20) and a 200-m (200M) constant velocity run. During the V20 test, the participants accelerated for 30 m and sprinted maximally for the subsequent 20-m distance. The 200M was run on a 200-m track at a pace of 4.55 m/s, for the purpose of examining running economy. Interestingly enough, the experimental group improved significantly in both of these tests whereas the control group did not. Referring back to the findings of Weyand et al. (65) and Weyand et al. (66), faster sprinters produce a higher RFD and shorter GCT during sprinting. These results were evident in the findings of this study, as the experimental group ran a faster V20 and had shorter GCT during the 200M. Accordingly, a sound case can be made that the improvements of the experimental group were derived from a higher RFD, which allowed them to express faster sprint velocities in V20 and better running economy in the 200M.

Based on the aforementioned evidence, RFD is a critical training consideration across a continuum of sports. As Stone et al. (54) indicated, it may in fact be the most important training variable in determining sporting success. Therefore, increased RFD may in fact be the ultimate goal of the training process.

CONCLUSION

In conclusion, we have shown evidence supporting the notion that RFD may be the most important fitness characteristic in sport. Through the development of high maximal strength and application of this skill through the vehicle of RFD, we can begin to provide a basis for optimal power production in training and competition. Ultimately, maximal strength will provide the upper limit for power production; however, RFD allows us to use this power production in a manner specific to each sporting task.

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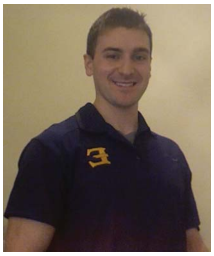

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REFERENCES

1. Aagaard P. Training-induced changes in neural function. *Exerc Sport Sci Rev* 31: 61–67, 2003.
2. 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 (1985)* 93: 1318–1326, 2002.
3. Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Halkjaer-Kristensen J, and Dyhre-Poulsen P. Neural inhibition during maximal eccentric and concentric quadriceps contraction: Effects of resistance training. *J Appl Physiol (1985)* 89: 2249–2257, 2000.
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. The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged Rugby league football players. *J Strength Cond Res* 15: 172–177, 2001.
6. 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.
7. Baker D and Nance S. The relation between running speed and measures of strength and power in professional rugby league players. *J Strength Cond Res* 13: 230–235, 1999.
8. Baker D, Nance S, and Moore M. The load that maximizes the average mechanical power output during jump squats in power-trained athletes. *J Strength Cond Res* 15: 92–97, 2001.
9. Barker M, Wyatt TJ, Johnson RL, Stone MH, O'Bryant HS, Poe C, and Kent M. Performance factors, physiological assessment, physical characteristics, and football playing ability. *J Strength Cond Res* 7: 224–233, 1993.
10. Barnes JL, Schilling BK, Falvo MJ, Weiss LW, Creasy AK, and Fry AC. Relationship of jumping and agility performance in female volleyball athletes. *J Strength Cond Res* 21: 1192–1196, 2007.
11. Beckham G, Mizuguchi S, Carter C, Sato K, Ramsey M, Lamont H, Hornsby G, Haff G, and Stone M. Relationships of isometric mid-thigh pull variables to weightlifting performance. *J Sports Med Phys Fitness* 53: 573–581, 2013.
12. 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.
13. Bottinelli R, Betto R, Schiaffino S, and Reggiani C. Maximum shortening velocity and coexistence of myosin heavy chain isoforms in single skinned fast fibres of rat skeletal muscle. *J Muscle Res Cell Motil* 15: 413–419, 1994.
14. Bottinelli R, Betto R, Schiaffino S, and Reggiani C. Unloaded shortening velocity and myosin heavy chain and alkali light chain isoform composition in rat skeletal muscle fibres. *J Physiol* 478(Pt 2): 341–349, 1994.
15. Bottinelli R, Canepari M, Pellegrino MA, and Reggiani C. Force-velocity properties of human skeletal muscle fibres: Myosin heavy chain isoform and temperature dependence. *J Physiol* 495(Pt 2): 573–586, 1996.
16. Bottinelli R, Pellegrino MA, Canepari M, Rossi R, and Reggiani C. Specific contributions of various muscle fibre types to human muscle performance: An in vitro study. *J Electromyogr Kinesiol* 9: 87–95, 1999.
17. Bottinelli R, Schiaffino S, and Reggiani C. Force-velocity relations and myosin heavy chain isoform compositions of skinned fibres from rat skeletal muscle. *J Physiol* 437: 655–672, 1991.
18. Cormie P, McBride JM, and McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: Impact of training. *J Strength Cond Res* 23: 177–186, 2009.
19. Cormie P, McGuigan MR, and Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc* 42: 1582–1598, 2010.
20. 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.
21. 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.
22. 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.

