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# A Biomechanical Evaluation of Resistance

## Fundamental Concepts for Training and Sports Performance

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## Abstract

Newton's second law of motion describes the acceleration of an object as being directly proportional to the magnitude of the net force, in the same direction as the net force and inversely proportional to its mass ($a = F/m$). With respect to linear motion, mass is also a numerical representation of an object's inertia, or its resistance to change in its state of motion and directly proportional to the magnitude of an object's momentum at any given velocity. To change an object's momentum, thereby increasing or decreasing its velocity, a proportional impulse must be generated. All motion is governed by these relationships, independent of the exercise being performed or the movement type being used; however, the degree to which this governance affects the associated kinematics, kinetics and muscle activity is dependent on the resistance type. Researchers have suggested that to facilitate the greatest improvements to athletic performance, the resistance-training programme employed by an athlete must be adapted to meet the specific demands of their sport. Therefore, it is conceivable that one mechanical stimulus, or resistance type, may not be appropriate for all applications. Although an excellent means of increasing maximal strength and the rate of force development, free-weight or mass-based training may not be the most conducive means to elicit velocity-specific adaptations. Attempts have been made to combat the inherent flaws of free weights, via accommodating and variable resistance-training devices; however, such approaches are not without problems that are specific to their mechanics. More recently, pneumatic-resistance devices (variable) have been introduced as a mechanical stimulus whereby the body mass of the athlete represents the only inertia that must be overcome to initiate movement, thus potentially affording the opportunity to develop velocity-specific power. However, there is no empirical evidence to support such a contention. Future research should place further emphasis on understanding the mechanical advantages/disadvantages inherent to the resistance types being used during training, so as to elicit the greatest improvements in athletic performance.

Dynamic strength training can be classified into the following three different categories: (i) constant, isoinertial or free-weight resistance; (ii) accommodating resistance; and (iii) variable resistance, based on the nature in which the resistance is imposed/applied on the contracting musculature,[1] thereby resulting in significant differences in the associated kinetics, kinematics and muscle activity.[2-5] However, to date, the majority of research into resistance training is conducted with the aim of examining specific performance parameters, while failing to address or even understand the biomechanical determinants underlying the resistance or muscular effort being used. An increased understanding of the biomechanical properties that govern each resistance type, and/or how they can be manipulated, will provide the researcher, clinician and practitioner with a much greater appreciation of the benefits and limitations associated with each resistance-training mode. With this in mind, we will briefly introduce some mechanical formulae that are important for understanding the mechanics of loading muscle.

Newton's second law of motion (law of acceleration) dictates that the acceleration of an object, as produced by a force, is directly proportional to the magnitude of the net force, in the same direction as the net force and inversely proportional to its mass. For example, an object with a smaller mass requires less force to elicit the same acceleration (see equation 1):

$$F_{net} = m \times a \qquad \text{(Eq. 1)}$$

where $F_{net}$ is the sum of all external forces acting on the object (N), m is the mass of the object (kg) and a is the acceleration of the object (m/sec$^2$). For example, see equation 2:

$$F_{net} = \sum F_{ext} = F_{app} + F_{load} \qquad \text{(Eq. 2)}$$

where $F_{ext}$ is equal to $F_{net}$ (N), $F_{app}$ is the force being applied by the athlete (N) and $F_{load}$ is resistive force of the load (N). The acceleration of an object can also be defined as a first-order derivative of the velocity time curve, or the change in velocity over a specific period of time (see equation 3):

$$a = (v_2 - v_1)/(t_2 - t_1) \qquad \text{(Eq. 3)}$$

where $v_2$ is the velocity (m/sec) of the object at time, $t_2$ (seconds) and $v_1$ is the velocity (m/sec) of the object at time, $t_1$ (seconds). Therefore, equation 1 can be expressed as follows (see equation 4):

$$F_{net} = m \times (v_2 - v_1)/(t_2 - t_1) \qquad \text{(Eq. 4)}$$

By rearranging and expanding equation 4 we get equation 5:

$$F_{net} \times (t_2 - t_1) = (m \times v_2) - (m \times v_1) \qquad \text{(Eq. 5)}$$

Newton's first law of motion (law of inertia) describes how an object at rest will remain at rest and an object in motion will remain in motion with the same magnitude and direction of velocity unless acted on by an unbalanced force. An object's resistance to a change in its state of motion, defined as its inertia, is directly proportional to its mass (mass of an object is a numerical value of its inertia). Once an object acquires a velocity, it can also be characterized as having momentum, which is the product of its mass and velocity (see equation 6):

$$p = m \times v \qquad \text{(Eq. 6)}$$

where p is the momentum of the object (kg • m/sec). By comparing equation 6 with equation 5, it is evident that the change in the momentum of an object is directly proportional to the magnitude and duration of the net force on the object (impulse); however, for resistance-training applications in which the net force does not remain constant (as a result of changing mechanical and physiological advantage) during the muscular action, equation 5 must be integrated with respect to time to provide a representation of the change in momentum that occurs over the entire muscular effort (see equation 7):

$$\int_{t1}^{t2} F_{net} \times dt = m \times \int_{t1}^{t2} dv \qquad \text{(Eq. 7)}$$

where $\int_{t1}^{t2} F_{net} \times dt$ is the integral of the force-time curve (n • sec) between time t2 and time t1, and $\int_{t1}^{t2} dv$ is the integral of the velocity (m/sec) between time t2 and time t1.

Newton's third law (law of action/reaction) affirms that for every action, there is an equal and opposite reaction, implying that each time an athlete applies a force against an object, an equivalent force in the opposite direction is exerted on the athlete by the object (see equation 8):

$$F_{app} = -F_{react} \qquad \text{(Eq. 8)}$$

where $F_{app}$ is the sum of the net force and the resistive force of the load and $F_{react}$ is the force exerted by the object on the athlete. The product of this applied force and the object's resultant movement velocity (v) is defined as the power output (P) of the system, as measured in watts (W) for a specific instant in time (see equation 9).

$$P = F_{app} \times v \qquad \text{(Eq. 9)}$$

In the subsequent sections of this review, these kinetic and kinematic formulae will be discussed with respect to each resistance type. Understanding the biomechanical differences between these resistance types will allow researchers and strength coaches alike to utilize the resistance-training mode that is most conducive to their specific exercise or training goal. Although not the focus of this review, it is important to note that the calculation and reporting of some variables (e.g. power) will depend on the inclusion or exclusion of bodyweight. An athlete's performance is often dictated by their ability to generate sufficient force to move a load at a given velocity, and for the purpose of understanding various resistance types, it must be realized that bodyweight is a load (bodyweight = $m \times g$) and must be included in all kinematic and kinetic calculations. Because there remains to be consistency in the literature in regards to the reporting of such variables for whole-body movements (e.g. squats), the discussion in this review will be focused on the bench-press movement (limited bodyweight involved), unless otherwise stated.

## 1. Constant Resistance

Dynamic training with constant resistance, or isoinertial training,[6,7] is characterized by exercises in which the entire resistive force is dependent on the mass of the object being lifted (force = mass × [gravity + acceleration]), and is currently the most widely used method to enhance strength and power capacity for sport. The use of constant resistance, or free weight, allows the strength coach/practitioner to prescribe sport-specific, multiple-joint efforts that involve both concentric and eccentric muscular actions, at various velocities. However, to increase the movement velocity, and thus the acceleration, a proportional increase in the net force is required when using the same load (equation 1). As a result, an athlete's ability to move quickly might be limited by his/her rate of force development, potentially resulting in the development of force-specific and not velocity-specific power. Furthermore, when using constant resistance, athletes may not be able to elicit maximal activation of the primary musculature throughout the entire range of motion[8] as a result of mechanical advantages or disadvantages at specific joint angles. This can result in significant reductions in movement velocity and power output during the early and/or later stages of the concentric phase.[9]

Researchers have investigated the kinematics and kinetics of various non-ballistic (concentric-only, stretch-shortening cycle [SSC]) and ballistic constant resistance efforts with the intent of identifying possible mechanical benefits that may lead to improved transference to sport performance. A concentric-only, non-ballistic effort differs from SSC and ballistic movements in that the concentric phase begins without any pre-load from the eccentric phase and it ends without projecting the load into free space, respectively. Given that each of these efforts has different mechanical characteristics, each should be investigated separately to determine their role as a stimulus for strength and power adaptation.

## 1.1 Concentric Only

The initiation of the concentric (ascending) phase during constant resistance movements requires that the applied force be greater than the weight of the load, thus resulting in a net force and a proportional acceleration in the positive direction (equation 2).

