Force-Velocity Analysis of Strength-Training Techniques and Load: Implications for Training Strategy and Research

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ABSTRACT
The purpose of this study was to investigate the force-velocity response of the neuromuscular system to a variety of concentric only, stretch-shorten cycle, and ballistic bench press movements. Twenty-seven men of an athletic background (21.9 ± 3.1 years, 89.0 ± 12.5 kg, 86.3 ± 13.6 kg 1 repetition maximum [1RM]) performed 4 types of bench presses, concentric only, concentric throw, rebound, and rebound throw, across loads of 30–80% 1RM. Average force output was unaffected by the technique used across all loads. Greater force output was recorded using higher loading intensities. The use of rebound was found to produce greater average velocities (12.3% higher mean across loads) and peak forces (14.1% higher mean across loads). Throw or ballistic training generated greater velocities across all loads (4.4% higher average velocity and 6.7% higher peak velocity), and acceleration-deceleration profiles provided greater movement pattern specificity. However, the movement velocities (0.69–1.68 m·s⁻¹) associated with the loads used in this study did not approach actual movement velocities associated with functional performance. Suggestions were made as to how these findings may be applied to improve strength, power, and functional performance.

Key Words: bench press, stretch-shorten cycle, contractile component, elastic component


Introduction
The force-velocity relationship characterizes the dynamic capability of the neuromuscular system to function under various loading conditions and, therefore, has considerable significance in the performance of movement (11). Understanding how various acute program variables and their interactions affect either force or velocity would seem important in determining how to alter the performance capability of muscle for a given purpose. However, there is very little published information on the effects of regular exercise on this relationship. Research that does investigate velocity-related force production typically uses isokinetic testing and training paradigms. However, this type of muscle action does not simulate the natural movements of the body, which include accelerations, decelerations, and eccentric stretching phases before the concentric or shortening phases. As such, the external and logical validity of findings from isokinetic research would appear questionable.

Isoinertial assessment (constant gravitational load), however, does not suffer the same problems with validity because this type of motion simulates the movement patterns encountered in everyday and sporting activities better. However, little attention has been paid to the effect of different techniques and loading intensities on the development of force and velocity using isoinertial assessment (1). The effects of various derivations and combinations of the traditional bench press on a variety of kinematic and kinetic measures have been studied by Newton, Wilson, and colleagues (21–24, 30, 31). These researchers have found explosive techniques that allow the load to be projected, as in a throw or jump, produced higher velocity, acceleration, force, and power. Such training has been described “ballistic” and allows the individual to accelerate the load through most of the movement (21). Supplementing this technique with rebound, i.e., using an eccentric muscle action to augment the concentric contraction (stretch-shorten cycle—SSC), produced greater initial impulse, higher peak bar velocities, and higher accelerations throughout the range of movement, and increased work and power. A limitation of this research, however, is that the effects of the different bench press techniques and loads were not investigated in a single research. That is, to gain a complete
understanding on the effect of SSC, load, or projection of the bar, one must compare and extrapolate the findings across laboratories, with different subjects using different procedures. To negate the problems inherent in such an approach, the interaction between technique and load needs to be investigated in a single paradigm. This study, therefore, compared 4 isoinertial weight-training techniques across loads ranging from 30 to 80% 1 repetition maximum (1RM). Increasing load would increase force and decrease velocity across techniques. Although the interaction between contraction type, movement, and load is difficult to predict, it was thought that ballistic techniques that used rebound would result in greater force and velocity as compared with the other techniques. Understanding the effects of these factors on the performance capability of muscle should allow for better training prescription.

Methods

Experimental Approach to the Problem

Subjects visited the laboratory on 2 separate occasions. The first visit involved familiarization with the 4 different bench press techniques and determination of each subject's bench press 1RM. During the next session, the 4 bench press techniques were performed for 6 training loads (30, 40, 50, 60, 70, and 80% 1RM). Thereafter, the interactions between technique and load were statistically analyzed.

Subjects

Twenty-seven men volunteered to participate in this research. The subjects’ mean (±SD) age, weight, and maximal bench press strength (1RM) were 21.9 ± 3.1 years, 89.0 ± 12.5 kg, and 86.3 ± 13.7 kg. All the subjects were from an athletic background (principally club rugby players); however, no subject reported using strength training in the previous 6 months. The Ethics Committee of the University of Auckland approved all the procedures used, and the subjects provided informed consent to participate in the study.

