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PRACTICAL APPLICATIONS OF BIOMECHANICAL PRINCIPLES IN RESISTANCE TRAINING: NEUROMUSCULAR FACTORS AND RELATIONSHIPS

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ABSTRACT

This paper is the second in our three part series examining how a variety of biomechanical principles and concepts have direct relevance to the prescription of resistance training for the general and athletic populations as well as for musculoskeletal injury rehabilitation. In this paper, we considered different neuromuscular characteristics of resistance exercise. We started by defining the causes of motion, discussing force and Newton's second law of linear motion. This led to discussion of impulse, and how its relationship with momentum can be used to study force-time curves recorded from different ground-based resistance exercises. This enables the sports biomechanist to derive movement velocity, which enables study of the relationship between force and velocity, and we concluded that as the force required to cause movement increases the velocity of movement must decrease. This relationship is critical because it enables strength and conditioning coaches and exercise professionals to manipulate resistance-training loads to maximise training gains for sports performance. We described representative force-time curves from basic human movements to provide a foundation for discussion about how different resistance-training gains can be achieved. This focused on exercise technique, including use of the stretch-shortening cycle, magnitude of load, ballistic resistance exercise, and elastic band and chain resistance (although elements of this will receive greater attention in our final article). Finally, we defined and explained the concept of mechanical work and power output, examining the effect that load has on power output by considering the load-power relationships of different common resistance exercises. We hope that exercise professionals will benefit from this knowledge of applied resistance training biomechanics. Specifically, we feel that the take home message of this article is that resistance exercise load and technique can be manipulated to maximise resistance-training gains, and that this can be particularly useful for athletes trying to improve sporting performance.

Keywords: biomechanics; forces; velocity; impulse; work; power; resistance exercise.

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INTRODUCTION

This is the second article in our three part series that considers the practical application of biomechanics to resistance training prescription. In the first article [1], we introduced biomechanical concepts that included moment arms and joint moments, discussing their application to resistance exercise and some of the factors that can influence them. This explanation of how muscle force is transmitted to external loads (i.e., barbells, dumbbells, body mass) via skeletal joints sets the scene for this second article in the series. This article focuses on how *net force* (force minus weight, the cause of movement) produced by the neuromuscular system is applied during resistance exercise, hereafter referred to as *force output*, and the factors that affect this.

The purpose of this article, therefore, is to present key biomechanical concepts related to force output, i.e. the impulse-momentum relationship, mechanical work and power. Following this, useful explanations about how resistance exercise type, technique, and the external load itself can influence force output and their possible effects on biomechanical parameters and training outcomes will be developed.

KEY BIOMECHANICAL CONCEPTS

What is force and what does it do?

To understand the importance of the biomechanics of resistance exercise, we must first have a basic understanding of Newton's laws of motion. From Newton's three laws of motion, the second law appears to be of major importance to resistance training (although from the perspective of this article it is closely followed by the first law of inertia). Usually referred as the law of acceleration, it is commonly expressed with the following equation:

$$F = ma$$

Where the F (N) refers to *net force*, while m (kg) and a (m/s^2) refer to *mass* and *acceleration* respectively. Force is often defined as a *pushing* or *pulling* action [2], and can be thought of as an expression of strength, because how hard we can *push* or *pull* an external load relies largely on how strong we are. While the first article considered how force is transmitted from muscles via the joints of the skeleton, this article focuses on the summation of these forces and their effect on what is often referred to as a body's or segment's centre of mass (COM). The COM is a theoretical point where all the mass can be considered to reside, and includes any mass that is being *pushed* or *pulled* against.

Resistance exercise typically requires the exercising human to move (*accelerate*) an external load (*mass*) through a range of motion, and the *law of acceleration* defines the relationship that exists between movement and external load, and, perhaps more importantly, how movement of an external load relies on force. It should be noted that we only consider isoinertial (constant) loading as provided by free-weight, pin- and plate-loaded machine and bodyweight resistance in this article. Other types of resistance exercise are often included in resistance training programs, but these are beyond the scope of this article. These other forms of resistance include: isometric, isokinetic, hydraulic, pneumatic, and cam- and lever-based systems, and interested readers should consider the extensive review by Frost *et al.* [3].

It should also be noted that the direction of force output is a factor because force is a vector quantity that considers how hard we *push* or *pull* an object and the direction in which we *push* or *pull* it. This article will focus on vertical force, as this tends to represent the largest force that is recorded during most resistance exercises, mainly because of the effect of gravity, but also because most forms of resistance training are performed in the vertical plane. However, large amounts of horizontal force are necessary in many sporting movements, and interested readers should consider the excellent review by Randell *et al.* [4].

It remains that how fast an external load is moved during resistance exercise, which is related to its acceleration, depends on how much force is applied to it. Therefore, if a known amount of force is applied to an external load it will experience a certain amount of acceleration in the direction of the force. If more force is applied to the same external load then the acceleration magnitude increases, while if the same amount of force is applied to a greater mass, acceleration magnitude decreases. Research shows that the effect that mass can have on acceleration, and, more specifically biomechanical variables, like velocity and power, can have significant implications for the way we respond to resistance training [5, 6, 7]. However, the amount of force that can be applied to an external load is governed by many factors, which will be discussed later, but include the relationship between force and velocity.

Force-velocity relationship

The force-velocity relationship applies to all human movements. If we consider a movement such as a vertical jump (with and without barbell load), performed with the intent to move as fast as possible, the force-velocity relationship, illustrated in Figure 1 shows that when an individual attempts to jump without any additional load, they will be able to move very quickly (high velocity; bottom of the peak and mean force-velocity trend lines in Figure 1), demonstrating an inverse relationship between force output and movement. Conversely, jumping with additional load will involve a lower

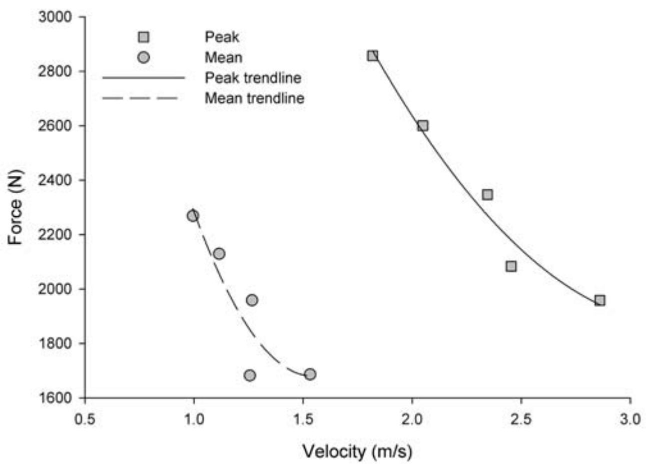

Figure 1: Peak and mean force-velocity trendlines from unloaded and loaded (+25%, +50%, +75%, and +100% body mass [BM]) CMJ performance. Velocity moves from the right to the left as load increases.

movement velocity (top of the peak and mean force-velocity trend lines in Figure 1) [3, 8, 9, 10, 11, 12, 13].