### *1.1.1 Kinematics and Kinetics*

#### Velocity

Mean concentric velocity is a function of the displacement and duration of the concentric action. Therefore, the mean movement velocity should increase proportionally with a decrease in movement duration, assuming that the displacement (dictated in the bench press by limb length) is unchanged. Cronin et al.[2] have shown that an increase in the mean velocity is associated with a decrease in both the duration of the concentric phase and the magnitude of the load lifted, although such changes are not proportional (table I). Using the mean velocities and the durations of the concentric phase reported by Cronin et al.[2] for loads of 30–80% of the one repetition maximum (1RM), the calculated displacement was found to vary by as much as 0.169 metres. Because of the explosive nature of the efforts performed, such a difference in the displacement is likely due to greater protraction of the scapula with lighter loads.

Similar to the mean concentric velocity, greater peak concentric velocities are produced with lighter loads. However, Cronin et al.[2] reported that a 100% increase in mean velocity necessitated a 37.5% reduction in the load, whereas a 50% reduction in load was required to attain an equivalent increase in the peak velocity (tables I and II). Conversely, the time to peak velocity, a key variable of interest among researchers,[9,12,13] was greater for heavier loads, even when expressed as a percentage of the total duration of the concentric phase (table I). Its position marks the point at which acceleration is equal to zero (equation 3), and the applied force is equivalent to the load (equation 2) and, thus, the separation of the acceleration and deceleration phases of the movement. These results highlight one of the major disadvantages of using constant resistance for high-velocity training: lighter loads are required to increase the movement velocity (1.49 vs 0.68 m/sec for 30% and 80% 1RM loads, respectively) but this is associated with a decrease in the duration of

**Table I.** A comparison of power and velocity across loads[2,10]

| Load | Power | | | | | Velocity | | | |
|---|---|---|---|---|---|---|---|---|---|
| % 1RM | MP | PP | % PP/MP | TPP | % TTP/DC | MV | PV | TPV | % TPV/DC |
| 80 | 232.2 | 515.1 | 221.8 | 0.784 | 63.6 | NA | NA | NA | NA |
| 80 | 207.8 | 440.3 | 211.9 | 0.717 | 61.2 | NA | NA | NA | NA |
| 80 | 222.0 | 478.2 | 215.4 | NA | NA | 0.33 | 0.68 | 0.928 | 82.9 |
| 70 | 266.8 | 542.4 | 203.3 | NA | NA | 0.36 | 0.86 | 0.774 | 80.3 |
| 60 | 280.8 | 549.3 | 196.0 | NA | NA | 0.55 | 1.01 | 0.620 | 75.8 |
| 60 | 314.6 | 572.7 | 182.0 | 0.595 | 71.3 | NA | NA | NA | NA |
| 60 | 237.6 | 501.8 | 211.2 | 0.564 | 67.3 | NA | NA | NA | NA |
| 50 | 271.1 | 552.1 | 203.7 | NA | NA | 0.64 | 1.16 | 0.528 | 69.4 |
| 40 | 290.8 | 613.6 | 211.0 | 0.452 | 65.7 | NA | NA | NA | NA |
| 40 | 201.1 | 445.1 | 221.3 | 0.434 | 63.0 | NA | NA | NA | NA |
| 40 | 250.0 | 532.0 | 212.8 | NA | NA | 0.73 | 1.35 | 0.459 | 67.2 |
| 30 | 211.1 | 467.4 | 221.4 | NA | NA | 0.82 | 1.49 | 0.401 | 63.8 |

**1RM** = one repetition maximum; **DC** = duration of concentric phase (sec); **MP** = mean power (W); **MV** = mean velocity (m/sec); **NA** = not reported/could not calculate; **PP** = peak power (W); **PV** = peak velocity; **TPP** = time to PP (sec); **TPV** = time to PV (sec).

the acceleration phase during the concentric effort; 63.8% and 82.9% of the duration of the concentric phase for 30% and 80% 1RM loads, respectively.[2]

### Acceleration and Force

Distinct start- and endpoints of the concentric phase, at which the movement velocity is zero, result in a mean acceleration of zero for all non-ballistic movements (equation 3). Furthermore, since force is directly proportional to the acceleration of the load, the mean net force will be equal to zero and the mean applied force will be equivalent to the weight of the load (equation 1), regardless of mass. This is illustrated in table II; mean forces are equal to the load lifted despite differences in strength or percentage of the 1RM being used.

The magnitude of the peak force produced is directly proportional to the peak acceleration and the mass (inertia) of the object (equation 1); thus, to achieve greater concentric accelerations, peak force must be equal to a higher percentage of the object weight (table II). However, the peak force required with a specific load to elicit an acceleration or movement velocity similar to athletic performance may not be achievable. Therefore, a lighter load must be lifted to produce the desired acceleration (table II), possibly reducing the training specificity; with constant resistance, concentric-only efforts, extremely light loads may not provide an appropriate training stimulus even if the acceleration is high at the onset of the movement; peak force (acceleration) has been shown to occur at the onset of the concentric action,[9,11] which in turn leads to more variation in the force curve, greater changes in momentum[2,12,14] and, thus, may be one of the reasons for an extended deceleration phase. The displacement-limited nature of these efforts requires that the movement velocity be zero at the end of the concentric phase; thus, larger accelerations will need to be matched by larger decelerations or an extended deceleration phase. Therefore, concentric-only, non-ballistic movements may be an appropriate stimulus to improve an athlete's rate of force development; however, caution must be exercised since this will occur in concert with a reduction in velocity towards the end range of movement.[13]

### Power

Power output, as defined in equation 9, is a function of the applied force and movement velocity of an object. Researchers and practitioners alike have regarded improvements in power output as being important in improving athletic performance.[15-18] Since mean acceleration

 

**Table II.** A comparison of force and acceleration across loads[2,3,9,11]

| Load | | | Force | | | | Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|
| % 1RM | W | M | MF | PF | % PF/W | % PPF/TCD | MA | PA | DC |
| 100 | 1668 | 170.0 | NA | NA | NA | NA | NA | 2.08 | 2.27 |
| 100 | 2349 | 239.5 | NA | 2621 | 111.6 | 2.46 | NA | 1.91 | 1.14 |
| 100 | 1814 | 184.9 | NA | 2004 | 110.5 | 2.60 | NA | 2.21 | 1.00 |
| 100 | 995 | 101.4 | NA | 1349 | 135.6 | 2.49 | NA | 3.54 | 1.76 |
| 90 | 1370 | 139.7 | NA | 2003 | 146.2 | NA | NA | NA | 1.30 |
| 81 | 1381 | 140.8 | NA | NA | 112.1 | 4.38 | NA | NA | NA |
| 80 | 677 | 69.0 | 678 | 826 | 122.0 | NA | 0.00 | 1.93 | 1.12 |
| 75 | 1138 | 116.0 | NA | 2097 | 184.3 | NA | NA | NA | 0.86 |
| 70 | 593 | 60.4 | 589 | 766 | 129.3 | NA | 0.06 | 2.43 | 0.96 |
| 60 | 508 | 51.8 | 509 | 661 | 130.0 | NA | 0.03 | 2.96 | 0.82 |
| 50 | 423 | 43.2 | 429 | 584 | 138.0 | NA | 0.14 | 3.78 | 0.76 |
| 40 | 339 | 34.5 | 340 | 506 | 149.4 | NA | –0.03 | 4.63 | 0.68 |
| 30 | 254 | 25.9 | 258 | 414 | 163.0 | NA | 0.15 | 5.87 | 0.63 |

**1RM** = one repetition maximum; **DC** = duration of concentric phase (sec); **M** = mass of load (kg); **MA** = mean acceleration (m/sec$^2$); **MF** = mean force (N); **NA** = not reported/could not calculate; **PA** = peak acceleration (m/sec$^2$); **PF** = peak force (N); **PPF** = position of peak force (m); **TCD** = total concentric displacement (m); **W** = weight of free weight load (N).

and mean net force for non-ballistic movements are both zero, the mean concentric power becomes a product of the magnitude of the resistance (force) and the mean movement velocity over the concentric phase. However, identifying the degree to which each variable (force and velocity) contributes may prove to be of greater theoretical and practical significance. Most researchers continue to report an optimal load that disregards separate force and velocity contributions,[2,10,12,15-30] which could limit the transference to athletic performance. Although it has been stated that maximum power is developed at one-third of the maximum speed and one-quarter of the maximum force,[24,31] figure 1 depicts the potential effect of increasing either the maximal strength or peak velocity on the power output of muscle; both require an alteration in the force capability, but are the product of different training stimuli.

Cronin et al.[2] reported minimum and maximum mean power outputs for the concentric phase of the bench press of 211 W (30% 1RM) and 281 W (60% 1RM), respectively (table II). Extrapolating their force and velocity data from tables I and II (figure 2) using a second-order polynomial, maximum force and velocity were estimated at 1120 N and 2.20 m/sec, respectively. These values were subsequently used to determine the respective contributions of force and velocity for each power output, expressed as a percentage of the maximum (table III).