23. Doan BK, Newton RU, Kwon YH, and Kraemer WJ. Effects of physical conditioning on intercollegiate golfer performance. *J Strength Cond Res* 20: 62–72, 2006.
24. Fletcher IM and Hartwell M. Effect of an 8-week combined weights and plyometrics training program on golf drive performance. *J Strength Cond Res* 18: 59–62, 2004.
25. Fry AC and Kraemer WJ. Physical performance characteristics of American collegiate football players. *J Strength Cond Res* 5: 126–138, 1991.
26. Garhammer J. Power production by Olympic weightlifters. *Med Sci Sports Exerc* 12: 54–60, 1980.
27. Haff GG and Nimphius S. Training principles for power. *Strength Cond J* 34: 2–12, 2012.
28. Hakkinen K. Neuromuscular and hormonal adaptations during strength and power training. A review. *J Sports Med Phys Fitness* 29: 9–26, 1989.
29. Hammett JB and Hey WT. Neuromuscular adaptation to short-term (4 weeks) ballistic training in trained high school athletes. *J Strength Cond Res* 17: 556–560, 2003.
30. 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.
31. 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.
32. Hartmann H, Bob A, Wirth K, and Schmidtbleicher D. Effects of different periodization models on rate of force development and power ability of the upper extremity. *J Strength Cond Res* 23: 1921–1932, 2009.
33. Hawley JA, Williams MM, Vickovic MM, and Handcock PJ. Muscle power predicts freestyle swimming performance. *Br J Sports Med* 26: 151–155, 1992.
34. Hori N, Newton RU, Andrews WA, Kawamori N, McGuigan MR, and Nosaka K. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *J Strength Cond Res* 22: 412–418, 2008.
35. Koenig K, Mitchell ND, Thomas HE, and Clutter JK. The influence of moment of inertia of baseball/softball bat swing speed. *Sports Eng* 7: 105–117, 2004.
36. Marques MC, Saavedra FJ, Abrantes C, and Aidar FJ. Associations between rate of force development metrics and throwing velocity in elite team handball players: A short research report. *J Hum Kinet* 29A: 53–57, 2011.
37. McEvoy KP and Newton RU. Baseball throwing speed and base running speed: The effects of ballistic resistance training. *J Strength Cond Res* 12: 211–271, 1998.
38. McLellan CP, Lovell DI, and Gass GC. The role of rate of force development on vertical jump performance. *J Strength Cond Res* 25: 379–385, 2011.
39. 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 Occup Physiol* 75: 193–199, 1997.
40. 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.
41. 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.
42. Noakes TD. Implications of exercise testing for prediction of athletic performance: A contemporary perspective. *Med Sci Sports Exerc* 20: 319–330, 1988.
43. Nyitrai M, Rossi R, Adamek N, Pellegrino MA, Bottinelli R, and Geeves MA. What limits the velocity of fast-skeletal muscle contraction in mammals? *J Mol Biol* 355: 432–442, 2006.
44. Østerås H, Helgerud J, and Hoff J. Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol* 88: 255–263, 2002.
45. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol (1985)* 86: 1527–1533, 1999.
46. Painter KB. *A Practical Comparison Between Traditional Periodization and Daily-Undulated Weight Training Among Collegiate Track and Field Athletes*. East Tennesse State University, 2009.
47. Painter KB, Haff GG, Ramsey MW, McBride J, Triplett T, Sands WA, Lamont HS, Stone ME, and Stone MH. Strength gains: Block versus daily undulating periodization weight training among track and field athletes. *Int J Sports Physiol Perform* 7: 161–169, 2012.
48. Salaj S and Markovic G. Specificity of jumping, sprinting, and quick change-of-direction motor abilities. *J Strength Cond Res* 25: 1249–1255, 2011.
49. Sargeant AJ. Structural and functional determinants of human muscle power. *Exp Physiol* 92: 323–331, 2007.
50. Schmidtbleicher D. *Training for Power Events. Strength and Power in Sports, in Training for Power Events*. London, United Kingdom: Blackwell Scientific Publications, 1992.
51. Sharp RL, Troup JP, and Costill DL. Relationship between power and sprint freestyle swimming. *Med Sci Sports Exerc* 14: 53–56, 1982.
52. Spiteri T, Nimphius S, and Cochrane JL. Comparison of running times during reactive offensive and defensive agility protocols. *J Aus Strength Cond* 20: 73–78, 2012.
53. Stodden DF, Fleisig GS, McLean SP, and Andrews JR. Relationship of biomechanical factors to baseball pitching velocity: Within pitcher variation. *J Appl Biomech* 21: 44–56, 2005.
54. Stone MH, Moir G, Glaister M, and Sanders R. How much strength is necessary? *Phys Ther* 3: 88–96, 2002.
55. Stone MH, O'Bryant H, and Garhammer J. A hypothetical model for strength training. *J Sports Med Phys Fitness* 21: 342–351, 1981.
56. Stone MH, O'Bryant HS, McCoy L, Coglianese R, Lehmkuhl M, and Schilling B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *J Strength Cond Res* 17: 140–147, 2003.
57. Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL, and Hartman M. The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res* 18: 878–884, 2004.
58. Stone MH, Sands WA, Pierce KC, Newton RU, Haff G, and Carlock J. Maximum strength and strength training-a relationship to endurance? *Strength Cond J* 28: 44–53, 2006.
59. Stone MH, Stone M, and Sands WA. *Principles and Practice of Strength*

Training. Champaign, IL: Human Kinetics, 2007.

60. Thomas C, Jones PA, Rothwell J, Chiang CY, and Comfort P. An investigation into the relationship between maximum isometric strength and vertical jump performance. *J Strength Cond Res* 29: 2176–2185, 2015.
61. Toji H and Kaneko M. Effect of multiple-load training on the force-velocity relationship. *J Strength Cond Res* 18: 792–795, 2004.
62. 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 Fit Sport* 44: 439–446, 1995.
63. Toji H, Suei K, and Kaneko M. Effects of combined training loads on relations among force, velocity, and power development. *Can J Appl Physiol* 22: 328–336, 1997.
64. Vescovi JD and McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci* 26: 97–107, 2008.
65. Weyand PG, Sandell RF, Prime DN, and Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol (1985)* 108: 950–961, 2010.
66. Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol (1985)* 89: 1991–1999, 2000.
67. 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.
68. Zatsiorsky VM and Kraemer WJ. *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics, 2006.