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Case report

Force-velocity, impulse-momentum relationships: Implications for efficacy of purposefully slow resistance training

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Abstract

The purpose of this brief review is to explain the *mechanical* relationship between impulse and momentum when resistance exercise is performed in a purposefully slow manner (PS). PS is recognized by ~10s concentric and ~4-10s eccentric actions. While several papers have reviewed the effects of PS, none has yet explained such resistance training in the context of the impulse-momentum relationship. A case study of normal versus PS back squats was also performed. An 85kg man performed both normal speed (3 sec eccentric action and maximal acceleration concentric action) and PS back squats over a several loads. Normal speed back squats produced both greater peak and mean propulsive forces than PS action when measured across all loads. However, TUT was greatly increased in the PS condition, with values fourfold greater than maximal acceleration repetitions. The data and explanation herein point to superior forces produced by the neuromuscular system via traditional speed training indicating a superior modality for inducing neuromuscular adaptation.

Key words: Impulse, momentum, purposefully slow, time-under-tension.

Introduction

Performing exercise under any type of resistance is broadly defined as resistance training (Newton, 1999). Because the effect of the earth's gravity is universally present on earth, the physics of resistance training with a constant load (isoinertial) are relatively simple. What are not simple, however, are the ultimate physiological and morphological effects of resistance training. Several variables can be manipulated in resistance training programs to bring about a specific desired result (Wernbom et al., 2007). Load, number of sets, number of repetitions per set, number of exercises, mode (machine or free weight), repetition speed, rest period length, exercise order, training frequency, and the specific exercises selected can all be manipulated to promote a precise desired outcome. Such outcomes include increased muscular endurance, muscle size, increased muscle strength, increased muscle power, and decreased relative body fat. *It is unlikely that a single program or method will be effective in realizing all of the possible benefits of resistance training equally.*

Training programs have been developed that aim to regulate repetition speed, specifically recommending purposefully slow actions (~10s for the concentric and ~4-10s for eccentric portions). Much of the support for

such programs exists only in lay media (Brzycki, 1995; Hutchins, 2001; Wescott, 1999), with little empirical evidence (Greer, 2005). The arguments for prescribing such training programs often use terminology that is not soundly based in classical physics, or is derived from other resistance training/testing modalities uncommon to that of question (i.e. isokinetic, *in vitro* or *in situ* studies). For instance, protocols such as this have been confusingly called "low force" (Hutchins 2001) while at the same time touted as having "more muscle tension" (Wescott et al., 2001), "more muscle force" and "less momentum" (Wescott, 1999). It is the purpose of this paper to correctly describe the *mechanical* aspects of such training, as these programs have been used in several empirical studies (Greer, 2005). We will also provide a case example where the mechanical properties of a common resistance training exercise will be shown. Specific training studies will not be reviewed in detail as they are primarily interested in *physiological* effects (for such a review see Greer, 2005), but we hope that this *mechanical* review will lay the groundwork for productive evaluation of resistance training over the load and velocity spectrum.

Force-velocity relationship

The force-generating capability of the neuromuscular system under maximal voluntary or involuntary activation is dependent on movement velocity, as illustrated through the force-velocity (F-V) relationship (Fitts and Widrick, 1996; Gülch, 1994). Essentially, the F-V relationship is a hyperbolic curve constructed from the results of numerous experiments describing the dependence of force on the velocity of movement (Hill, 1953). This relationship has been examined *in vitro*, *in situ*, and *in vivo*. *The force that the muscles can produce decreases at a given predetermined velocity (computer-controlled in vivo isokinetic/isovelocity modalities) as that velocity increases.* The F-V relationship assumes that at a given velocity, the muscles are generating the maximum force possible. A similar load-velocity relationship is also demonstrated in *in vivo* exercise with maximal voluntary acceleration (Cronin et al., 2003). In this case, as the external load (i.e. mass) increases, the maximal velocity that such load achieves decreases. The load-velocity relationship assumes that the movement velocity is the maximum possible for the given load. The likely source of the F-V relationship is the fact that when the cross-bridge cycling speed increases, there are fewer cross-bridges formed to develop force (Gülch, 1994). This relationship between

force and velocity is what may have prompted some to suggest that the voluntary muscle action should be carried out over a 10-s period so that the velocity is low, thereby increasing force (Wescott, 1999).