Maximum mean power was produced with approximately one-half (45.4%) of the maximum force and one-quarter (25.0%) of the maximum velocity for a non-ballistic, concentric-only bench press (table III). Such an analysis might provide greater insight into the components that contribute to power output, which may in turn be used to monitor and programme for power development in a more systematic and sport-specific fashion (e.g. monitoring the effects of

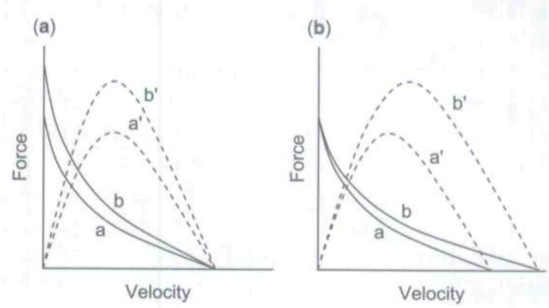


**Fig. 1.** The effect of increasing: (**a**) maximal strength; and (**b**) contraction velocity of muscle on power output (dashed line). **a** = before; **b** = after.

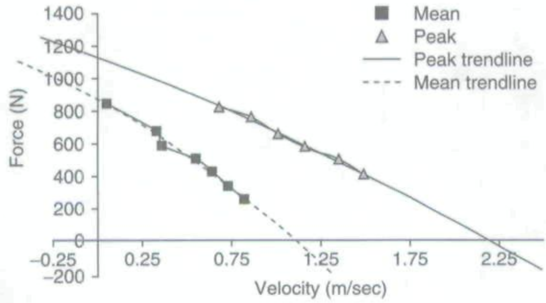


**Fig. 2.** Extrapolated force and velocity curves (reproduced from Cronin et al.,[2] with permission from Lippincott Williams & Wilkins).

different training methods on either the force or velocity capabilities of muscle, with the aim of determining whether an athlete is force or velocity deficient). In this example, maximum mean power during constant resistance exercise appeared to have a greater dependence on the applied force than the movement velocity (table III). In such cases, it may be advantageous to attempt to increase the movement velocity contribution to power output and, thus, the transference to sport performance. However, as previously outlined, loading with constant resistance necessitates a proportional increase in force to attain this velocity, which in turn limits the possibility of achieving such training goals.

Peak power must be identified via an analysis of the force-velocity curve for each of the loads, which makes a similar extrapolation of the data impossible. Table I shows similar peak power outputs for all loads between 30% and 80% 1RM, despite reports stating that a load of 40–60% 1RM is optimal for producing maximum power.[2,10] Furthermore, as reported by Cronin et al.,[10] time to peak power is reduced with a subsequent decrease in the load, although there is little difference when it is expressed as a percentage of the total concentric duration (table I). However, as can be seen in table I, the point of the concentric phase at which peak velocity occurs is reduced with a decrease in load. Therefore, the contributions from force and velocity are changing despite similar power outputs. If velocity-specific power is of greater importance to improving sport specificity, then future research should separate the components of power output to better understand the adaptations to training with various loads.

### Concentric Phases

Lander et al.[3] has proposed that concentric action of a constant resistance, non-ballistic movement actually involves two acceleration and deceleration phases when using loads between 75% and 100% of the 1RM. The first and true acceleration phase is defined as the initial portion of the ascending phase that describes the period of maximum acceleration, whereas the late stages described by the period of maximum deceleration is defined as the second and true deceleration phase. The middle portion of the ascent is composed of the first deceleration phase, or the sticking region, and is defined as the portion of the effort where the applied force falls below the weight of the load. The second acceleration phase, or the maximum strength region, is defined as the period where the applied force becomes greater than the load for the second time (figure 3).

**Table III.** Force and velocity contributions to concentric-only and stretch-shortening cycle (SSC) mean power [reproduced from Cronin et al.,[2] with permission from Lippincott Williams & Wilkins]

| Load | Concentric only | | | SSC | | |
|---|---|---|---|---|---|---|
| % 1RM | MP (W) | % MF/$F_{max}$ | % MV/$V_{max}$ | MP (W) | % MF/$F_{max}$ | % MV/$V_{max}$ |
| 80 | 222.0 | 60.5 | 15.0 | 261.3 | 60.6 | 17.7 |
| 70 | 266.8 | 52.6 | 16.4 | 316.3 | 53.5 | 24.1 |
| 60 | 281.8 | 45.4 | 25.0 | 315.4 | 45.8 | 28.2 |
| 50 | 271.1 | 38.3 | 29.1 | 312.8 | 38.1 | 34.1 |
| 40 | 250.0 | 30.3 | 33.2 | 283.1 | 30.4 | 37.7 |
| 30 | 211.1 | 23.0 | 37.3 | 237.0 | 23.4 | 41.4 |

**1RM** = one repetition maximum; $\mathbf{F_{max}}$ = maximum force (N); **MF** = mean force (N); **MP** = mean power (W); **MV** = mean velocity (m/sec); $\mathbf{V_{max}}$ = maximum velocity (m/sec).

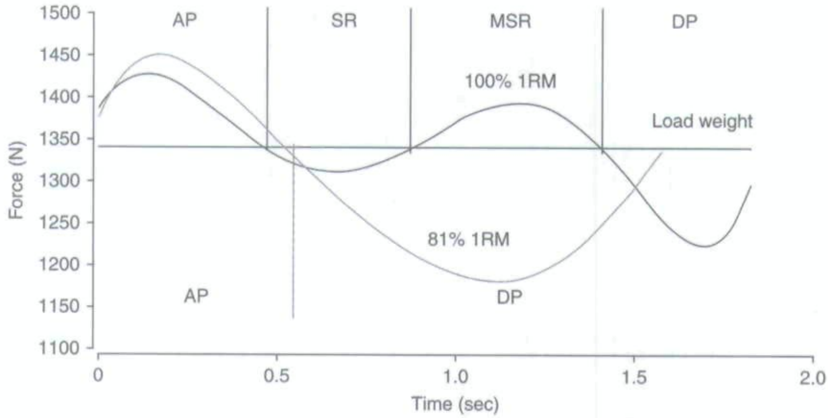


**Fig. 3.** Force-time curve for 81% and 100% one repetition maximum (1RM) loads (reproduced from Elliott et al.,[9] from Lippincott, Williams & Wilkins). **AP** =acceleration phase; **DP** = deceleration phase; **MSR** = maximum strength region; **SR** = sticking region.

Using athletes with similar bench-press experience, Elliott et al.[9] found that a 100% 1RM load produced the same four phases as reported by Lander et al.;[3] however, an 81% load was described as having one acceleration and deceleration phase (figure 3). The researchers suggested that the differences between the two studies could have resulted from the sequencing of the lifts: the heavier load was lifted first in the study by Lander et al.,[3] resulting in muscular fatigue and, thus, a reduced ability to accelerate the load through the sticking region. Although Elliott et al.[9] reported that only 48.3% of the concentric phase was spent accelerating with a load of 81% of the 1RM, combining the duration of the acceleration phase and maximum strength region and the sticking region and deceleration phase for the 100% 1RM condition resulted in similar acceleration and deceleration durations (47.9% and 52.1%, respectively). Expressed as the point of the concentric phase at which peak velocity occurred, Cronin et al.[2] reported acceleration phases lasting between 63.8% and 82.9% of the duration of the concentric effort for loads of 30–80% 1RM, respectively (table II). However, force and velocity profiles were not described, making it difficult to determine whether the curves were similar to the 81% or 100% 1RM load as shown in figure 3. Changing the load lifted or the way a repetition is performed may alter the point at which peak velocity occurs and, thus, the duration of the acceleration phase; however, in the absence of the force and velocity data for the entire concentric movement, conclusions may be misrepresentative.

Regardless of the attempts made to increase the length of the acceleration phase during a non-ballistic movement, mean force will always equal the weight of the load. This implies that if a higher peak force is achieved early in the concentric phase, a subsequent decrease in force will be seen during the later stages of the movement or, conversely, if the time to peak velocity is delayed and the subsequent acceleration phase is longer, there will be a greater decline in force and a drastic deceleration at the conclusion of the concentric phase. This highlights another disadvantage of using non-ballistic, constant resistance movements; the peak forces required to elicit high-movement velocities will cause greater variation in the force-displacement curves, via accentuated accelerations and decelerations, which will lead to changes in the muscle activity and might increase the risk of injury.[13]

#### *1.1.2 Muscle Activity*

Elliott et al.[9] has reported large sustained increases of the agonist musculature during the acceleration phase of a concentric effort. However, once the load begins to decelerate, muscle activity subsides and subsequent reductions in agonist activity are seen. Using 60% and 80%

1RM loads, McCaw and Friday[5] found that peak triceps brachii activity occurred at 70% and 60% of the total concentric duration, peak anterior deltoid activity was produced at approximately 60% and 75%, although this dropped dramatically after an additional 10% duration, and peak pectoralis major activity occurred at 17% and 10%, although this was halved after completing only 50% of the movement. An inability to maintain a greater percentage of the maximum activity throughout the entire range of motion may inhibit an athlete's ability to maximize any number of kinetic and kinematic variables (e.g. power, force and velocity); however, such a contention requires further investigation.