Another way of considering the relationship between force and velocity is to plot continuous data sets against one another. Cormie *et al.* [14] have used this approach extensively in their research to show the effect that different resistance training strategies can have on different strength components. Figure 2 shows the force-velocity loops resulting from this type of analysis. In this example, force and velocity obtained from an individual jumping with no additional load, and with barbell loads equivalent to 25, 50, 75, and 100% of their body mass, are plotted against one another. The resulting graph shows that as load increases not only does force output increase and velocity decrease, but also the interaction between them changes.

This appears of importance as it: 1) governs resistance exercise intensity, 2) governs the outcome of a resistance-training program, and 3) allows exercise professionals and sports scientists to identify and explore the relevance and development of different strength components. The excellent textbook by Zatsiorsky and Kraemer [15] provides detailed description of this relationship. However, the main thing that should be highlighted about this is the effect that it can have on any resistance training loading strategy, and this will be discussed in greater depth when we move on to the biomechanical concepts of mechanical work and power.

GRAPHICAL REPRESENTATION OF FORCE: THE FORCE-TIME CURVE

We will discuss the effect that mass can have on biomechanical variables, like velocity and power, later in this article. First, we should consider how a greater understanding of Newton's law of acceleration can be gained by understanding how force is typically applied during resistance exercise, what the resulting *force-time curves* mean, and how they are used to obtain more information about

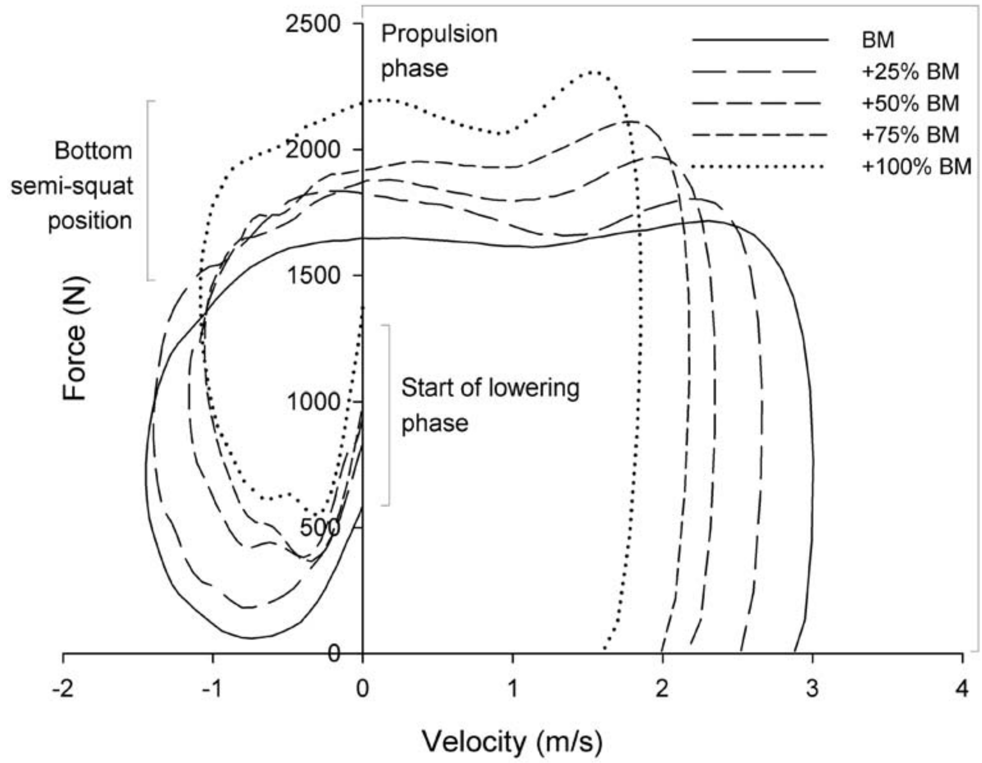

Figure 2: Continuous force-velocity loops from unloaded and loaded (+25%, +50%, +75%, and +100% body mass [BM]) CMJ performance. Zero velocity marks the start of the lowering phase (unweighting and eccentric sub-phases), which continues until the curve crosses zero. This marks the bottom, semi-squat position, and the start of the propulsion phase (active concentric and momentum sub-phases).

performance using the impulse-momentum relationship - an extension of Newton's law of *acceleration*. Although the focus of these articles is resistance training, it is often easier to explain what force-time curves show us using variations of vertical jumping because: 1) most readers will be familiar with this movement, doing some sort of variation either in their chosen sport or as part of their strength and conditioning program, 2) because vertical jumping is easy to visualise – we push, we take off, we land, and 3) because the effect that technique and load can have are easily explored.

What are they?

Force-time curves are the product of plotting force output, on the vertical axis of the graph, against the time over which it is applied, on the horizontal axis of the graph. Biomechanists use force platforms (a device like a very sophisticated set of bathroom scales that is typically bolted to a solid base and houses sensitive transducers that detect and record changes in the force applied to them), to record force output, relying on the foot-floor interaction inherent in most resistance exercise.

Different types of force-time curve

The force-time curve is particularly useful because it illustrates both the pattern of force output, or 'how' force is applied, and how much force is applied at any given time. In accordance with Newton's law of *acceleration*, the force-time curve pattern is influenced by the total mass that is moved. However, exercise type also influences the force-time curve pattern. Figure 3 shows a typical force-time curve from a squat jump (SJ), which consists of the jumper holding a semi-squat position for few seconds before trying to jump upwards, applying force on the ground by extending the hip, knee and ankle joints. Figure 3 is an excellent example of a bell shaped force-time curve.

