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Effect of Loading on Unintentional Lifting Velocity Declines During Single Sets of Repetitions to Failure During Upper and Lower Extremity Muscle Actions

Abstract

The purpose of this study was to examine the effect of different loads on repetition speed during single sets of repetitions to failure in bench press and parallel squat. Thirty-six physical active men performed 1-repetition maximum in a bench press ($1\ RM_{BP}$) and half squat position ($1\ RM_{HS}$), and performed maximal power-output continuous repetition sets randomly every 10 days until failure with a submaximal load (60%, 65%, 70%, and 75% of 1RM, respectively) during bench press and parallel squat. Average velocity of each repetition was recorded by linking a rotary encoder to the end part of the bar. The values of $1\ RM_{BP}$ and $1\ RM_{HS}$ were 91 ± 17 and 200 ± 20 kg, respectively. The number of repetitions performed for a given percentage of 1RM was significantly higher ($p < 0.001$) in half squat than in bench press performance. Average repetition velocity decreased at a greater rate in bench press than in parallel squat. The significant reductions observed in the average repetition velocity (expressed as a percentage of the average velocity achieved during the initial repetition) were observed at higher percentage of the total number of repetitions performed in parallel squat (48 – 69%) than in bench press (34 – 40%) actions. The major finding in this study was that, for a given muscle action (bench press or parallel squat), the pattern of reduction in the relative average velocity achieved during each repetition and the relative number of repetitions performed was the same for all percentages of 1RM tested. However, relative average velocity decreased at a greater rate in bench press than in parallel squat performance. This would indicate that in bench press the significant reductions observed in the average repetition velocity occurred when the number of repetitions was over one third (34%) of the total number of repetitions performed, whereas in parallel squat it was nearly one half (48%). Conceptually, this would indicate that for a given exercise (bench press or squat) and percentage of maximal dynamic strength (1RM), the pattern of velocity decrease can be predicted over a set of repetitions, so that a minimum repetition threshold to ensure maximal speed performance is determined.

Key words
Bench press · parallel squat · load-velocity relationship

Introduction

Coaches and researchers in the field of resistance training attempt to identify the proper handling of training variables to determine the training stimulus that maximizes performance enhancement. One variable that is less considered when designing programs to optimize athletic performance is movement velocity. Classically, the choice of the load should impact the velocity of the movement but most of the data examining this phenomenon have been obtained with isokinetic exercise [11]. The veloc-

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ity of movement will impact the training stimulus and subsequently the adaptations to training. It has been suggested, therefore, that athletes should try to perform exercises "explosively" at a velocity allowed by the resistance used in a volitional manner. Training at a specific velocity improves the application of force and maximum rate of force development mainly at that velocity, so that less effective training effect will occur if training velocity deviates from the specific trained velocity [1 – 3,10,17]. Greater average and peak velocity, average force, and average power output have been recorded by using training stimulus aiming at decreasing the deceleration phase by allowing the load to be projected as in a throw or a jump [2,3,14]. Velocity and acceleration profiles will also differ according to different loading regimens for overall set performance and velocity. However, the impact of loading on repetition and set velocity is unclear.

In the classical concentric force-velocity curve, muscle contraction velocity decreases with an increase in muscle tension, reaching the maximal repetition speed in unloaded condition [6,9]. It has been also reported that over a set of repetitions to failure the speed of the repetition slows naturally as fatigue increases. The impact of such velocity changes or the mean velocity over a set of repetitions at a given percentage of the maximal dynamic strength (1RM) remains unclear. Using different percentages of the 1RM load and making comparisons between the resulting average velocities would give initial insights into comparisons among percentages as well as between differing muscular groups. Future research needs to examine the subsequent fatigue that exists with continuous sets of the same exercise using different rest period lengths.