Researchers have reported antagonist activity;[5,9,32,33] however, additional research is required to investigate the electromyographic profiles, particularly during high-velocity movements. A stronger antagonist will allow for a shorter deceleration phase, thus enabling the agonists to develop higher movement velocities,[34] although, as stated above, this may increase the risk of injury.[13]

## 1.2 Stretch-Shortening Cycle

Muscle actions in which the concentric action is immediately preceded by an eccentric action (pre-stretch) are referred to as SSC movements.[35] Use of the SSC alters the profiles of several kinetic, kinematic and electromyographic variables because of the inertial properties of mass and the physiological characteristics of the muscle. Researchers have shown that a pre-stretch can increase mean velocity and power output by as much as 16% and 6%, respectively,[2,21,36-38] although the mechanisms responsible for the augmentation to the concentric action remain unclear. Potential mechanisms include the utilization of elastic strain energy stored in the series elastic component, reflexively induced neural input and a higher active muscle state prior to the onset of the concentric muscle action; however, a detailed explanation of each is beyond the scope of this review and the authors refer those interested to several papers on this topic.[10,12,35,36,38-43]

### *1.2.1 Kinematics and Kinetics*

#### Velocity

Similar to concentric-only non-ballistic movements, the mean velocity of non-ballistic SSC movements is equal to the change in displacement divided by the duration of the displacement. However, it has been consistently shown that the use of a pre-stretch can augment the velocity curve by decreasing the duration of the concentric phase.[2,36-38] Cronin et al.[2] reported that mean velocity could be increased by as much as 47% with a 70% 1RM load and by an average of 20% across loads of 30–80% 1RM (table IV). Similarly, using ballistic efforts, Newton et al.[12] presented an average increase of 30%, with the largest increase being produced with the greatest load tested (90% 1RM).

Conversely, the use of an SSC has been unable to elicit any change in the peak velocity or the time to peak velocity, expressed as a percentage of the total concentric duration, at any load tested.[2,12]

As can be observed in equation 4, the change in movement velocity over a specific duration is proportional to the net force being applied and inversely proportional to the mass of the load being lifted. Therefore, an increase in mean velocity requires that a greater force be generated over the same time or that the same force be applied over a longer time. However, changing the peak velocity necessitates the production of greater accelerations over the same period of time, or the same acceleration over a longer period of time. If it is not possible to extend the duration, as is the case during movements with a fixed range of motion (e.g. limb length), larger accelerations and, thus, larger forces are needed. This may be difficult to accomplish with constant resistance.

#### Acceleration and Force

For non-ballistic SSC movements, mean acceleration and, thus, mean force are zero since there is no change in the velocity between the start and end of the muscular effort. Conversely, peak acceleration and peak force have been shown to increase by as much as 69.5% and

**Table IV.** A comparison of the velocity and power between a concentric-only and stretch-shortening cycle (SSC) bench press [reproduced from Cronin et al.,[2] with permission from Lippincott Williams & Wilkins]

| Load | Concentric only | | | | | SSC | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| % 1RM | MV | PV | % TPV/DC | MP | PP | MV | PV | % TPV/DC | MP | PP |
| 80 | 0.33 | 0.68 | 82.9 | 222.0 | 478.2 | 0.39 | 0.65 | 75.4 | 261.3 | 468.9 |
| 70 | 0.36 | 0.86 | 80.3 | 266.8 | 542.4 | 0.53 | 0.83 | 76.2 | 316.3 | 542.3 |
| 60 | 0.55 | 1.01 | 75.8 | 280.8 | 549.3 | 0.62 | 0.99 | 73.8 | 315.4 | 550.6 |
| 50 | 0.64 | 1.16 | 69.4 | 271.1 | 552.1 | 0.75 | 1.21 | 68.7 | 312.8 | 557.9 |
| 40 | 0.73 | 1.35 | 67.2 | 250.0 | 532.0 | 0.83 | 1.37 | 66.2 | 283.1 | 536.3 |
| 30 | 0.82 | 1.49 | 63.8 | 211.1 | 467.4 | 0.91 | 1.52 | 56.7 | 237.0 | 463.2 |

**1RM** = one repetition maximum; **DC** = duration of concentric phase (sec); **MP** = mean power (W); **MV** = mean velocity (m/sec); **PP** = peak power (W); **PV** = peak velocity (m/sec); **TPV** = time to PV (sec).

19.0% at loads of 70% and 60% 1RM, respectively (table V).

An SSC movement requires sufficient force to reduce the eccentric velocity of the load to zero prior to beginning the concentric action (figure 4). As can be observed in figure 4, the change in momentum is directly proportional to the change in velocity and the mass of the load. This change in momentum is also proportional to the force that is causing such a change, and the duration over which the change takes place (see equation 5). Compared with a non-ballistic, concentric-only movement that requires no reduction in eccentric velocity, the sum of the external forces (equation 2) may be greater, thus changing the external demands placed on the athlete. Consequently, higher accelerations may be produced during the initial portion of the concentric action, although this is not always the case. Without a subsequent increase in the peak velocity or duration of the acceleration phase, it is difficult to speculate as to whether the SSC action alone is advantageous to athletic performance when the movement duration exceeds ~200 ms.[10,12] Perhaps, the benefits of such a movement stem from an ability to utilize the increased force quickly, via muscle tendon interactions in terms of elastic and contractile tension, thus allowing for a greater peak velocity to be achieved. In any case, further research is required to investigate the effects of an increased peak force and, thus, variation in the force-displacement curve, on the kinetic, kinematic and electromyographic profiles during the later stages of the movement.

### Power

Non-ballistic, SSC movements are characterized by mean forces that are identical to the magnitude of the resistance being lifted (equation 1) and mean velocities that are significantly greater than their concentric-only equivalents.[2] Since power is the product of force and velocity, mean power should be increased to the same degree as the mean velocity. Cronin et al.[2] reported an average increase in mean power of 14.8%

**Table V.** A comparison of the acceleration and force between a concentric-only and stretch-shortening cycle (SSC) bench press[2,44]

| Load | Concentric only | | | | SSC | | | |
|---|---|---|---|---|---|---|---|---|
| % 1RM | MA | PA | MF | PF | MA | PA | MF | PF |
| 80 | 0.00 | 1.93 | 677.8 | 826.3 | 0.02 | 3.19 | 679.0 | 906.5 |
| 70 | −0.06 | 2.43 | 588.8 | 766.4 | 0.11 | 4.12 | 599.1 | 876.6 |
| 60 | 0.03 | 2.96 | 509.4 | 660.9 | 0.11 | 4.97 | 513.4 | 786.4 |
| 50 | 0.14 | 3.78 | 429.2 | 583.8 | 0.09 | 6.33 | 427.2 | 692.7 |
| 40 | 0.02 | 4.63 | 339.5 | 505.9 | 0.05 | 7.11 | 340.5 | 596.1 |
| 30 | 0.15 | 5.87 | 257.9 | 414.1 | 0.31 | 8.54 | 262.1 | 491.8 |

**1RM** = one repetition maximum; **MA** = mean acceleration (m/sec$^2$); **MF** = mean force (N); **PA** = peak acceleration (m/sec$^2$); **PF** = peak force (N).

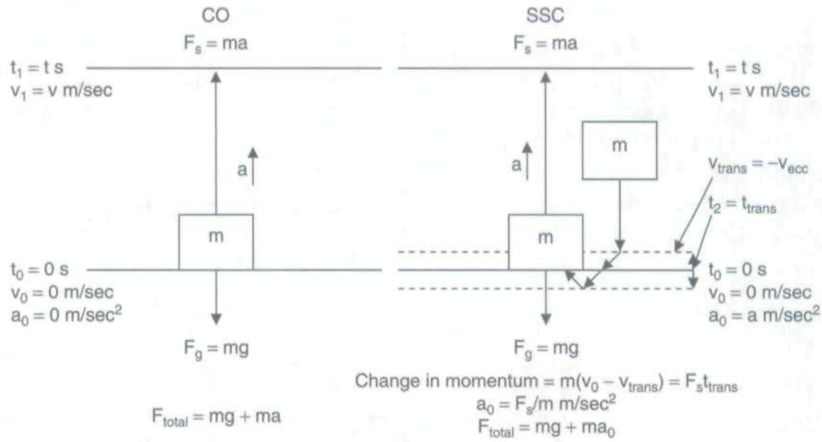


**Fig. 4.** Force contributions during concentric-only (CO) and stretch-shortening cycle (SSC) movements. The total force ($F_{total}$) at time zero ($t_0$), which represents the transition between the eccentric and concentric phase, is the sum of the system weight ($F_g = mg$) and the force due to acceleration ($F_s = ma$). The total force during SSC movements will be greater than the CO equivalent if the acceleration ($a_0$) at this timepoint is greater than zero. The velocity at a specific instant in time ($t_{trans}$), prior to the completion of the eccentric phase, is represented by $v_{trans}$.