The shape of the force-time curve can be influenced by the composition of the external load. For example, traditional back squat loading is

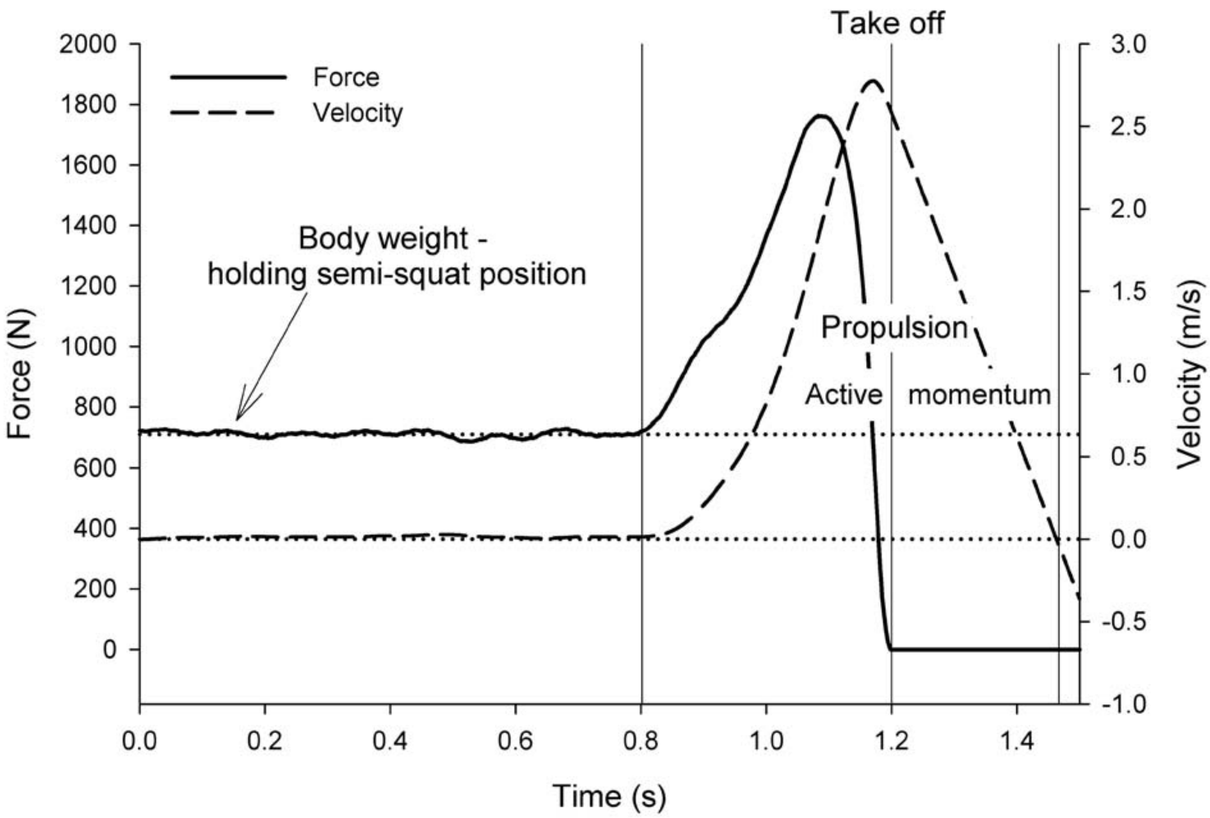

Figure 3: Force-time and velocity-time curves of unloaded SJ performance.

applied by a plate-loaded barbell. However, powerlifters often manipulate this by providing a certain percentage of the load with either elastic band or chain resistance. This sort of loading strategy can influence the force-time curve because although the load remains isoinertial, it increases throughout the concentric range of motion to provide accommodating resistance during the less problematic phases of the lift [16, 17, 18]. Similarly, elastic band assistance is sometimes used to either assist the lifter through a particular sticking point of the resistance exercise, or, in some cases enable athletes to train 'over-speed' vertical jumps[19]. The result of these slight alterations to loading can produce three distinctly different types of force-time curve: ascending, the product of additional elastic band or chain resistance; bell-shaped, which is typically found in traditional back squat, bench press, or vertical jump performance (Figure 3), and descending, which is typically found in resistance exercises, like the back squat, deadlift, or vertical jump, where elastic bands are used to assist the athlete. Interested readers should consider the review of load manipulation strategies by Baker and Newton [18]. It should be noted that the type and variation of resistance exercise significantly influences the force-time relationship, and, as such, can influence the training stimulus.

WHAT CAN WE DO WITH THE FORCE-TIME CURVE?

The impulse-momentum relationship

The relationship between force and acceleration tells us that to move (accelerate) an external load we have to apply a force to it, and that the amount of force we apply dictates how far and how fast the external load will move. However, we can take this a stage further by considering how long the force is applied for. The biomechanical concept of impulse describes this relationship, which is of particular importance because many human movements, particularly sporting movements tend to occur under some form of time constraint. For example, the amount of time typically available for athletes sprinting at top speed to apply force is limited to about 100th of a second [20]. Researchers have shown that impulse may be a key determinant of adaptation because of its relationship with motion [21, 22]. Here we will provide a more comprehensive explanation of the relationship between force and movement by focusing on the impulse-momentum relationship. We now know that impulse is the product of force and time. Momentum, on the other hand, is the product of *mass* (or external load) and *velocity*. Newton's first law of motion, the law of inertia can help consolidate the role of each of these parameters. This law states that stationary and moving objects possess inertia, their reluctance to change their velocity, which is represented by mass and momentum, respectively. A simple way to understand *velocity* is to consider it as *speed* in a given direction; so how quickly something moves in a given direction. The impulse-momentum relationship tells us that impulse equals a change in (where Δ is scientific shorthand for 'change in') momentum, and is represented by each half of the following equation, respectively:

$$Force \times \Delta time = mass \times \Delta velocity$$

The impulse-momentum relationship shows us that this influences how quickly and how far a mass, moves. In theory, both the *mass* and *velocity* components of momentum can be manipulated, however a change in mass is unlikely during resistance exercise so we focus on its change in velocity. This relationship can be thought of as a natural extension of Newton's second law of motion, the *law of acceleration*, and the take home points from this then should be that: 1) the amount and rate of movement of a mass depends on how hard we *push* or *pull* it, and 2) the amount and rate of movement can be directly related to how long we *push* or *pull* it for. Such information could be obtained from force-time curves, which underpin its importance for sport scientists and exercise biomechanists (Figure 3 and 4).