Impulse and momentum

The relationship between force and velocity for a constant mass (such as is encountered in free-weight training) is given in the relationship between impulse and momentum. A constant mass under the influence of a force can be expressed with Newton's second law represented by equation 1.

$$\text{Eq 1. } F = ma = m \frac{dv}{dt} = \frac{d}{dt}(mv)$$

In the above case, the acceleration (a) experienced by an object is directly proportional to the force impressed (F) and inversely proportional to its mass (m). Since acceleration is the first derivative (d) of velocity with respect to time, the equation can also be written to reflect the first derivative with respect to time (rate of change) in the quantity mv . In such a case linear momentum (L) is expressed as equation 2.

$$\text{Eq 2. } L = mv$$

When a force acts upon the object from a time period from t_1 to t_2 , equation 1 can be integrated in time to obtain equation 3.

$$\text{Eq 3. } I = \int_{t_1}^{t_2} F dt$$

Equation 3 defines linear impulse (I), and is equal to the change in linear momentum, as shown in equation 4.

$$\text{Eq 4. } \int_{t_1}^{t_2} F dt = \int_{t_1}^{t_2} \dot{L} dt = L_2 - L_1 = \Delta L$$

As mass is constant during free-weight resistance training, a greater impulse will result in a greater velocity.

In human movement, force is required first to maintain static equilibrium and second to generate acceleration. The force required to maintain static equilibrium is equal to an object's mass multiplied by gravitational acceleration. Additional force results in acceleration of a mass or a change in momentum. These components of acceleration are described in equation 5:

$$\text{Eq 5. } F = mg + ma = mg + mdv/dt$$

Therefore, as generation of force greater than the weight of the resistance increases (i.e. propulsive force; Garhammer and Gregor, 1992) higher movement velocities and/or decreased movement times result. As velocity approaches zero, propulsive force approaches zero, therefore slow moving objects only require force approximately equal to the weight of the resistance. *The slower*

the intended velocity, the closer the force expressed comes to equalling the linear inertia of the load (i.e. the amount of force needed to hold the weight motionless). From Equation 1, force is inversely proportional to time. That is, to perform a movement in a shorter period of time, greater force must be generated. Arguments have been made that the muscle tension will be constant through the given range of motion, and thus provide optimum stimulation throughout such range (Wescott, 1999). This statement has not been experimentally verified and unfortunately neglects the changes in moment arm and muscle length which ultimately change the muscle force regardless of speed of action. This argument does, however, have some factual basis, as the impulse increases as time increases (Equation 4), in the case of maximal effort actions. In the case of PS, increasing time decreases force, and excessive time duration will not maximize impulse.

Arguments for purposefully slow (PS) training

Muscle force: While PS proponents vary in their reasoning for suggesting this method, the basic premise is that when the weight is moving quickly, the muscles will not be able to exert as much force and thus the training effect will be diminished (Brzycki 1995; Wescott 1999). While true that the muscles will not produce as much force at the higher velocities during maximum effort velocity-controlled actions, the previous statement ignores the requisite force to *initiate* high velocity movements for a given load in an isoinertial condition. In addition, the aforementioned F-V relationship was derived under conditions of maximal acceleration (maximal voluntary muscle activation), and thus differs from intentionally slow movements. An attempt to reduce the speed of motion subsequently reduces the force expressed (Keogh et al 1999).

Metabolic stimulus: Metabolic factors influenced by muscle contraction include H^+ production, sarcoplasmic calcium concentration, intramuscular oxygen concentration, growth factors, cytokines, and availability of hormones and receptors (Crewther et al., 2006; Rennie et al., 2004). Modifications to any one of these metabolic factors during exercise may alter signal transduction pathways and hence modify gene transcription for muscle growth (Rennie et al., 2004). Potential strength adaptations due to acute metabolic stimuli have recently been reviewed elsewhere (Crewther et al., 2006) and arguments for the importance of metabolic factors in resistance training adaptation have been made (Kawada and Naokata 2005; Kanehisa et al., 2002; Schott et al., 1995; Smith and Rutherford 1995). The metabolic hypothesis has not yet been examined in conjunction with PS training studies; therefore these ideas are currently speculative for this type of training.

Time-under-tension: Movements performed at low velocities prolong the time of contraction in each repetition for a given range of motion (time-under-tension; TUT). Proponents of PS training regard this increased time as a positive characteristic to stimulate training adaptation (Wescott et al., 2001). TUT can be considered a manner by which to prescribe a dose of resistance exercise (Tran and Docherty, 2006), which is crucial as the

optimal dose for weight training is subject to tremendous debate (Carpinelli and Otto, 1998; Stone et al., 1998). PS advocates suggest that this time dose or TUT is of greater importance than the actual load lifted, which could be related to the fact that perceived effort in PS and normal training session have been shown to be similar (Egan et al., 2006). This rationale originates from the hypothesis of a direct relationship between the duration of contraction and metabolic stimulus, but this hypothesis has not been supported in studies examining PS exercise (Gentil et al., 2006; Hunter et al., 2003; Keogh et al., 1999).