(velocity was 20%) across loads of 30–80% 1RM, compared with a concentric-only movement. The increase in mean power production for a SSC movement is a function of the greater relative contribution from velocity (table III). However, upon further examination of the power profiles for SSC actions, significant increases are limited to the initial 200 ms of a movement,[10,12,42,43] and any benefit of the pre-stretch has been reported lost if the concentric duration exceeds 0.37 seconds.[10,41,42]

Cronin et al.[2,10] have provided further support for these claims by finding no difference in the peak power or time to peak power, expressed as a percentage of the concentric duration, between SSC and concentric-only conditions. However, in the absence of any acute or long-term training studies investigating the force and velocity contributions to power output, any conclusions pertaining to the effect of an SSC action on power development, or sport-specific applications may be misleading and/ or misrepresentative.

#### *1.2.2 Muscle Activity*

Although the electromyographic (EMG) profiles of the agonist musculature have been shown to parallel the force profiles for SSC actions,[13] there remains to be sufficient evidence to make definitive claims regarding this relationship. If the mechanism responsible for the augmentation to the concentric action stems from an ability to utilize stored elastic energy, then there should not be any change in the muscle activity at the beginning of the concentric phase. However, if the SSC enhancement is the result of a higher active muscle state, then increases in agonist activity could be expected during the initial duration of the concentric phase. Newton et al.[12] found that pectoralis major and triceps brachii activity were significantly higher during the first 50 ms of the concentric phase for an SSC movement, although no differences were seen when expressed as mean or peak values of the entire repetition. Consequently, additional research is required to verify the underlying mechanism(s), identify the role of the agonist and antagonist musculature throughout an SSC action and improve the transference of these training principles to sport-specific applications.

### 1.3 Ballistic

In the strength-training literature, ballistic denotes accelerative, of high velocity and with projection into free space.[45] Ballistic efforts have been introduced as a potentially superior form of constant resistance training because the athlete is no longer limited by having to decelerate the load at the end of the concentric phase,[12] consequently resulting in higher mean velocity, force and muscle activity. This type of training may also provide a stimulus more representative of athletic movements in which objects are thrown or the body is propelled in a certain direction as quickly as possible.[46]

#### *1.3.1 Kinematics and Kinetics*

Velocity

The mean velocity produced with a ballistic effort is equal to the change in displacement between the onset of the concentric action and the point at which the load is projected, divided by the duration of this phase. Furthermore, it should exceed the mean velocity of a non-ballistic movement performed with the same load. The point at which the load loses contact with the athlete, he/she is no longer able to apply any muscular force and, therefore, any subsequent change in velocity is a result of the force of gravity and should not be included in any kinetic or kinematic calculations. Comparing ballistic and non-ballistic techniques at a load of 45% 1RM, Newton et al.[13] found that projecting the load at the end of the concentric phase increased the mean velocity by 27.3%. Conversely, Cronin et al.[2] reported similar mean velocities between ballistic and non-ballistic efforts for loads ranging from 30% to 80% 1RM; however, the velocity data were calculated by differentiating the entire displacement curve, including the duration of the movement during which the load had been released (the barbell was no longer in contact with the hands but it was still travelling in an upwards direction), making it a non-ballistic analysis.

Ballistic movements have been regarded as a superior form of power training because they allow for a greater portion of the concentric phase to be spent accelerating; 96% compared with 60% of total displacement with a 45% 1RM load,[13] which resulted in a 36.5% increase in peak velocity.[13] However, additional research is required to fully understand the transference of such a stimulus to sport performance.

Acceleration and Force

The kinetics and kinematics of ballistic efforts are not constrained by a predetermined displacement or a final concentric velocity of zero. Consequently, mean acceleration and mean force will both be greater than their non-ballistic equivalent, contrary to some reports.[2] Comparing a ballistic and non-ballistic bench press, Newton et al.[13] found that projecting the load at the end of the concentric phase could increase the mean force by 35%. This finding, in combination with the increases to mean and peak velocity, led the researchers to conclude that ballistic training provided superior loading conditions for the neuromuscular system and a more sport-specific training stimulus. However, projecting the load failed to increase the peak acceleration, peak force or the time to peak force, even when utilizing an intermediate load of 45% 1RM. This implies that the maximum rate of force development or the ability to produce maximal force in minimal time,[24] and the force achieved early in the concentric phase (e.g. 30 ms) or the ability to increase force as rapidly as possible once the effort has begun,[24] was not changed. Participants in the study simply extended the duration of the acceleration phase, thereby increasing the peak velocity, without changing the 'explosiveness' of the movement. Extending the duration of the acceleration phase simply requires that an athlete provide a force greater than the weight of the load over a longer period of time. Increasing the explosiveness of a movement demands that a greater percentage of the absolute maximum force is produced during the initial portion of the concentric effort. With regards to athletic ability, it is important that the practitioner and researcher understand the demands of the sport and the training status of the athlete in question so that they are able to provide the stimulus most conducive to improving performance.

Power

The ability to increase the mean velocity and mean force via ballistic efforts will result in greater mean power (equation 9), provided that the kinetic and kinematic analysis is completed from the point at which the load is projected and does not include data from thereafter. Using a 45% 1RM load, Newton et al.[13] found that mean power could be increased by 70% in comparison to a non-ballistic equivalent, whereas Cronin et al.[2] failed to report any significant differences for loads of 30–80% 1RM. However, the data from Cronin et al.[2] were analysed from the onset of the concentric phase to the point at which the load achieved a velocity of zero, making it a non-ballistic analysis and thereby masking any differences that may have been produced.

Compared with a non-ballistic movement, similar increases in peak power output have been reported,[2] whether performed with or without an SSC action (13.3% and 9.2% for SSC and concentric-only, respectively). Newton et al.[13] reported an increase of 67%, although it was not made clear whether the enhancement was due to a greater contribution from force or velocity. Ballistic training may provide a means of increasing the specificity of training; however, there may be disadvantages associated with a protocol that simply emphasizes the projection of the load (e.g. reduced rate of force development). An in-depth analysis of the force and velocity profiles of ballistic movement is required to fully understand their potential, or limitations, and identify possible means to increase the degree of specificity.

#### *1.3.2 Muscle Activity*

Ballistic movements have been described as having a particular neural pattern of motor unit firing known as the tri-phasic or 'ABC' pattern.[47,48] This pattern is characterized by a large burst of activity by the agonist musculature followed by a brief period of concomitant inactivity of the agonist and activity of the antagonist musculature, concluding finally with a second burst of agonist activity.[47-49] Behm[48] contended that while both the initial agonist and antagonist muscle activity are pre-programmed and immutable, the agonist has the responsibility of driving the movement while the antagonist protects the integrity of the joint and provides greater accuracy. Behm[48] also suggested that the pre-movement silent period of the agonist may help to synchronize the motor units for the subsequent second burst of activity by the agonist musculature, which is largely controlled by sensory feedback.

Because the net force produced during a movement is a trade off between the force of the agonist muscles and the counteracting force of the antagonist muscles, the interaction between these bursts of myoelectrical activity warrants further research. Although more prevalent in trained individuals,[48] the interfering effect of the co-contraction between agonist and antagonist muscles in ballistic movements is reduced with strength training. Therefore, a more efficient control of the ABC pattern may benefit the power athlete.

Newton et al.[13] compared the electromyographic profiles between a non-ballistic and ballistic SSC movement, but did not address the notion of an ABC pattern. The researchers reported increases in the peak and mean EMG for each muscle investigated; pectoralis major (70–84% 1RM and 69–70% 1RM), deltoid (70–93% 1RM and 56–68% 1RM), triceps brachii (59–85% 1RM and 57–68%) and biceps brachii (65–83% 1RM and 61–67% 1RM). The most significant differences were seen during the later portion of the concentric phase, which is reflected by the changes in the force-displacement curve.

Although increasing an individual's muscle activity during the concentric phase of movement may elicit performance improvements, the complexity of intermuscular and intramuscular coordination make a direct correlation highly unlikely.

## 2. Accommodating Resistance

Accommodating resistance training allows for the development of maximal tension throughout the complete range of motion rather than at a particular point.[50] The use of accommodating resistance allows athletes to develop maximal force at various velocities, while being unaffected by the inertial properties of the load. That is, if velocity remains constant for the entire muscular effort, acceleration will be zero, meaning that the force produced is not dependent on the mass of the load. This reportedly results in increased force and motor unit recruitment at training velocities similar to those achieved with a constant resistance equivalent.[4] However, many researchers question the validity and efficiency of these devices because they are biomechanically different from natural movements, and the degrees of freedom, or permissible movement directions, are reduced from six to one.[50]

Currently, there are two types of devices used to accomplish these goals: hydraulics and isokinetics. The kinetics, kinematics and muscle activity associated with both these devices will form the basis of the discussion in this next section.