Equipment

Modified Smith Machine. Subjects performed bench presses on a modified Smith press machine. A linear transducer (Unimeasure, Corvallis, OR) was attached to the bar. This transducer measured bar displacement with an accuracy of 0.1 cm. Bar displacement data were sampled at 200 Hz and relayed to a computer-based data acquisition and analysis program. Displacement time data were filtered using a low-pass filter with a cutoff frequency of 10 Hz. Validation of the linear transducer with a force platform (AMTI Force Plate and Amplifier; Advanced Medical Technology Inc., Watertown, MA) has been studied previously. Measures of peak force, mean force, and time to peak force were gathered from both pieces of equipment for a variety of jumps. No intraclass correlation coefficient was less than 0.92 and most ranged between 0.97 and 0.99. The reliability of this system has been reported in earlier research (6).

The filtered data were differentiated using a finite differences algorithm to determine velocity and acceleration data. The force data were determined by multiplying the mass by the acceleration data. The concentric phase of the rebound bench press (RBPT) was determined at the time when bar velocity changed from positive to negative. For the concentric-only bench press (BP) and concentric throw (BPT), the start of the concentric phase was determined as the point at which the vertical force increased (23). Average velocity, peak velocity, peak acceleration, average force, peak force, and the duration of concentric action during the concentric phase were calculated for all techniques and loads. The duration of the eccentric phases was calculated for the techniques that used rebound.

Determination of 1RM Bench Press and Familiarization

The testing procedures used in this research were similar to those outlined by Newton et al. (23). A repetition to failure protocol was used to determine each subject's maximal bench press strength. At the completion of the 1RM testing, subjects performed a number of bench presses to familiarize themselves with the power movements. For BP, a mechanical brake was positioned so that the bar rested approximately 5 cm above each subject's chest, parallel to the nipples. The bar was then projected from rest as fast as possible and was either held at the end of the movement or thrown. For RBPT, subjects were instructed to begin with the weighted barbell at arm's length and lower the bar as quickly as possible to just above the nipples, and then immediately push the bar upward. The bar was either held at the end of the movement or thrown.

Bench Press Assessment

The second session began with a generalized warm-up of arm- or shoulder-mobilization exercises, 2 sets of 10 repetitions at 40% of the 1RM, followed by 5 minutes of pectoral and triceps brachii static stretches. The subject was strapped on the bench and was instructed to move the bar as fast as possible for all loads and movement types. Four movements were performed for 6 training loads (30, 40, 50, 60, 70, and 80% 1RM). The 4 movements were a concentric bench press, a concentric bench press throw, a concentric bench press preceded by an eccentric contraction, and an eccentric-concentric bench press throw. One trial was completed per movement type and load, and rest periods of a minute between each explosive movement and 2 minutes between change of loads were provided. For the rebound movements, no pause was allowed.
between the eccentric and concentric phases, and the trial was rejected if the bar touched the chest in any manner or the eccentric phase was terminated greater than 5 cm from the chest. Starting loads and movement types were randomized between subjects to reduce the possible confounding effects of order and fatigue before the proceedings. The reliability of this procedure was established in pilot testing. Data for 1 and 3 trials were assessed within and across days. Intraclass correlation coefficients of 0.85–0.99 were calculated for the variables peak and average velocity, and peak and average force.

**Statistical Analyses**

The results for mean velocity, peak velocity, peak acceleration, average force, and peak force were compared using a 2 x 2 x 6 repeated measures analysis of variance (contraction, movement, and load). Post hoc contrasts were used to determine significant differences between the means. The criterion level for significance was set at $p \leq 0.05$ and was adjusted using the Bonferroni procedure if more than one post hoc contrast was needed.

**Results**

It is worth noting the limited weight-training experience of the subjects as denoted by the relationship of their maximal bench press strength (86.3 kg) to their body mass (89.0 kg). Furthermore, the rebound bench press movements investigated are an example of slow (>250 ms) SSC motion (28); therefore, the application of the findings to faster SSC movements is not implicit. The interpretation and discussion of the present findings should be considered with these limitations in mind.

It can be observed from Figure 1 that there was no significant difference in average force output between the various techniques at all loads. However, as load increased so did average force ($p < 0.05$). A 10% increase in load corresponded to a 20% increase in force output on average across all loads. The load of 80% 1RM produced the greatest average force output across all techniques.

The relationship between load and peak force is similar in that greater peak forces are recorded with higher loading intensities (see Tables 1 and 2). Although there was no significant difference in peak force between held and throw conditions, the rebound technique produced significantly higher peak forces across all loads (14.1%) compared with the concentric-only movements. The effect of rebound was to produce higher initial accelerations, which ultimately affected force.