The first stage of this force-time curve analysis is to take an average value from the first period of the SJ, where the athlete maintains a static semi-squat position (this maybe a static standing position in other exercises), shown in Figure 3. This provides

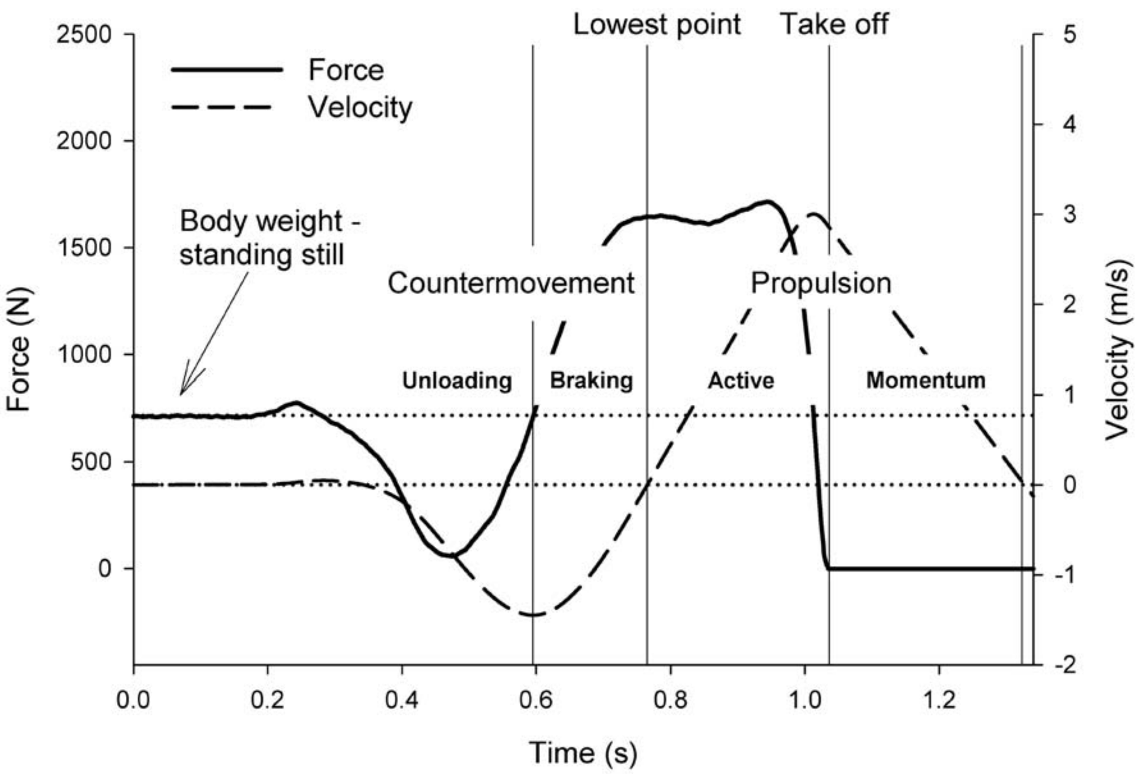

Figure 4: Force-time and velocity-time curves of unloaded CMJ performance.

the *weight* of the jumper. We subtract this from the original force-time curve, to obtain *net force*, because calculations of acceleration, velocity and displacement are based on the forces that overcome *inertia* (cause a change in velocity), and weight is the effect of mass and the acceleration of gravity. This is then divided by the mass of the jumper to yield the acceleration of the COM, which is then integrated once to yield the velocity of his centre of mass, and integrated again to yield the displacement of the COM. Power can then be calculated by multiplying force by velocity [3, 6, 7, 23, 24, 25]. Velocity can then be used to identify the different phases of a movement because it shows not only how fast the external load moves, but also its direction (Figure 3 and 4). While this series of calculations appear quite complicated, the integration approach is similar in complexity and acts in reverse to the differentiation approach used by relatively inexpensive linear transducers such as the GymAware™ [26]. It should be noted that other similar devices, like the Bosco ErgoPower [8], FitroDYNE [11], and Plyometric Power System [27], are commercially available, and that some of these systems also calculate variables such as force, power and velocity for each repetition of many resistance training exercises [26, 28].

The effect of resistance exercise type on force-time curves

While this is important, knowing just how force-time curves vary as a consequence of different resistance exercise types can have significant implications for the exercise selection component of resistance training prescription, particularly with regards to resistance training responses. In our first article [1], we demonstrated the effect that load's vector has on joint moments, and illustrated the practical relevance of the interpretation of force-time curves (depending on the type of resistance exercise) and the implications for resistance exercise prescription and subsequent training responses. Similarly, in this second article of the series, we will illustrate the effect that resistance exercise type has on the respective force-time curves by comparing ballistic, semi-ballistic and non-ballistic resistance exercise.

Resistance exercise becomes ballistic when the external load (body mass, barbell mass, or both) is projected into free space [3, 29]. The simplest example presents itself in the form of comparison between bench press and bench throw exercise [29, 30, 31], and back squat and loaded vertical jump (often referred to as squat jump [SJ]) exercise [32, 33], and interested readers are referred the excellent review by Frost *et al.* [3]. The main difference between ballistic and non-ballistic resistance exercise is that, during ballistic resistance exercise, the lifter leaves the ground or the external load is projected into space. As a consequence, force tends to be applied over a shorter propulsion phase, which is advantageous for athletes who need to apply force under time constraint. Research has shown that differences between ballistic and non-ballistic resistance exercise may not be as large as first thought, and that the way in which the concentric phase of resistance exercise is determined may explain some of these differences [32, 34]. However, there is no avoiding the fact that the agonist muscles may reduce their activation towards the end of the concentric phase and the antagonist muscles produce force to slow down at the end of range during non-ballistic resistance exercise, which is why ballistic resistance exercises are often preferred for power training. This has led many strength and conditioning coaches and exercise professionals to use other forms of semi-ballistic resistance exercise like variations of the Olympic weightlifts (like the power snatch and power clean) [23] and kettlebell exercises (like the two-handed swing) [35], and elastic band resistance [17, 18]. We should also point out that ballistic resistance exercise, like loaded SJ, should be introduced gradually into athlete strength and conditioning programs and caution taken because of the increased mechanical demands that are associated with both propulsion and landing (or catching in the case of throwing) phases [36].