A potential caveat of increased TUT is that the load must be decreased to perform a successful 10-s concentric contraction as compared to a maximal acceleration repetition (i.e. decreased TUT). This is concerning as the load, or mechanical stimuli, has been suggested to be of critical importance for inducing adaptation (Dudley et al., 1991; Hortobagyi et al., 1996; McDonagh and Davies, 1984). Evidence for the load used in resistance exercise emphasizing hypertrophy indicates a possible optimal threshold of 85% 1RM (Fry, 2004), but the multitude of acute training variables that may be altered in addition to load make a precise recommendation difficult. However, the reduced load advocated by PS might be less effective for hypertrophy due to the load constraints. This reduction in load is seen by PS advocates as inconsequential to the ultimate physiological effects. However, a basic premise of tissue adaptation (i.e. Wolff's and Davis' Laws (Biewener and Bertram, 1994) is that a minimum threshold of force is required to elicit adaptation. The notion that load is peripheral in its importance is in direct opposition to other authors' demonstrating the magnitude of mechanical stress (i.e. load) is most responsible, in the context of exercise volume, for strength gains and muscle hypertrophy (Dudley et al., 1991; Hortobagyi et al., 1996). Please note that although related, load and muscle force are not equal, as propulsive forces can differ.

Increasing TUT for an exercise session can be accomplished by simply increasing the number of total repetitions of maximal-acceleration exercises (increased volume-load; Tran and Docherty, 2006). This would ultimately increase the time that the muscle has been under tension for that session, but the force output of the muscle will have been greater due to the relatively larger loads. The complex relationship between load and TUT requires further investigation.

Resistance training applications: Forms of resistance training fall within a continuum from slow to fast velocities. Resistance training such as powerlifting (relatively slow) and weightlifting (relatively fast) are quite far apart on this continuum. Weightlifting (WL) is the sport by which athletes attempt to lift maximal weight in the snatch and clean and jerk (Chiu and Schilling, 2005). WL is characterized by high accelerations and fast velocities due to the inherent nature of the sport by which a loaded barbell is moved from the ground at an initial velocity of '0' to an eventual overhead position. Successful performances of these lifts necessitate great velocities and thus great power (Garhammer, 1980; 1993). However, the relative loads (resistance) are not as great as seen in the sport of powerlifting (PL). PL is comprised of the bench press, squat, and deadlift exercises, and PL is performed

at substantially lower velocities than WL. Elite PL records exceed 400kg in each of their respective lifts (Kraemer and Koziris, 1994). While these lifts begin with an explosive muscle contraction (high RFD), the overall velocity is slow due primarily to the high load (Brown and Abani, 1985; Garhammer and McLaughlin, 1980). Both PL and WL typically involve maximal acceleration, with the resultant velocity a function of the load lifted, and it has been suggested that it is the intent to maximally accelerate the load is common amongst PL and WL (Behm and Sale, 1993). In fact, PL and WL display similar levels of strength on some movements (McBride et al., 2002). Analogous to PL, PS training employs similar low velocities, but with substantially less resistance, as the velocity is *deliberately* slow (low acceleration). Considering these unique features, a simplistic case of the impulse-momentum relationship can be used to conceptually compare these forms of resistance training (Table 1). The relationships between force and various modes of resistance training identified in Table 1 exposes the potential for superior force production for WL and PL, but not with PS training. These conceptual relationships have been substantiated with lower eccentric and concentric forces seen in deliberately slow repetitions, as compared with those done with no restrictions on speed (Keogh et al., 1999).

Table 1. Simplistic impulse-momentum relationship in various forms of resistance training.

Basic impulse-momentum relationship	$F\Delta t = m\Delta v$
Weightlifting	$\uparrow F = \leftrightarrow m \uparrow \Delta v$ $\downarrow \Delta t$
Powerlifting	$\uparrow F = \uparrow m \leftrightarrow \Delta v$ $\leftrightarrow \Delta t$
Purposefully slow training	$\downarrow F = \downarrow m \downarrow \Delta v$ $\uparrow \Delta t$

F = force, v = velocity, m = mass, t = time, \uparrow = large, \downarrow = small, \leftrightarrow = moderate