For loads of 30–60% 1RM, throw techniques produced greater average and peak velocities (4.4 and 6.7%, respectively) than did techniques that held the bar at the conclusion of the concentric phase (see Figure 2). The potentiating effect of the throwing motion was found to be insignificant when using heavier loads of 70–80% 1RM. Motion that used rebound pro-
duced greater average velocities (12.3%) across all loads. As load increased, average and peak velocity were found to decrease; the lowest average and peak velocities for all bench press techniques occurred at 80% 1RM. Higher peak velocities were recorded for techniques that used projection or release of the load. The effect of rebound on peak velocity across all loads was nonsignificant (see Tables 1 and 2).

Greater loads affected the temporal characteristics of each technique in a predictable and similar manner. As load increased so did the duration of the eccentric and concentric phases of the respective contractions. The time required for achieving peak velocity also increased as a function of load. Also, if the RBP and CBP are compared, motion that uses rebound is terminated earlier.

**Discussion**

The force-velocity relationship of muscle dictates that the faster the velocity of concentric muscle action, the lower the force that can be produced. This has been attributed to the increased rate of cross-bridge attachment-detachment cycling, which equates to less time to generate tension for force production (14) and greater internal resistance or viscosity that equates to loss of force (4). One can observe this relationship from Figures 1 and 2, i.e., the decreasing velocity of concentric muscle action and increasing force output, with increasing load.

Average force output was unchanged between explosive techniques for a given loading intensity. The role of rebound and release had no effect on concentric average force production. This conflicts with the findings of Newton et al. (23) who found greater average force across loads when comparing an SSC bench press throw with a concentric-only throw. Because rebound was found to produce greater peak accelerations and, therefore, peak forces, it would be assumed that greater average force would result. However, the effect of the greater peak force generated during the rebound bench presses appeared to have a negligible effect on average force production. This finding could be explained by the force-velocity relationship, as the velocity enhancement occurring due to rebound and release may be lost due to the inability of the muscle to generate force at higher shortening velocities. The findings could also be explained by peak force occurring very early during the concentric contraction, and the benefits of prestretching a muscle are lost if the movement continues over too long a time period. For example, very long stretching phases (approximately 500 ms) are associated with long coupling times (transition from eccentric to concentric contractions) and loss of elastic energy (2). Both the eccentric and concentric phases of all bench press techniques, across all the loads used in this study, exceeded 500 ms. Finally, the similar average force between the concentric-only and rebound techniques could be attributed to early termination of the concentric phase associated with motion that uses rebound (23).

Although the exact mechanism by which strength training elicits enhanced net synthesis of contractile proteins to increase the cross-sectional area (CSA) of muscle is yet to be determined, it is thought that both active and passive muscle tensions initiate this process (10). MacDougall (18) stated that whatever the exact mechanism for stimulating protein synthesis, loading intensity is the main determinant of whether increments in strength and size will occur. He continued to state that muscle must be activated at an intensity of at least 60–70% of maximum force-generating capacity before an increase in total muscle size and, hence, strength occurs. If muscle growth and contractile strength are related to the amount (load-tension) and time that tension is developed within the muscle (12), it would seem that the slower velocity training associated with higher 1RM training would be a better alternative for hypertrophic adaptation. Such loading augments both the duration of the stimulus (DOE and DOC) and the tension developed (average force) thus favoring a greater development of strength and muscle mass. This is not novel information. However, the use of SSC training to produce greater strength and CSA adaptation may warrant investigation. That is, the net effect of motion using SSC (RBP and RBPT) was to

**Table 1.** Mean values ± SD for peak velocity (PV), peak force (PF), time to peak velocity (TPV), and duration of concentric contraction (DOCC) for concentric only bench presses at loads ranging from 30 to 80% 1 repetition maximum.