## 2.1 Hydraulic

Hydraulic devices do not offer a true type of accommodating resistance, in the sense that they do not provide a resistance equal to the force that is being applied.[51] Instead, hydraulic devices provide a resistance that is proportional to the applied force and accommodate for the movement velocity[50] by allowing the user to adjust the opening diameter of a valve that controls the speed at which hydraulic fluid flows through the system;[52,53] the greater the velocity, the greater the resistance.[50]

### *2.1.1 Kinematics and Kinetics*

There are a limited number of researchers who have used hydraulic equipment in their studies[51,53-59] and even fewer who have reported the associated kinetics and kinematics.[53,55] Most studies using hydraulics have tested with isokinetic devices[54,57-59] and simply used these devices as a means of training.

In one of the only studies reporting kinetics, Hortobagyi et al.[53] compared slow (0.037 m/sec) and fast (0.126 m/sec) hydraulic bench-press movements with a 1RM free-weight effort. For the slow and fast conditions, respectively, the mean force was found to be 8.3% greater and 62.6% lower, relative to the free-weight condition. However, the researchers failed to report either peak forces or accelerations, which would have allowed for better comparisons with free weights and an improved insight into the sport-specific training effects of hydraulic resistance.

Burke et al.[55] found that forces equivalent to 171% and 231% of the mean force could be produced with slow (2.5-second) and fast (0.8-second) concentric efforts, respectively. Comparing these results with similar free-weight efforts is difficult because the total displacement was not reported and the subjects in the study by Burke et al.[55] performed the concentric action from a seated position. Cronin et al.[2] found that for a similar concentric duration (0.76 seconds), the peak force produced was only equivalent to 130% of the mean value, suggesting that there are much greater variations in the magnitude of the force-displacement curves for hydraulic resistance.

Telle and Gorman[56] have advocated the combination of free weights and hydraulics as a superior strength-training mode, rationalizing that the inherent disadvantages associated with either type of resistance will compensate for the other. Hydraulic devices provide a resistance that is negligible at the onset of the concentric phase, gradually increases over the duration of the effort and is reduced to zero for the eccentric phase. Despite these claims, researchers and strength coaches alike do not regard hydraulic resistance as a superior stimulus to free weights as it lacks the training specificity thought to be necessary to elicit improvements in athletic performance.

### *2.1.2 Muscle Activity*

At the time of writing this review, the authors were unable to locate any research that had investigated the acute or long-term effect of hydraulic-resistance exercise on muscle activity. Since hydraulics are a form of accommodating resistance, it could be hypothesized that maximum agonist activity is produced; however, this is assuming maximum voluntary efforts, which may not always be the case.

## 2.2 Isokinetic

The concept of isokinetic exercise was introduced in 1967 by Hislop and Perrine[4] as an alternative to isotonic (constant resistance) and isometric exercise. It was proposed that by keeping a constant velocity, and thus zero acceleration, they could provide a more suitable mechanical means of obtaining a maximal concentric effort throughout a range of motion compared with isotonic training, while still allowing for work to be done (work = force × displacement), in contrast to isometric training. Although some degree of generality may exist between single-joint isokinetic efforts and athletic movement, it is thought that being limited to machine use, the lack of mechanical feedback and the absence of an eccentric component on some of the earlier systems do not provide a training stimulus conducive to high degrees of sport specificity; therefore, some researchers have began to challenge the effectiveness of isokinetic dynamometry.[8,50,60,61] However, isokinetics do offer a unique method of altering the kinetics and kinematics associated with resistance training and have assisted in improving our understanding of velocity specificity;[62-64] thus, they are still regarded as an effective means of high-velocity training.

#### *2.2.1 Kinematics and Kinetics*

The majority of studies that have used isokinetic devices as a means of training or testing have attempted to identify a velocity-specific response or an increase in torque over a specific training period.[41,62-68] Few researchers have actually attempted a comparison of the kinetics between isokinetics and other resistance-training modes.[3]

##### Velocity

Isokinetic devices are characterized by their ability to control the movement velocity and keep the acceleration at zero. However, all movement must start from a position of rest, or zero velocity, and terminate in a similar fashion, implying that exercises completed within a specific range of motion will involve some form of an acceleration and deceleration phase.[69,70] Chen et al.[69] has stated that the duration of an isokinetic movement spent at constant velocity and the accuracy of measurements are limited by acceleration, oscillation and deceleration phases of the exercising limb (figure 5). As the movement velocity is increased, the three non-constant velocity phases represent a greater relative portion of the concentric phase,[3,65,69,70] and can limit the constant velocity duration to 16% of the exercise if the movement velocity is high enough.[65]

Although an increase in velocity is associated with a subsequent reduction in force, the magnitude of such a reduction is much less than for constant resistance efforts. A 100% increase in the mean angular velocity of a knee extension only elicited a 10.5% reduction in force, or torque[62] compared with a 37.5% reduction during constant resistance exercise (37.5%).[2] In order to reduce the torque by 37%, researchers have had to increase the angular velocity by 400% (38%),[65] 500% (42%)[62] and 1000% (37%).[66] Furthermore, the group of subjects who required a 1000% increase in velocity were able to attenuate their reduction in force to just 30% after becoming familiarized with the isokinetic device.[66]

##### Acceleration and Force

The load acting in an isokinetic exercise is the result of the mechanical process of energy absorption.[4] Compared with constant resistance exercise in which part of the energy is dissipated with accelerations, isokinetic acceleration is, theoretically, always zero, allowing for complete energy absorption and a resisting force that is proportional to the magnitude of the input.[4] As such, the mean force for an isokinetic movement should be greater than its free-weight equivalent, at a comparable movement velocity. Comparing the force-time profiles of equivalent isokinetic

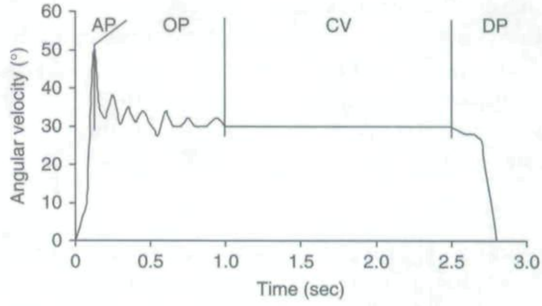


**Fig. 5.** An example isokinetic angular velocity-time curve for a movement performed at 30°/sec (reproduced from Chen et al.,[69] with permission from the Orthopaedic and Sports Physical Therapy Sections of the American Physical Therapy Association). **AP** = acceleration phase; **CV** = constant velocity; **DP** = deceleration phase; **OP** = oscillation phase.

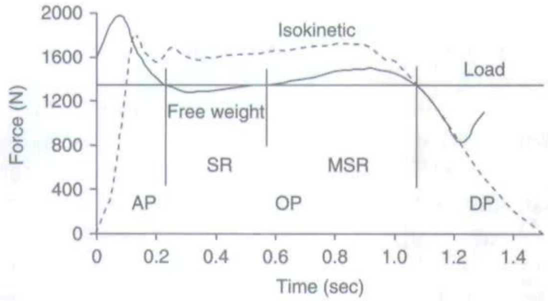


**Fig. 6.** Slow isokinetic (0.45–0.84 rad/sec) and heavy free-weight (90% one repetition maximum) bench press force-time profiles (reproduced from Lander et al.,[3] with permission from Lippincott Williams & Wilkins). **AP** = acceleration phase; **DP** = deceleration phase; **MSR** = maximum strength region; **OP** = oscillation phase; **SR** = sticking region.

and free-weight resistance exercises, Lander et al.[3] reported 5% and 6% greater mean forces during the isokinetic condition when testing at velocities equivalent to a 90% (0.45–0.84 rad/sec) and 75% (0.79–1.61 rad/sec) 1RM lift, respectively. Furthermore, isokinetic mean forces during the sticking and maximum-strength regions (oscillation phase) were equivalent to 130.2% and 116.2% of the 90% 1RM free-weight movement and 133.3% and 126.6% of the 75% 1RM movement (figure 6).

Although there were no significant differences between the peak forces seen during the acceleration phase, peak forces were consistently lower for the isokinetic condition. Peak force is directly proportional to the peak acceleration achieved in the initial stage of the concentric phase. Because isokinetics seek to limit the duration of the acceleration phase, the maximum force that an athlete is able to produce may be compromised using this form of dynamometry; however, there is no evidence to substantiate this contention.

Power

Referring to equation 9, the power output of a muscle is the product of its velocity of shortening and force production.[71] Kanehisa and Miyashita[68] and Caiozzo et al.[62] both reported maximum mean powers at an angular velocity of 4.19 rad/sec. However, it is difficult to assess this claim in terms of sport-specific power development because there is an important difference between the power produced during coordinated multiple-joint efforts and the power generated during a single joint movement,[71] as is traditionally the case with isokinetics. Furthermore, controlling the movement velocity will encourage the development of force-specific power development, resulting in an upward shift of the force-velocity curve (figure 1a) and potentially less transference to sport.