Case example

Method

A former United States National level weightlifter in the 85 kg weight class performed back squats with loads of 110, 130, 150 and 170 kg on a uniaxial force platform (Roughdeck; Rice Lake Weighing Systems). The end of the bar was tethered to a velocity transducer (VP510; Unimeasure) to record the vertical speed of the bar. Data were collected via a 12-bit analog-to-digital board interfaced with Datapac 2K2 (v3.17; Run Technologies). Following a warm-up, two single repetitions were performed at each load, one with a maximal acceleration concentric portion and one attempting a deliberately slow 10 second concentric and 4 s eccentric actions. Five minutes of rest was allowed between sets to reduce effects of fatigue. Passive demeaning was used to obviate for the effects of the load in addition to body mass, so that the forces recorded are propulsive only (the load is constant between PS and normal conditions, and equal to the linear inertia of the system). This force is present regardless of movement. The variables of interest were impulse, peak velocity and mean/peak force, as well as elapsed time. Low

Table 2. Data for both purposefully slow and maximal acceleration back squats over a load spectrum.

Condition	Load (kg)	Mean Propulsive Force (N)	Peak Propulsive Force (N)	Peak Velocity (m/s)	Time (s)
Slow	170	6.2	623.8	0.3	10.9
Slow	150	4.2	360.6	0.3	11.1
Slow	130	2.9	528.9	0.4	13.3
Slow	110	2.7	257.1	0.2	12.9
Normal	170	45.3	1189.7	1.2	2.8
Normal	150	17.9	1210.3	1.4	2.4
Normal	130	72.6	1332.0	1.5	2.3
Normal	110	21.3	1007.9	1.6	2.2

pass filtering of the velocity and force data was accomplished utilizing a 4th order Butterworth filter with cut-off frequencies of 10 and 20 Hz, respectively. Reliability and precision were previously determined to be $ICC_{3,1} > 0.7$ and $CV < 15\%$, respectively. All procedures were approved by the institutional review board for human subject research (E07-291).

Results

Data from the six trials are shown in Table 2. The force/velocity histories for the 130 kg load are shown in Figures 1 (fast) and 2 (slow) respectively. As evident from these force histories, the maximal acceleration squats produced greater peak and mean propulsive forces than PS action when averaged across loads. As stated previously, force is required first to maintain static equilibrium and second to generate acceleration. The force required to maintain static equilibrium is equal to an object's mass multiplied by gravitational acceleration, and in

this case is constant between conditions. Additional force results in acceleration of a mass or a change in momentum. Again, since the PS movement reduces acceleration, the force used to accelerate the object is near '0'. TUT was greatly increased in the PS condition, with values nearly four times greater than maximal acceleration repetitions. Clearly, PS results in lower propulsive forces, and the interaction of time and load must be more clearly examined for definitive conclusions on the efficacy of such training.

Discussion

Proponents of PS training often use the inverse relationship between muscle force and velocity as a basis for resistance exercise tempo prescription. This relationship states that as the velocity of shortening increases during maximal-effort actions, the force that can be developed at a given velocity decreases in a hyperbolic fashion. It is evident that the original F-V relationship does not hold