To the authors' knowledge one study showed a significant increase due to fatigue of the concentric phase from the first repetition to the last repetition during a 5RM bench press [13]. However, the optimal number of repetitions with different loads at which maximal repetition speed is not decreased due to fatigue is not known. It is also likely that time-course decreases in unintentional velocity may vary between the upper and lower extremity. For example, in relation to differences in biomechanical characteristics of the open and closed upper/lower kinetic chain exercises or to different muscle fiber distribution between muscle groups. Hoeger and coworkers [7] also demonstrated that the lower the percentage the higher the number of repetitions. However, this was affected by the amount of muscle used in the exercise, with large muscle groups requiring higher percentages to elicit lower RM values. The purpose of this study, therefore, was to examine two major exercises, one for the upper body (bench press), and one for the lower body (the parallel squat) in order to compare the resulting average velocity among sets at different percentages of the 1RM. Whether a different pattern of velocity declines might be expected between the upper and lower extremity muscle actions is an important question that remains to be addressed.

Methods

Subjects

A group of thirty-six Basque ball players, with a regular training and competitive background in basque ball (12.5 ± 5 yr) volunteered to participate in the study. The subjects' mean (± SD) age, height, body mass, and percentage of body fat were 24 (± 2.9) years, 1.80 (± 0.01) m, 80 (± 2.01) kg, and 12.2 (± 4.4) %, respectively. All the subjects were members of the Spanish national team of Basque ball. This study was performed during the first pre-season period (February to April), prior to commencing the XIV World Basque Ball Championship. All the subjects had experience with the exercises. During the fifteen months preceding the beginning of the study the subjects took part in a resistance training program, consisting mainly of typical (free weight) weight lifting exercises (i.e. including the test exercises of bench press, back squats) for 3 sets of 6 – 8 repetitions, with a relative intensity of 60 – 75 % of 1RM.

The last strength training session took place 5 – 7 days before the first test session. The study was conducted according to the Declaration of Helsinki and was approved by the Institutional Review Committee of the Instituto Navarro de Deporte y Juventud (Navarra, Spain). The subjects were not taking exogenous anabolic-androgenic steroids or other drugs or substances expected to affect physical performance or hormonal balance for several months before or during this study, nor were they on any medication that would impact the results of the study.

Experimental design

Subjects completed a 5-day experimental protocol on five different occasions separated by 10 days. Body weight and percent body fat, estimated from the measurements of seven skin-fold thickness, were taken at the beginning of the testing session. During the first testing session, each subject was tested for one repetition maximum (1RM) in bench press (1 RM_{BP}) and parallel squat (1 RM_{HS}) in order to determine the percentages that would be used in the set of repetitions to failure. During subsequent test sessions, each subject was tested to perform a maximal repetitive high power-output set randomly every 10 days until failure with a submaximal load (60 %, 65 %, 70 %, and 75 % of 1RM, respectively) during bench press and parallel squat. All the subjects were familiar with the testing protocol, as they had been previously tested on several occasions during the season with the same testing procedures. The test-retest intraclass correlations coefficients of the testing procedure variables used in this study were greater than 0.91 and the coefficients of variation (CV) ranged from 0.9 % to 2.3 %.

Performance testing

Maximal bench press and parallel squat strength

A detailed description of the maximal strength and muscle power testing procedure can be found elsewhere [9]. In brief, during the first test session, lower and upper body maximal strength was assessed using one repetition maximum bench press (1 RM_{BP}) and parallel squat (1 RM_{HS}) actions. In the 1 RM_{BP} protocol, the test began with the subject lowering the bar with the arms fully extended above the chest, until the bar was positioned 1 cm above the subject's chest and supported by the bottom stops of the measurement device. From that position, the subject was instructed to perform, a purely concentric action (as fast as possible) maintaining the shoulders in a 90-degree abducted position to ensure consistency of the shoulder and elbow joints throughout the testing movement. No bouncing or arching of the back was allowed. In the 1 RM_{HS} protocol, the test began with the shoulders in contact with the bar from an extended leg position, lower down under control to the position of the thigh being parallel to the floor. On command the subject performed a concentric leg extension (as fast as possible) starting from the flexed position to reach the full extension of 180 degrees against the resistance determined by the weight plates added to both ends of the bar. The motion was completed when the torso was upright. All the tests were performed in a Smith's machine in which the barbell was attached to both ends, with linear bearings on two vertical bars allowing only vertical movements. Warm-up consisted of a set of 5 repetitions at loads of 40 – 60% of the perceived maximum. Thereafter, four to five separate single attempts were performed until the subject was unable to extend his legs or arms to reach the full extension. The rest between maximal attempts was always 2 min.