The main point for the interested reader to take from this is that different types of resistance exercise will require a different pattern of force output because of: 1) the different range of movement, 2) the different relative contribution of upper and/or lower-body joints to the movement, 3) the load that can be lifted will differ across different resistance exercises (mainly because of the first and second points), and 4) application of force will be more efficient because of the way in which the lever system of the body is used. A relatively simple practical example presents itself in the recent study by Swinton *et al.* [37]. They compared biomechanical characteristics of the straight and hexagonal barbell deadlift exercise, and their results showed that performing the same exercise with a different barbell caused a significant shift in the COM that facilitated improved mechanical efficiency by enabling the COM of the hexagonal barbell to pass close to the body's COM as viewed from the side position.

The effect of resistance exercise technique on force-time curves

This point was briefly introduced in the particular context of SJ exercise force-time curves. However, further discussion is warranted because, in this context, the effect that technique can have on the force-time curve can have important implications, not only for the type of resistance exercises that are prescribed, but also in the way in which we perform basic human movements.

The most common technique adaptation applied to basic human movements is the performance of some form of countermovement (countermovement jump = CMJ), which is a movement performed in the direction opposite to the intended movement direction (eccentric contraction) immediately before movement in the intended direction (concentric contraction). If performed efficiently this countermovement recruits what is commonly referred as the stretch-shortening, cycle (SSC), which has been shown to improve jumping performance [38]. Review of the mechanisms that underpin improved performance are beyond the scope of this article, and the interested reader is directed to the thorough explanations provided by Bobbert *et al.* [38] and Cormie *et al.* [39, 40]. However, it is important to note that use of the SSC, through addition of a countermovement, can affect joint positions at key points of performance, particularly during jumping, which in turn can affect force output and associated biomechanical parameters [38].

The effect that the SSC has on the force-time relationship is shown in the differences in force-time curves of SJ and CMJ (Figure 3 and 4). From the practitioner's perspective it may be useful to understand not only the effect of a technique alteration on the respective force-time curve, and then performance, but also why we might want to prescribe resistance exercises that either use or don't use the SSC to manipulate training response.

Figure 4 shows the typical force-time curve from a CMJ, including the different phases (note differences with Figure 3). Compared to SJ (Figure 3), Figure 4 illustrates two additional key phases that occur during the CMJ: *unloading* and *braking*. Force decreases below the jumper's body weight during the unloading phase because the COM moves in the same direction that the acceleration of gravity acts. During the second phase of the downward movement the COM continues to move this way. However, the jumper now begins to decelerate the COM, *braking* the downward movement by applying eccentric force to the ground via eccentric contraction (lengthening) of the primary jumping muscles. This continues until the jumper stops in the bottom semi-squat position for a fraction of a second before the propulsion, or upward, phase begins. This phase contains an active and passive sub-phase. Figure 4 shows how force-time and velocity-time curves can be combined to identify changes in COM movement direction. The beginning of the propulsion phase (bottom position) is indicated by the change from a negative to positive COM velocity. The active sub-phase is characterised by concentric force output and continues until take off. Continued displacement, to the highest point of the jump is a consequence of the momentum the mass has and is subject to the acceleration of gravity, which eventually causes the jumper's return to the ground. The main point for the interested reader to take from this is that changing technique, to use the SSC, changes the force-time curve, and can improve performance significantly.

Mechanical work

We know that if we apply force that is sufficient to overcome the inertia of an external load it will accelerate. Whenever an external load moves because we have either *pushed* or *pulled* it, mechanical work is performed. Mechanical work is a relatively simple concept in as much as it is the product of the force applied to an external load and the distance the external load moves as a consequence. It is important to note however, that while simple, we must remain mindful of the direction the force is applied and the direction that the external load moves.

If both force application and movement occur in the same direction we have performed *positive* mechanical work, however if they oppose one another then we have performed *negative* work. Practically, the easiest way to visualise this might be to consider performance of the bench press exercise. After taking the barbell from the rack, force is applied upwards (via eccentric contraction of the agonist muscles) into the barbell as it is lowered under control toward the chest: *negative work is performed*. During the ascent phase, the force is again applied upwards in to the barbell (via concentric contraction of the agonist muscles) to move it, from the chest upwards, in the same direction that force is applied: *positive work* is performed. As with most biomechanical concepts, manipulating either of the two variables that underpin mechanical work can influence the amount of mechanical work that we perform during resistance exercise: 1) the amount of force we apply to the external load, 2) the distance the external load moves, 3) or a combination of 1 and 2.

Mechanical power output

Mechanical power describes the rate at which mechanical work is performed. This can have important implications for the way we prescribe resistance-training programs to athletes because most sports and athletic events tend to be based on performance of mechanical work under some kind of time constraint. We can use the force-time curve (Figure 3 and 4) to find out just how much force was applied during the *pushing* part of the vertical

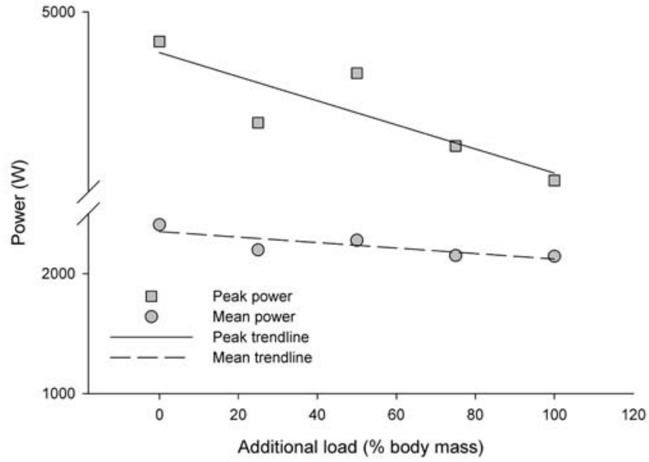

Figure 5: Unloaded and loaded (+25%, +50%, +75%, and +100% body mass [BM]) peak and mean load-power relationships from ballistic exercise (CMJ).