<table>
<thead>
<tr>
<th>%</th>
<th>Concentric bench press</th>
<th>Concentric bench press throw</th>
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<tbody>
<tr>
<td></td>
<td>PV (m·s⁻¹)</td>
<td>PF (N)</td>
</tr>
<tr>
<td>30</td>
<td>1.49 ± 0.15</td>
<td>414.1 ± 74.7</td>
</tr>
<tr>
<td>40</td>
<td>1.35 ± 0.15</td>
<td>505.9 ± 82.8</td>
</tr>
<tr>
<td>50</td>
<td>1.16 ± 0.13</td>
<td>583.8 ± 84.9</td>
</tr>
<tr>
<td>60</td>
<td>1.01 ± 0.13</td>
<td>660.9 ± 99.4</td>
</tr>
<tr>
<td>70</td>
<td>0.86 ± 0.12</td>
<td>766.4 ± 151.9</td>
</tr>
<tr>
<td>80</td>
<td>0.68 ± 0.16</td>
<td>826.3 ± 138.2</td>
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produce greater average velocities (12.3% higher mean across loads) and peak forces (14.1% higher mean across loads). However, neither rebound nor release afforded greater load-tension (average force). Techniques (concentric only) that maintain tension for longer durations, maximize the contribution of the contractile component and minimize the recoil contribution of the passive elastic component, may be the most desirable techniques for changing the strength and CSA of muscle. Some literature supports such a contention because similar gains in muscle strength and size have been reported for eccentric-only training as compared with eccentric-concentric training (15–17) or greater gains with eccentric training (13). Further justification for such an approach is that the eccentric force implemented in an SSC appears to be ultimately limited by concentric force production (13). That is, as reported previously, prestretch potentiates the concentric contraction by 12–18%. If such augmentation is evident, the only manner in which greater SSC performance may ensue is by developing the ability of the muscle to generate greater concentric force. Intuitively and according to the principle of specificity, it would seem that techniques that minimize the contribution of rebound and maximize concentric contribution should be the methods of choice to achieve this purpose.

An interesting study, which raises questions as to the importance of load and tension in maximal strength development, trained the elbow flexors of the non-dominant arm using loads of 15% (10 reps), 35% (7 reps), and 90% (2 reps) of 1RM (20). Training volume was equated by matching the total time under tension between loads, and subjects were encouraged to move their respective loads with maximal effort. After 9 weeks of training, significant maximal strength gains were recorded (6–7%), but the differences between the light (15% 1RM) and heavy (90% 1RM) groups were nonsignificant. Similar methodologies and findings by other researchers support the findings of Moss et al. (8, 27). It was concluded that their results were not in conflict with the idea that high tension may be the stimulus for increased maximal strength albeit high forces were of shorter duration. It may be that load is not as important a stimulus as initially proposed. If the results of this study were extended to compare equi-volume (load) training between a strength-training stimulus (80% 1RM) and a power-training stimulus (40% 1RM), the results in Table 3 would hypothetically eventuate.

It is obvious from the table that when training controls or equates for volume, as much of the research in this area does, the actual set kinematics and kinetics between training protocols vary dramatically. It can be observed from Table 3 that the power-training stimulus (40% 1RM) offers similar average force and greater time under tension, peak force, and power outputs.
Figure 2. Average velocity (m·s\(^{-1}\)) at different loads relative to 1 repetition maximum for 4 different explosive weight-training techniques.

Table 3. Hypothetical values for various kinematic and kinetic variables when equated by volume.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>2 reps at 80% 1RM</th>
<th>4 reps at 40% 1RM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of eccentric phase (s)</td>
<td>2 × 1.23 = 2.46</td>
<td>4 × 0.642 = 2.56</td>
</tr>
<tr>
<td>Duration of concentric phase (s)</td>
<td>2 × 0.831 = 1.662</td>
<td>4 × 0.629 = 2.516</td>
</tr>
<tr>
<td>Total time under tension (s)</td>
<td>4.122</td>
<td>5.076</td>
</tr>
<tr>
<td>Average force (N)</td>
<td>2 × 678.9 = 1,377.8</td>
<td>4 × 340.4 = 1,361.6</td>
</tr>
<tr>
<td>Peak force (N)</td>
<td>2 × 902.5 = 1,804.0</td>
<td>4 × 596.1 = 2,384.4</td>
</tr>
<tr>
<td>Average power (W)</td>
<td>2 × 232.2 = 464.4</td>
<td>4 × 263.3 = 1,053.2</td>
</tr>
<tr>
<td>Peak power (W)</td>
<td>2 × 468.8 = 937.6</td>
<td>4 × 536.6 = 2,145.2</td>
</tr>
</tbody>
</table>

* Volume estimated from 1 repetition maximum (1 RM) of 100 kg. Therefore 2 reps at 80% 1RM = 160 kg. For equi-volume loading to occur at 40% 1RM, 4 repetitions must be performed. The individual values for each variable are multiplied by the number of repetitions to calculate the total per variable per set.

Given the limitations of this example, more research of this nature that analyses the kinematic and kinetic characteristics of reps and sets would give better insights into the changes and adaptations occurring with the repeated application of that training stimulus. For example, a better understanding of the findings of Moss et al. is enabled if framed in a set kinematic or kinetics context. Certainly this type of paradigm that investigates set kinematics and kinetics and the effects of such training on maximal strength and power development warrants further investigation.