Sets of maximal power-output continuous repetitions were performed *until failure with submaximal loads.* During subsequent test sessions, each subject performed a maximal repetitive high power-output set randomly every 10 days until failure with a submaximal load (60%, 65%, 70%, and 75% of 1RM, respectively) during bench press and parallel squat. The subjects were asked to move the bar as fast as possible during the concentric phase of each repetition, until failure. Failure was defined at the time point when the bar ceased to move, if the subject paused more than 1 s when the leg or arms were in the extended position, or if the subject was unable to reach the full extension position of the arms or legs. During the first repetitions the cadence was controlled with a metronome with a frequency of 19 Hz. As fatigue increased and performance of repetitions became progressively more difficult an own rate cadence under 19 Hz was allowed, the time of rest between the repetitions remaining constant.

During the lower extremity test actions, bar displacement, average velocity ($m \cdot s^{-1}$), and mean power (watts) were recorded by linking a rotary encoder to the end of the bar. The rotary encoder (Computer Optical Products Inc, California, USA) recorded the position and direction of the bar within an accuracy of 0.2 mm and time events with an accuracy of 1 ms. Customized software (JLML I + D, Madrid, Spain) was used to calculate the power output for each repetition of half squat performed throughout the whole range of motion. Total repetitions for each set of bench presses and average velocity for each repetition of half squat and bench press were determined. Velocity curves were plotted using average velocity over the whole range of movement as the most representative mechanical parameter associated with a contraction cycle of leg and arm extensor muscles participating in the parallel squat (i. e. hip, knee, and ankle joints) and bench press performance (i. e. shoulder and elbow joints) [9]. For comparison purposes, velocity of each repetition was expressed in absolute values as a percentage of the average velocity attained during the first two repetitions of each set.

Statistical methods

Standard statistical methods were used for the calculation of the mean and standard deviations (SD). Average velocity declines were compared in both absolute and relative terms via a two-way analysis of variance with repeated measures design. When a significant F-value was achieved, Sheffé post hoc procedures were performed to locate the pairwise differences between the means. The $p < 0.05$ criterion was used for establishing statistical significance.

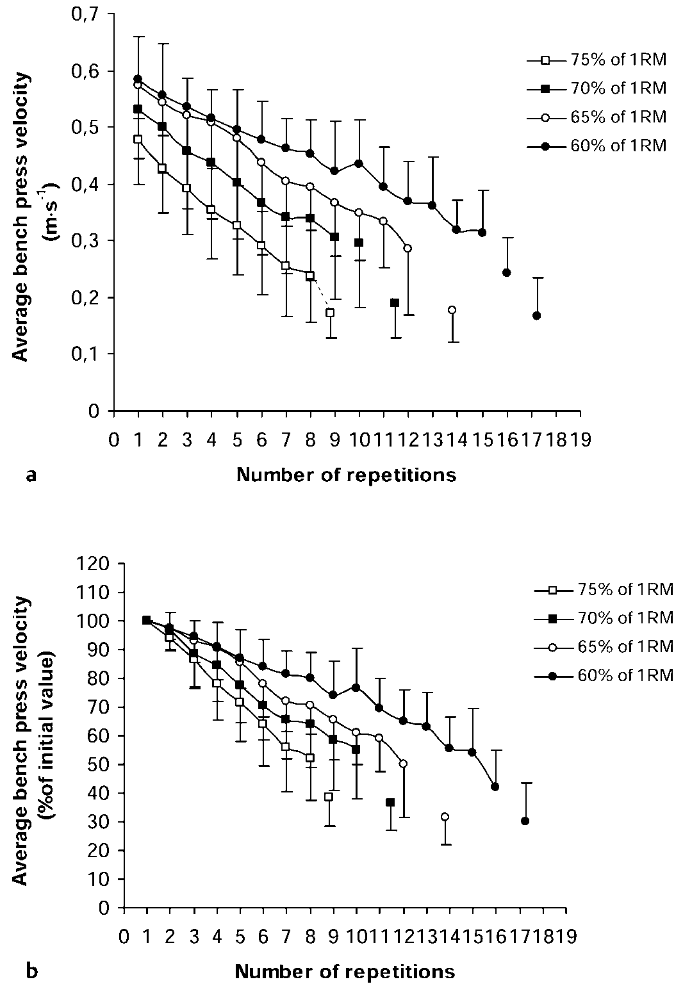

Fig. **1 a** and **b** Average bench press velocity changes during the course of submaximal single sets of repetitions to failure with different percentages of 1-RM (60, 65, 70, and 75%) in a bench press action. Values of bench press velocities are expressed in absolute values (**a**) and as a percentage of velocity of first repetition (**b**). See text for significant declines in average repetition speed within the loads.