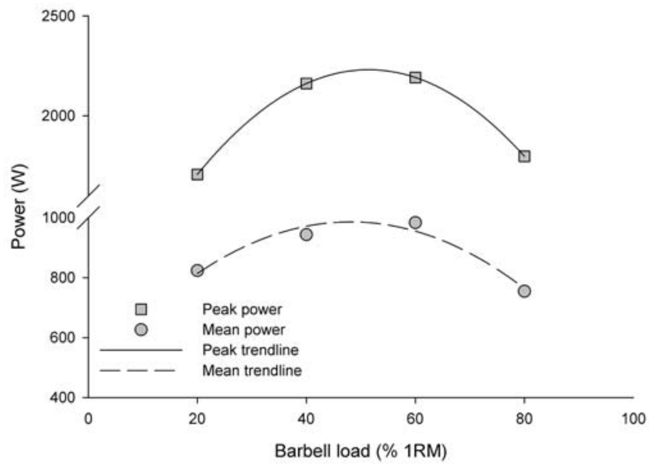

Figure 6: Unloaded and loaded (+20%, +40%, +60%, and +80% 1 repetition maximum [1RM]) peak and mean load-power relationships from non-ballistic exercise (back squat).

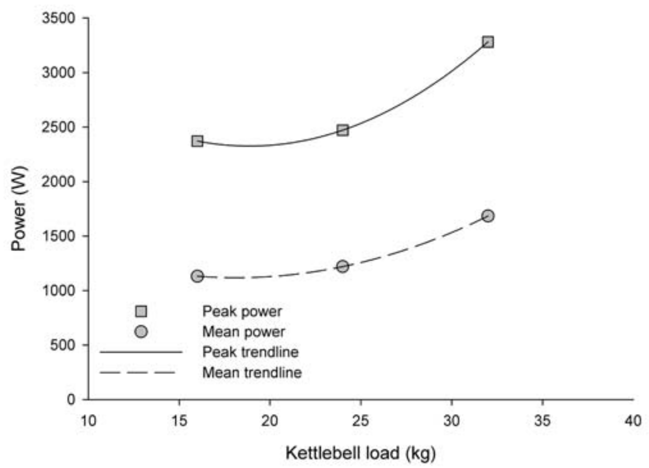

Figure 7: Peak and mean load-power relationships from semi-ballistic exercise (2-handed kettlebell swing) with 16, 24 and 32 kg.

jump (in this example), and then derive how far the external load (the body mass) moved (see description above). This tells us how much mechanical work was performed during the *pushing* phase. Dividing mechanical work by the duration of the *pushing* phase yields *mechanical power output*, or, more specifically, *average power output* during that phase. More mechanical power is achieved if we: 1) perform more mechanical work in the same amount of time, 2) perform the same amount of mechanical work in less time (faster), or 3) a combination of 1 and 2. These points have important implications for sports performance, and, as a consequence, significant parts of the strength and conditioning process focus on the development of power.

The effect of external load: The relationship between load and power

So far we've introduced, defined and discussed different neuromuscular concepts, like force, impulse and momentum, and relationships, like the force-velocity and impulse-momentum relationship, and the typical force-time relationship of different types of vertical jump performance. This section will briefly explore the effect that load has on mechanical power output, which has been the focus of considerable research attention [5, 7, 12, 24, 26, 27, 29, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53]. Early research focused on exploring the effect that resistance training with the load that maximises mechanical power output had on strength and power. Results presented by Kaneko *et al.* [12] showed that such training led to significant improvements in both strength and power. Subsequent research has been split into two key areas: 1) continued study of the effect that resistance training with the load that maximises power, the optimal load, has on strength and power, and 2) establishing the load that maximises power in different resistance exercises and in different populations. Many studies have noted that training with the load that maximises mechanical power output can have a positive effect on power [5, 14, 47, 52], and, in some cases, maximal strength [47, 52]. However, the concept of an optimal load has been contested [54]. Furthermore, research into these two areas can get a little confusing because of the different response that power has to load in different resistance exercises, complicating the identification of an optimal load, because of the different methods that are often used to measure and report power [43, 55, 56].

For example three main methods are typically used to obtain vertical jump power, and these are based around: 1) deriving it from the motion of an obvious landmark (like the barbell – using either barbell mass, body mass, or both) [11, 26, 27, 28, 44], 2) deriving it from vertical ground reaction force (as discussed previously) [24, 41, 46, 47, 53, 57, 58], or 3) from a combination of method 1 and 2 [5, 9, 37, 42, 59]. The interested reader is directed to method comparisons that have been performed in an effort to establish the relative validity of these methods [43, 48, 56, 60], but it should be noted that while the method used to obtain power influences the load that maximises power, it remains a contentious issue. Additionally, some studies have reported the highest instantaneous power output recorded during the pushing phase of a resistance exercise, while others have reported the average power output of the pushing phase [43]. It should be noted that Dugan *et al.* [43] noted that, with regard to vertical jumping, reporting either peak or mean power is technically correct, and that it may be more logical to report the parameter most associated with (jumping) performance (peak power). However, Knudson [21] has pointed out that: "…*net vertical impulse exactly determines vertical jump height*…" (pp. 1904). Therefore, because the result of net vertical impulse is related by the phase over which it is applied, mean performance values may also be of interest and could yield important information.

The effect that different resistance exercises have on the load-power relationship warrants discussion because of the effect that it can have on resistance training load prescription and response (regardless of the method used and whether peak or mean power is reported). Examples of load-power relationships obtained from different types of resistance exercise (ballistic, non-ballistic, and semi-ballistic) are presented in Figures 5, 6 & 7, respectively. They clearly illustrate the effect that resistance exercise type can have on the load-power relationship. Therefore, care must be taken when designing resistance-training programs to improve power.

The concept of an optimal load for the development of power has become a controversial issue in strength and conditioning research. This appears to have come about by the rationale that has been used in which power has been said to be the strongest predictor of vertical jump performance. Critics rightly point out that impulse is the strongest predictor of vertical jump performance because it is directly related to take off velocity[21], which governs vertical jump height, in accordance with the laws of uniform acceleration, and this was discussed in a little more detail earlier in this review. However, this shouldn't detract from the importance of power output in terms of both its importance in athletic performance, and its development in resistance training programs, particularly when advances in resistance training program design, like combined strength and power training, are considered [5]. The take home point for the strength and conditioning coach and exercise professional is that power responds differently to load in different resistance exercises, and this should be considered when planning resistance training programs that focus on the development of power.

CONCLUSIONS

This article has defined and explained key neuromuscular characteristics of resistance exercise. Perhaps more importantly it has discussed how they can be manipulated to maximise resistance-training gains. We feel that the key points to take from this article are that: 1) to maximise power output and transfer to sports performance, resistance exercises based on movement patterns similar to sporting movements should be performed with loads that reflect the principle force-velocity-power relationship of that sport; 2) resistance exercises that enable use of the stretch-shortening cycle may augment power, but should be matched to sporting demands; and 3) for hypertrophy, whereby impulse (force and time under tension) may be more important, slightly higher repetition ranges and slower repetition velocities may be more appropriate. The final article in this series will focus on explaining how the composition of resistance exercise load can be manipulated to maximise the effectiveness of resistance-training gains.