#### *2.2.2 Muscle Activity*

Isokinetics have been designed as a way to maximize the force and, thus, muscle activity at a specific movement velocity.[4] This type of dynamometry has received a great deal of advocacy as a means of testing pre- and post-measures of strength by allowing an individual to maximally contract throughout the range of motion.[64,68,72-74] However, upon further examination of the EMG-torque relationship during a single repetition of isokinetic knee flexion, Onishi et al.[75] found that all agonists do not achieve maximum levels of activity during maximal efforts, and that there are varying degrees of synergistic involvement depending on the knee-joint angle. Furthermore, dissimilar movement patterns, associated with isokinetic dynamometry, have relegated the importance of whole-body coordination and control and, thus, may not provide the most conducive means to improve athletic performance.

## 3. Variable Resistance

From as early as 1900, attempts have been made to develop innovative training devices that could combat the changing mechanical advantage and inertial properties associated with free weight or constant resistance.[76] At constant velocity, the resistance offered to the moving body segment remains constant; however, the resistance applied to the muscle varies with a change in joint angle.[4,77] Conversely, the acceleration of a load (equation 1), or a change in its velocity, necessitates an increase in peak force,[2,12] variation of the applied force[12,14] and an increase in the duration of the deceleration phase.[3,9] As much as 67% of the concentric effort may be spent decelerating with a load of 19.4% 1RM.[14] Variable resistance devices alter the resistive force during a movement to match changes in the joint leverage,[50] and provide compensatory accelerations[76,78] with the intent of reducing the effect of these limitations.

### 3.1 Cam- or Lever-Based System

Arthur Jones and Harold Zinkin, founders of Nautilus® and Universal,® respectively, began their careers with a similar hypothesis: a muscle works at maximum capacity during a very small portion of a dynamic repetition. Therefore, to facilitate maximum muscular involvement, the resistance must be varied. Both inventors developed a cam- or lever-based system that would vary the resistance to coincide with the changing leverage of the body during movement.[8,79] Unfortunately, individual differences in limb length, point of muscle attachment, velocity of movement and maximum-force development affect the torque-angle curve of the machines, rendering them ineffective for their intents and purposes.[8,67,80]

#### *3.1.1 Kinematics and Kinetics*

The inherent flaws associated with cam-based variable resistance have limited the amount of available research on these devices. Those who have used them in their studies have done so with the intent of examining their effectiveness[67,80] or as a means of increasing strength,[57,58] and not for the purpose of a kinetic or kinematic comparison.

Although found to be equally effective as hydraulics and surgical tubing to increase strength,[57,58] researchers have shown that there is little similarity between machine-resistive torque and human torque capabilities.[80]

The torque-angle curve for the Universal® bicep curl has been shown to be more representative of the maximum torque capabilities of the muscle than its free-weight counterpart;[79] however, these data were presented in a review on the device and not in a research study. Harman[80] showed that for the same exercise, machine-resistive torque varied up to 12% below maximum during the exercise movement, while human torque capabilities were as much as 59% below maximum at the extremes in the range of motion. Given the limitations of this type of equipment and the dissimilar resistance profiles to open- and closed-chain athletic movements, it should be deemed ineffective for the development of athletic performance and be reserved for recreational use.

#### *3.1.2 Muscle Activity*

To the authors' knowledge, there has been no research to investigate the EMG profiles of a cam-based variable resistance effort. As stated in the previous section,[9] the inertial properties of a constant resistance load cause muscle activity to fluctuate throughout the repetition; therefore, it was speculated that cam-based devices would provide a resistance that resulted in near maximum muscular involvement throughout the range of motion. However, such a contention is theoretically based, and now receives little to no support from researchers and practitioners alike.

### 3.2 Band and Chain

Bands and chains are used as a means of overcoming the mechanical disadvantages associated with specific joint angles[76,78,81-83] and increasing the degree of sport specificity.[84] Reviews by Simmons[76,78] have resulted in an increased advocacy among powerlifters and strength coaches alike, despite claims that they are not an appropriate mode for resistance training as they work in opposition to the way human muscles contract and produce force.[84] Often reviewed simultaneously,[78,81] different inertial properties between the two training modalities necessitate separate discussions of the associated kinetics and kinematics.

#### *3.2.1 Kinematics and Kinetics*

The addition of bands and chains to a constant resistance movement will alter the kinematic and kinetic profiles of the respective lift; however, the manner in which changes and, thus, the training effect occur is governed by the inertial properties of the additional resistance.

The acceleration of any object is proportional to the force causing such an acceleration and inversely proportional to its mass or inertia (equation 1). Therefore, using bands, which have a minimal mass, will allow for greater accelerations to be produced compared with a constant resistance movement with an equivalent load. However, the load being lifted and, thus, the force required to elicit movement will increase proportionally with the displacement or stretch of the band (see equation 10):

$$F_{band} = -k \times l \qquad \text{(Eq. 10)}$$

where k is the stretch coefficient of the band and l is the distance that the band is being stretched (m). Using equation 2, $F_{net} = \sum F_{ext} = F_{app} + F_{load}$, $F_{load}$ becomes equation 11:

$$F_{load} = F_{band} + F_{mass} \qquad \text{(Eq. 11)}$$

where $F_{mass}$ is the gravitational force of the load (N). Therefore, it becomes increasingly difficult to maintain high-movement velocities and accelerations towards the end of the concentric phase. However, the benefit of such a modality stems from these characteristics. A load that increases proportionally with the concentric displacement necessitates sufficient acceleration in the early stages of the effort to overcome the elastic recoil of the bands and still complete the movement.

Because the band resistance is primarily a function of its elastic properties and not the force of gravity, there is also opportunity for much greater eccentric accelerations to be achieved. Greater eccentric accelerations will result in proportional increases in eccentric forces and a greater involvement of the SSC when applicable. Behm[85] has suggested that the benefits of band resistance are most apparent when combined with free weights so that the inherent shortcomings of either resistance type compensate for one another. Used alone, the bands do not provide sufficient overloading to the initial portion of the movement, thereby potentially reducing any opportunity to increase the rate of force development. However, used in combination with free weights, the bands may benefit the end range of motion by controlling the associated momentum and providing needed additional resistance, which allows for the lift to be completed with greater effort later in the movement.

Contrary to bands, chains are an additional system mass. The magnitude of this mass is proportional to the percentage of the concentric phase completed, assuming that the chains are evenly distributed on the floor prior to the initiation of the concentric effort. Equation 11 becomes the sum of $F_{mass}$ and $F_{chain}$ where $F_{chain}$ at position z is (equation 12):

$$F_{chain} = m_z \times g \qquad \text{(Eq. 12)}$$

where $m_z$ is the mass of the chain (kg) at position z (m) and g is gravity (m/sec$^2$). However, $m_z$ can be stated as (see equation 13):

$$m_z = (m_{chain} \times z)/(d - c) \qquad \text{(Eq. 13)}$$

where $m_{chain}$ is the total mass of the chain (kg), d is the length of the concentric displacement (m) and c is the portion of the concentric displacement completed prior to the addition of any links in the chain (m). An increase in system mass also means that greater peak forces are required to achieve specific accelerations and movement velocities (equation 1 and 5). These forces, applied in 'x' amount of time, result in a change in momentum of the system, which is counteracted to some degree by the inertia of additional mass as subsequent chain links leave the ground.

Similar to bands, chains compensate for mechanical advantages at the end range of motion of a squat or bench press[76] by increasing the resistance and limiting the effects of momentum. As a result, the rate of force development, the time to peak force and time to peak power may be improved; however, this contention has yet to be researched.

#### *3.2.2 Muscle Activity*

Despite their emergent popularity, a limited number of studies have examined the muscle activity associated with bands or chains.[81,86] Cronin et al.[86] compared the concentric and eccentric EMG of the vastus lateralis for two supine squats: band and no band conditions, with an equivalent mean load. The only significant differences observed between the two conditions were in the last 40% of eccentric displacement where the band condition was greater. Similarly, Ebben and Jensen[81] examined quadriceps and hamstring EMG over the eccentric and concentric phase of a back squat over three conditions: squat with barbell and weight; squat with barbell, weights and chains to replace 10% of the load; and squat with barbell, weights and elastics to replace 10% of the load. No significant differences in the mean EMG were found between any of the conditions; however, presenting data as a mean may have masked any variations that did exist through the range of motion.