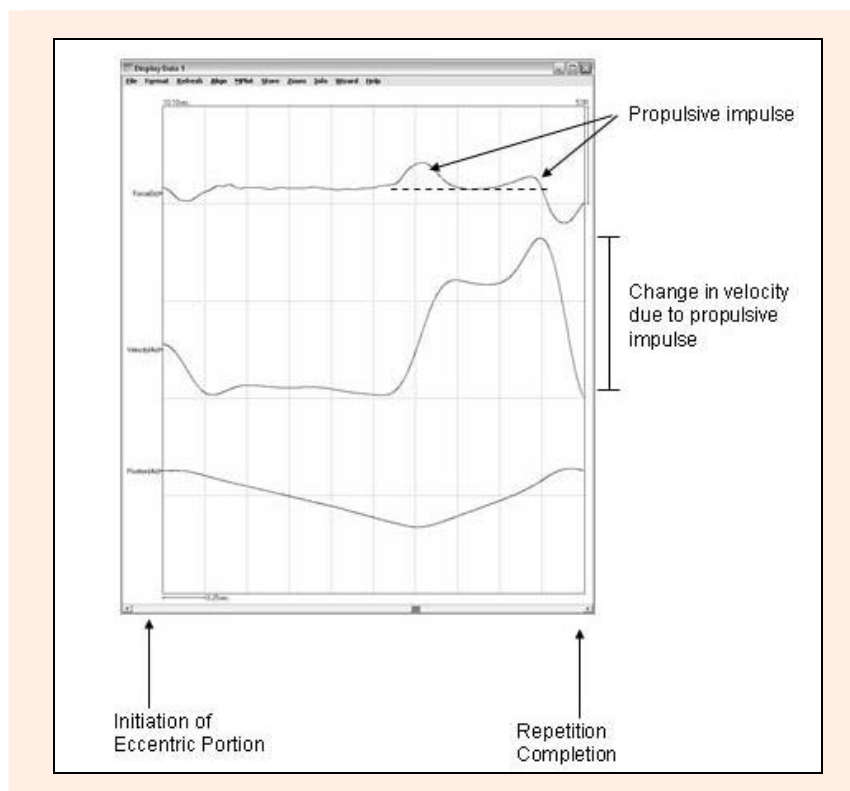


Figure 1. Force-time curve for a typical maximum acceleration back squat. The dotted line cursor is placed at the bottom position as noted by the position tracing. Note the large changes in force and velocity during the concentric portion.

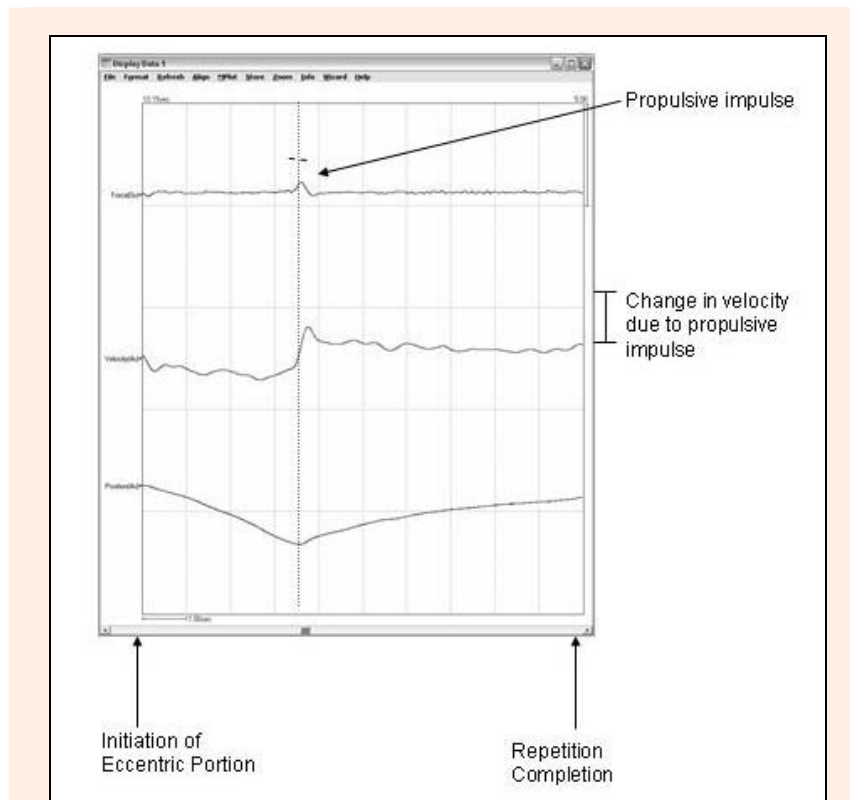


Figure 2. Force-time curve for a typical intentionally slow back squat. The dotted-line cursor is placed at the bottom position as noted by the position tracing. Notice the small fluctuations and minimal propulsive force. Force is similar to that of simply holding the weight motionless.

universal application when intended acceleration is less than maximal or when modalities other than isokinetics are used. What is not taken into account in such cases is the simple mechanical relationship between impulse and momentum for objects of constant mass. Simply stated, for a constant mass, a greater force and/or greater time period of *maximal* force action will produce the greatest change in velocity. For such a maximal action, the range-of-motion will prevent a long time period force application, so a larger force will cause the greatest change in velocity of the constant mass object.

Conclusion

The exercise professional must be aware of basic mechanical features of all styles of resistance training in order to render an educated prescription. While lay literature has suggested that forces are optimal with PS, the data herein along with reviewed studies and an examination of the impulse-momentum relationship suggests otherwise. The inferior propulsive forces accompanying PS suggest other methods of resistance training have the potential for superior neuromuscular adaptation. While it is reckless to suggest one universal style of training to all individuals, one must be careful in selecting a mode and designing a training program in order to achieve appropriate goals.

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Key points

- As velocity approaches zero, propulsive force approaches zero, therefore slow moving objects only require force approximately equal to the weight of the resistance.
- As mass is constant during resistance training, a greater impulse will result in a greater velocity.
- The inferior propulsive forces accompanying purposefully slow training suggest other methods of resistance training have a greater potential for adaptation.

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