REFERENCES

1. Keogh, J.W.L., Lake, J., & Swinton, P.A. (2013). Practical applications of biomechanical principles in resistance training: moments and moment arms. *Journal of Fitness Research, 2*(2), 39-48.
2. Bartlett, R. (2007). *Introduction to Sports Biomechanics: Analysing Human Movement Patterns* (Second ed.). Abingdon, Oxon: Routledge.
3. Frost, D.M., Cronin, J., & Newton, R.U. (2010). A biomechanical evaluation of resistance: fundamental concepts for training and sports performance. *Sports Medicine, 40*(4), 303-326.
4. Randell, A.D., Cronin, J.B., Keogh, J.W.L., & Gill, N.D. (2010). Transference of strength and power adaptation to sports performance – horizontal and vertical force production. *Strength and Conditioning Journal, 32*(4), 100-106.
5. Cormie, P., McCaulley, G.O., & McBride, J.M. (2007). Power versus strength-power jump squat training: influence on the load-power relationship. *Medicine and Science in Sports and Exercise, 39*(6), 996-1003.
6. Haff, G.G., & Nimphius, S. (2012). Training principles for power. *Strength and Conditioning Journal, 34*(6), 2-12.
7. Kawamori, N., & Haff, G.G. (2004). The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research, 18*(3), 675-684.
8. Bosco, C., Belli, A., Astrua, M., Tihanyi, J., Pozzo, R., Kellis, S., et al. (1995). A dynamometer for evaluation of dynamic muscle work. *European Journal of Applied Physiology, 70*(5), 379-386.
9. Cormie, P., McCaulley, G.O., Triplett, N.T., & McBride, J.M. (2007). Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports*

and Exercise, 39(2), 340-349.
10. Hill, A.V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B: Biological Sciences, 126*(843), 136-195.
11. Jennings, C.L., Viljoen, W., Durandt, J., & Lambert, M.I. (2005). The reliability of the FitroDyne as a measure of muscle power. *Journal of Strength and Conditioning Research, 19*(4), 859-863.
12. Kaneko, M., Fuchimoto, T., Toji, H., & Suei, K. (1983). Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scandanavian Journal of Sports Sciences, 5*(2), 50-55.
13. Crewther, B.T., Cronin, J., & Keogh, J.W. (2005). Possible stimuli for strength and power adaptation: Acute mechanical responses. *Sports Medicine, 35*(11), 967-989.
14. Cormie, P., McGuigan, M.R., & Newton, R.U. (2010). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine and Science in Sports and Exercise, 42*(9), 1731-1744.
15. Zatsiorsky, V.M., & Kraemer, W.J. (2006). *Science and Practice of Strength Training* (2nd ed.). Champaign, IL: Human Kinetics.
16. Wallace, B.J., Winchester, J.B., & McGuigan, M.R. (2006). Effects of elastic bands on force and power characteristics during the back squat exercise. *Journal of Strength and Conditioning Research, 20*(2), 268-272.
17. Swinton, P.A., Lloyd, R., Agouris, I., & Stewart, A. (2009). Contemporary training practices in elite british powerlifters: survey results from an international competition. *Journal of Strength and Conditioning Research, 23*(2), 380-384.
18. Baker, D., & Newton, R.U. (2005). Methods to increase the effectiveness of maximal power training for the upper-body. *Strength and Conditioning Journal, 27*(6), 24-32.
19. Markovic, G., & Jaric, S. (2007). Positive and negative loading and mechanical output in maximum vertical jumping. *Medicine and Science in Sports and Exercise, 39*(10), 1757-1764.
20. Weyand, P.G., Sternlight, D.B., Bellizzi, M.J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology, 89*(5), 1991-1999.
21. Knudson, D.V. (2009). Correcting the use of the term "power" in the strength and conditioning literature. *Journal of Strength and Conditioning Research, 23*(6), 1902-1908.
22. Crewther, B.T., Cronin, J., & Keogh, J.W. (2008). The contribution of volume, technique, and load to single-repetition and total-repetition kinematics and kinetics in response to three loading schemes. *Journal of Strength and Conditioning Research, 22*(6), 1908-1915.
23. Comfort, P., McMahon, J.J., & Fletcher, C. (2013). No kinetic differences during variations of the power clean in inexperienced female collegiate athletes. *Journal of Strength and Conditioning Research, 27*(2), 363-368.
24. Kawamori, N., Crum, A.J., Blumert, P.A., Kulik, J.R., Childers, J.T., Wood, J.A., et al. (2005). Influence of different relative intensities on power output during the hang power clean: identification of the optimal load. *Journal of Strength and Conditioning Research, 19*(3), 698-708.
25. Lake, J.P., Lauder, M.A., & Smith, N.A. (2012). Barbell kinematics should not be used to estimate power output applied to the Barbell-and-body system center of mass during lower-body resistance exercise. *Journal of Strength and Conditioning Research, 26*(5), 1302-1307.
26. Argus, C.K., Gill, N.D., Keogh, J.W., & Hopkins, W.G. (2011). Assessing lower-body peak power in elite rugby-union players. *Journal of Strength and Conditioning Research, 25*(6), 1616-1621.
27. Baker, D. (2001). A series of studies on the training of high-intensity muscle power in rugby league football players. *Journal of Strength and Conditioning Research, 15*(2), 198-209.
28. Drinkwater, E.J., Galna, B., McKenna, M.J., Hunt, P.H., & Pyne, D.B. (2007). Validation of an optical encoder during free weight resistance movements and analysis of bench press sticking point power during fatigue. *Journal of Strength and Conditioning Research, 21*(2), 510-517.
29. Frost, D.M., Cronin, J.B., & Newton, R.U.