Throwing the bar produced greater average velocities than traditional techniques that held the bar, for the lighter loading intensities of 30–60% 1RM. With heavier loading intensities (70–80% 1RM), the ability to release the load became compromised and the benefits of throwing the load negated. Temporal analysis of the signals revealed that peak velocities were achieved later in the concentric action for the throw conditions, indicating that the bar is being accelerated over a greater portion of the concentric phase. Newton et al. (22) found similar results, explaining that the bar was accelerated throughout a greater range in RBPT (96%) compared with RBP (60%), resulting in higher end velocities. As a result of the greater duration of concentric acceleration, a corresponding increase in force production would be expected. This was not the case, however, because the enhancement of bar velocity by the throw was apparently offset by the muscle’s inability to generate force at high shortening velocities according to the force-velocity relationship of the muscle.
Unlike force, the shortening velocity of muscle may be independent of the actual number of cross-bridges that interact with actin filaments (9). High-intensity, heavy-load training that increases myofilament number will have little benefit in producing changes in contraction velocity. Rather, training that aims at increasing the rate of the cross-bridge attach-detach cycle is needed. Maximal velocity training that uses light loads and allows projection of oneself or an object would appear to be the best option. Light-load ballistic training is typified by shorter contraction times, shorter time to peak velocity, higher average and peak velocities, and decreased force output. As such, this type of training is more likely to stimulate high-velocity adaptation within the muscle. It should be noted, however, that the training velocities recorded in this research and encountered in the weight-training environment (0.63–1.68 m·s\(^{-1}\)) do not simulate the actual release velocities recorded for functional tasks. For example, release velocities of 11.96 and 13.0 m·s\(^{-1}\) have been recorded for the netball chest pass and shot put, respectively (7, 26). The importance of velocity specificity in strength training for improved functional performance certainly appears to lack external validity. It may be that the value of ballistic training is not the actual velocity specificity of the weight-training movement but rather the movement pattern specificity the movement allows. That is, the acceleration or deceleration profiles better simulate everyday and sporting activities and, therefore, may lead to more efficient coordination and activation patterns. It may be that for functional high-velocity adaptation to occur, sport-specific motion training needs to occur in liaison with other resistance strength-training techniques and loading patterns (complex or combination training). More research that combines strength and conditioning and motor control perspectives would undoubtedly result in a better understanding of the transference of strength and power gains to functional performance.

**Practical Applications**

Because the force-velocity relationship of muscle characterizes the dynamic capability of muscle, the force-velocity response of muscle to a variety of strength-training techniques and loads was studied. Average force output was unaffected by the technique used across all loads. Greater force output was recorded using higher loading intensities. It was proposed that heavy loading coupled with techniques that maintain tension for longer durations, maximize the contribution of the contractile component, and minimize the recoil contribution of the passive elastic component would appear to be the most desirable for improving force output. Implicit in such an approach would be the use of techniques that minimize the contribution of rebound. In this regard, concentric-only training, super-slow training, pause training, functional isometrics, and interrep rest training may be the best resistance-training techniques to achieve these goals. Super-slow training uses extended eccentric and concentric phases to keep the muscle under constant tension. The added advantage of slow motion is that the rate of eccentric contraction and slow coupling times result in greater loss of elastic energy (5), thereby minimizing the contribution of the passive elastic elements. Pause training ensures that the contractile element is more forcibly worked because pauses of 4 seconds or greater at the completion of the eccentric phase of the motion ensure that any augmentation afforded by elastic energy is dissipated as heat (29). Functional isometrics combines a dynamic isoinertial contraction with an isometric contraction for a given movement and results in greater mean concentric forces and time under tension than do traditional weightlifting techniques (25). Interrep rest training incorporates the complete unloading of the active musculature for a period of time at the completion of the eccentric phase. It is thought that the periodic blood flow during the relaxation between repetitions is more likely to stimulate peripheral adaptations that result in improvements in aerobic function (3). However, transference of strength and power gains from this type of training to dynamic functional performance may be compromised because of the lack of specificity of such training to everyday and sporting activities. This problem may be minimized if such training is combined with ballistic training. Ballistic training (30–60% 1RM) led to greater movement velocities in this study. As such, this type of training is more likely to stimulate high-velocity adaptation within the muscle, especially if the training velocities approach the actual movement velocity of the athletic event. A further benefit of ballistic training was the movement pattern specificity it allowed, the acceleration-deceleration profiles similar to those encountered in the athletic environment. To what extent the repeated applications or combination of these different techniques affect strength, power, and functional performance needs to be examined in the future.

**References**


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