## 3.3 Pneumatic

The term 'pneumatic' denotes relating to or using air. Analogous to the resistive forces provided by band tension, pneumatic devices offer loads that are not dependent on an object's mass. Conversely, they are a function of the air pressure being produced and the area through which this pressure is exerted (see equation 14):

$$P = F_{pneumatic}/A \qquad \text{(Eq. 14)}$$

where P is the air pressure (Pa), $F_{pneumatic}$ is the resultant force (N) and A is the area through which the air is compressed ($m^2$). As a result, pneumatic loads will, theoretically, exhibit less variation in the muscular force required to complete an exercise stroke, thereby reducing the risk of strain and injury to the operator.[87]

The first pneumatic exercising device was developed in 1978,[88] with the aim of duplicating the superior operative characteristics of 'weight type' exercising machines while avoiding the undesirable characteristics.[88] Dennis Keiser, founder of Keiser's pneumatic technology, introduced a device that would not permit the operator to employ inertia to his/her advantage once the movement was initiated, but to exert a force during the return stroke, allowing for greater movement velocity to be achieved with an equivalent load.[88]

Limiting the mass of the load will augment the kinetic, kinematic and electromyographic profiles of a movement, potentially resulting in dissimilar training adaptations; however, this remains to be investigated. The numerous researchers that have implemented pneumatic technology in their respective protocols have done so as a means of training for the elderly[89-95] and not to assess the biomechanical characteristics of the resistance type. Therefore, the purpose of this section is to characterize pneumatic resistance in terms of Newton's laws of motion and provide the theoretical framework for future experimental research.

### 3.3.1 Kinematics and Kinetics

#### Velocity

As stated previously (see section 1), velocity is a function of the duration over which a specific displacement takes place. If the movement is non-ballistic in nature, then both the initial and final velocities of the eccentric and concentric phase will be zero, meaning that the only way to change the mean velocity, given a fixed range of motion, is via changes in the duration of the movement. Therefore, for mean velocity to be greater during a pneumatic effort, the duration of that effort needs to be reduced.

Peak velocity is a measure of the maximum instantaneous velocity at any point in time during the movement. Because it also represents a zero crossing on the acceleration curve (point that separates acceleration and deceleration phases), larger accelerations over a greater duration of the dynamic effort will elicit higher peak velocities. If pneumatic resistance does provide a means of increasing such acceleration, then there should be a proportional increase in the peak velocity.

#### Acceleration and Force

The proposed advantages of pneumatic technology stem from Newton's second law, which outlines the relationship between force, acceleration and mass. Referring to equation 1, the acceleration of an object is directly proportional to the sum of the net forces acting on the object and inversely proportional to its mass. Pneumatic devices utilize air pressure as a means of resistance, thereby reducing the mass component of the load to near zero. The magnitude of this mass component will vary in accordance with the body segments involved in producing such movement, but remain significantly lower than the free-weight equivalent, with greater differences being

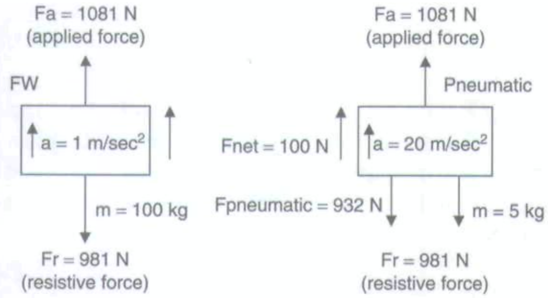


**Fig. 7.** A theoretical kinematic and kinetic comparison of free-weight (FW) and pneumatic resistance using equivalent loads.

seen at higher loads. Consequently, an athlete will be able to achieve greater accelerations with a pneumatic load of the same weight if an identical force is applied (figure 7).

Newton's first law implicitly states that an object will maintain its state of motion unless acted on by an unbalanced force. Resistance to change in this present state, defined as inertia, will depend on the mass of the object, with larger masses characterized by greater resistance. Furthermore, in equation 5, we note that specific changes in the movement velocity necessitate proportional increases in either the magnitude of the applied force or the duration of the applied force for a given mass. Considering sport-specific velocity and power development, the only viable option is to increase the magnitude of the applied force, which consequently limits the load that can be lifted (table I). Because an equivalent pneumatic load uses less mass, less force will be required to produce the same desired velocities, or conversely, the same force will produce greater velocities via greater acceleration (table VI), possibly improving the transference of high-velocity resistance training to sport.

Power

A negligible mass component and near zero momentum makes projecting a pneumatic load near impossible, which results in a mean force that is always equal to the weight of load. Therefore, any increase to mean power must be from a proportional increase in the mean velocity. There are two ways to increase mean velocity: increase the duration of the phase spent accelerating; or increase the magnitude of the acceleration. Pneumatic resistance provides a training stimulus conducive to increased accelerations by reducing the inertia, momentum and peak force requirements of a movement, which may possibly lead to greater mean power.

Furthermore, less mass implies less variation in the force curve, and the potential for peak power to be produced with a greater contribution from the movement velocity than the force (a rightward shift of the force-velocity curve; figure 1b). Peak power is an instantaneous measure of the optimal force-velocity combination at a specific point during the movement; however, to increase sport specificity, the velocity component should reflect the speeds at which movements are performed in athletic events. Pneumatic resistance may enable athletes to increase the peak power by producing greater movement velocities without necessitating proportional increases in the force; however, this contention needs validation from experimental research.

#### *3.3.2 Muscle Activity*

Newton et al.[12] has shown that during a bench press, the muscle activity of the agonists follow a similar pattern to the force-displacement curve; dramatic reductions in EMG activity are observed during the deceleration portion of the

**Table VI.** Force-velocity comparison of free-weight (FW) [reproduced from Lander et al.,[3] with permission from Lippincott Williams & Wilkins] and pneumatic resistance using the impulse-momentum theory

| Resistance | $F_{load}$ | M | $V_o$ | PV | MF | % MF/$F_{load}$ | TPV |
|---|---|---|---|---|---|---|---|
| FW | 1370 | 139.7 | 0.00 | 0.54 | 1704 | 1.24 | 0.225 |
| Pneumatic | 1370 | 10.0 | 0.00 | 0.54 | 1394 | 1.02 | 0.225 |
| Pneumatic | 1370 | 10.0 | 0.00 | 7.52 | 1704 | 1.24 | 0.225 |

Equation 5: $F_{net} \times (t_2 - t_1) = (m \times v_2) - (m \times v_1)$

**$F_{load}$** = resistive force (N); **M** = mass of load (kg); **MF** = mean force between $V_o$ and TPV (N); **PV** = peak velocity (m/sec); **TPV** = time to PV (sec); **$V_o$** = velocity at start of concentric phase (m/sec).

 

movement. Because pneumatic resistance will theoretically limit the variation in force, this resistance mode may also allow an athlete to maintain a more consistent muscular effort throughout a specified range of motion. An increase in agonist activity may result in a longer acceleration phase, thus allowing for greater movement velocities to be produced during the later stages of the concentric phase. However, as was stated for the isokinetic dynamometry, greater muscle activity does not necessarily equate to superior performance. Thus, it should be noted that increasing muscle activity alone is not sufficient evidence to validate a device as superior for performance development.

## 4. Conclusions

Mechanical disadvantages inherent to constant resistance movements may limit the degree to which velocity-specific power output can be produced and, therefore, transference to athletic performance may be compromised. Dramatic variations in the kinetics, kinematics and muscle activity have been reported for both concentric-only and SSC movements because of the inertial properties of the load. Ballistics can reduce the magnitude of these variations via increases in mean force and mean and peak velocity; however, they fail to increase the rate of force development. Consequently, alternative resistance-training strategies continue to be investigated. Isokinetics, hydraulics and variable-resistance devices using cams and levers have offered possible solutions to the constant resistance problems by controlling the movement velocity and/or system load, but have done so by introducing limitations of their own. Movements are restricted to machines, thereby reducing the permissible movement directions from six to one, and have negated the importance of an acceleration component to training, likely decreasing the transference of gym-based strength and power gains to sporting activity.

The addition of bands to constant resistance efforts may afford a promising solution, via compensatory accelerations, a variable resistance and a reduced mass. Compared with a constant resistance effort with an equivalent load, bands allow for greater accelerations and, thus, velocities to be produced at the onset of the concentric effort, and prevent a reduction in force, velocity, power and muscle activity during the later stages of the movement. As a result, transference to sport may be improved, although this contention is yet to be shown through research; most evidence reports no acute differences compared with similar free-weight movements. Possible characteristics, such as a reduced load at the onset of the concentric phase or large variations in the load-displacement curve, may result in adverse training effects with extended use.

Pneumatic resistance offers similar mechanical advantages to both constant resistance and band training: a reduced mass may allow for an increased acceleration and movement velocity at a given load; force, velocity, power and muscle activity should be maintained throughout the concentric phase; and the same load will theoretically be maintained for the duration of the movement. As a result, pneumatics may offer a resistance-training stimulus more conducive to sport-specific velocity and power development; however, this hypothesis remains to be investigated. Alternatively, perhaps it is naive to assume that one resistance type offers a mechanical stimulus conducive to improving all aspects of athletic performance. Sport is multifaceted and necessitates that a methodical strategy be implemented in order to achieve the best results. Understanding the biomechanical advantages and disadvantages associated with each resistance type may simply provide researchers and practitioners with a greater appreciation for the complex nature of performance enhancement, thereby prompting the evolution of hybrid or mixed-method training strategies.

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