(2008). A comparison of the kinematics, kinetics and muscle activity between pneumatic and free weight resistance. *European Journal of Applied Physiology, 104*(6), 937-956.
30. Newton, R.U., Kraemer, W.J., Hakkinen, K., Humphries, B.J., & Murphy, A.J. (1996). Kinematics, kinetics, and muscle activation during explosive upper body movements. *Journal of Applied Biomechanics, 12*, 31-43.
31. Newton, R.U., Murphy, A.J., Humphries, B.J., Wilson, G.J., Kraemer, W.J., & Hakkinen, K. (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *European Journal of Applied Physiology, 75*(4), 333-342.
32. Lake, J., Lauder, M., Smith, N., & Shorter, K. (2012). A comparison of ballistic and nonballistic lower-body resistance exercise and the methods used to identify their positive lifting phases. *Journal of Applied Biomechanics, 28*(4), 431-437.
33. Bobbert, M.F. Effect of unloading and loading on power simulated countermovement and squat jumps. *Medicine and Science in Sports and Exercise*, Epub ahead of print, 2013, Nov 2015.
34. Frost, D.M., Cronin, J.B., & Newton, R.U. (2008). Have we underestimated the kinematic and kinetic benefits of non-ballistic motion? *Sports Biomechanics, 7*(3), 372-385.
35. Lake, J.P., & Lauder, M.A. (2012). Mechanical demands of kettlebell swing exercise. *Journal of Strength and Conditioning Research, 26*(12), 3209-3216.
36. Hori, N., Newton, R.U., Kawamori, N., McGuigan, M.R., Andrews, W.A., Chapman, D.W., et al. (2008). Comparison of weighted jump squat training with and without eccentric braking. *Journal of Strength and Conditioning Research, 22*(1), 54-65.
37. Swinton, P.A., Stewart, A., Agouris, I., Keogh, J.W., & Lloyd, R. (2011). A biomechanical analysis of straight and hexagonal barbell deadlifts using submaximal loads. *Journal of Strength and Conditioning Research, 25*(7), 2000-2009.
38. Bobbert, M.F., Gerritsen, K.G., Litjens, M.C., & Van Soest, A.J. (1996). Why is countermovement jump height greater than squat jump height? *Medicine and Science in Sports and Exercise, 28*(11), 1402-1412.
39. Cormie, P., McGuigan, M.R., & Newton, R.U. (2011). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Medicine, 41*(2), 125-146.
40. Cormie, P., McGuigan, M.R., & Newton, R.U. (2011). Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports Medicine, 41*(1), 17-38.
41. Comfort, P., Fletcher, C., & McMahon, J.J. (2012). Determination of optimal loading during the power clean, in collegiate athletes. *Journal of Strength and Conditioning Research, 26*(11), 2970-2974.
42. Cormie, P., McGuigan, M.R., & Newton, R.U. (2010). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise, 42*(8), 1582-1598.
43. Dugan, E.L., Doyle, T.L., Humphries, B., Hasson, C.J., & Newton, R.U. (2004). Determining the optimal load for jump squats: a review of methods and calculations. *Journal of Strength and Conditioning Research, 18*(3), 668-674.
44. Harris, N.K., Cronin, J.B., & Hopkins, W.G. (2007). Power outputs of a machine squat-jump across a spectrum of loads. *Journal of Strength and Conditioning Research, 21*(4), 1260-1264.
45. Harris, N.K., Cronin, J.B., Hopkins, W.G., & Hansen, K.T. (2008). Squat jump training at maximal power loads vs. heavy loads: effect on sprint ability. *Journal of Strength and Conditioning Research, 22*(6), 1742-1749.
46. Kilduff, L.P., Bevan, H., Owen, N., Kingsley, M.I., Bunce, P., Bennett, M., et al. (2007). Optimal loading for peak power output during the hang power clean in professional rugby athletes. *International Journal of Sports Physiology and Performance, 2*(3), 260-269.
47. Lake, J.P., & Lauder, M.A. (2012). Kettlebell swing training improves maximal and explosive strength. *Journal of Strength and Conditioning Research, 26*(8), 2228-2233.
48. Li, L., Olson, M.W., & Winchester, J.B. (2008). A

proposed method for determining peak power in the jump squat exercise. *Journal of Strength and Conditioning Research, 22*(2), 326-331.
49. Lyttle, A.D., Wilson, G.J., & Ostrowski, K.J. (1996). Enhancing performance: Maximal power versus combined weights and plyometrics training. *Journal of Strength and Conditioning Research, 10*(3), 173-179.
50. Newton, R.U., Rogers, R.A., Volek, J.S., Hakkinen, K., & Kraemer, W.J. (2006). Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *Journal of Strength and Conditioning Research, 20*(4), 955-961.
51. Thomas, G.A., Kraemer, W.J., Spiering, B.A., Volek, J.S., Anderson, J.M., & Maresh, C.M. (2007). Maximal power at different percentages of one repetition maximum: influence of resistance and gender. *Journal of Strength and Conditioning Research, 21*(2), 336-342.
52. Wilson, G.J., Newton, R.U., Murphy, A.J., & Humphries, B.J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise, 25*(11), 1279-1286.
53. Winchester, J.B., McBride, J.M., Maher, M.A., Mikat, R.P., Allen, B.K., Kline, D.E., et al. (2008). Eight weeks of ballistic exercise improves power independently of changes in strength and muscle fiber type expression. *Journal of Strength and Conditioning Research, 22*(6), 1728-1734.
54. Chiu, L.Z.F. (2008). Does an optimal load exist for power training? *Strength and Conditioning Journal 30*(2), 67-68.
55. Comfort, P., Allen, M., & Graham-Smith, P. (2011). Kinetic comparisons during variations of the power clean. *Journal of Strength and Conditioning Research, 25*(12), 3269-3273.
56. Cormie, P., McBride, J.M., & McCaulley, G.O. (2007). Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics, 23*(2), 103-118.
57. Dowling, J.J., & Vamos, L. (1993). Identification of kinetic and temporal factors related to vertical jump performance. *Journal of Applied Biomechanics, 9*(2), 95-110.
58. Jaric, S., & Markovic, G. (2013). Body mass maximizes power output in human jumping: A strength-independent optimum loading behaviour. *European Journal of Applied Physiology, 113*(12), 2913-2923.
59. Nibali, M.L., Chapman, D.W., Robergs, R.A., & Drinkwater, E.J. (2013). Influence of rest interval duration on muscular power production in the lower-body power profile. *Journal of Strength and Conditioning Research, 27*(10), 2723-2729.
60. Hori, N., Newton, R.U., Andrews, W.A., Kawamori, N., McGuigan, M.R., & Nosaka, K. (2007). Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *Journal of Strength and Conditioning Research, 21*(2), 314-320.