Results

Bench press performance

The value of 1 RM_{BP} was 91 ± 17 kg. A significantly ($p < 0.001$) different number of repetitions were performed during the sets at 75% (8.8 ± 2), 70% (11.4 ± 2), 65% (13.8 ± 2), and 60% (17.25 ± 2) of 1 RM_{BP}. Absolute average bench press velocity declined consistently during the sets performed with all percentages of 1RM tested (Fig. **1 a**). When expressed as a percentage of the average velocity achieved during the initial two repetitions, significant declines ($p < 0.05 – 0.001$) in average relative velocity were observed at repetitions 3, 4, 5, and 7 during the sets performed at 75%, 70%, 65%, and 60% of 1RM, respectively (Fig. **1 b**). The repetition at which a significant decrease in the initial relative velocity occurred corresponded to 34%, 35%, 36%, and 40% of the total number of repetitions achieved at 75%, 70%, 65%, and 60% of

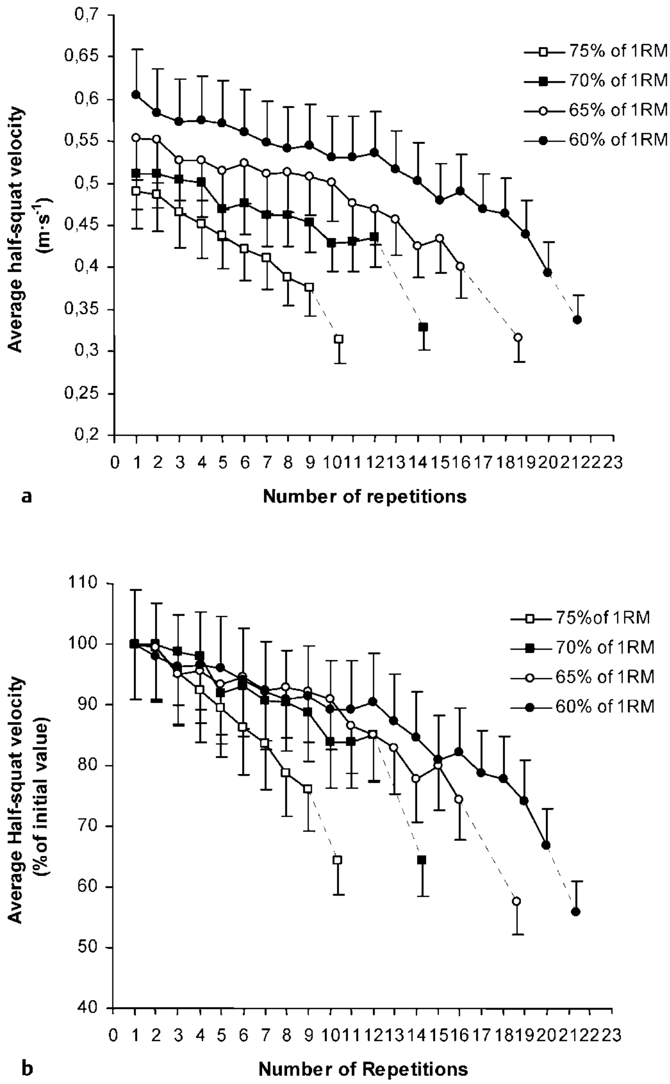

Fig. **2a** and **b** Average parallel squat velocity changes during the course of submaximal single sets of repetitions to failure with different percentages of 1-RM (60, 65, 70, and 75%) in a parallel squat action. Values of parallel squat velocities are expressed in absolute values (**a**) and as a percentage of velocity of first repetition (**b**). See text for significant declines in average repetition speed within the loads.

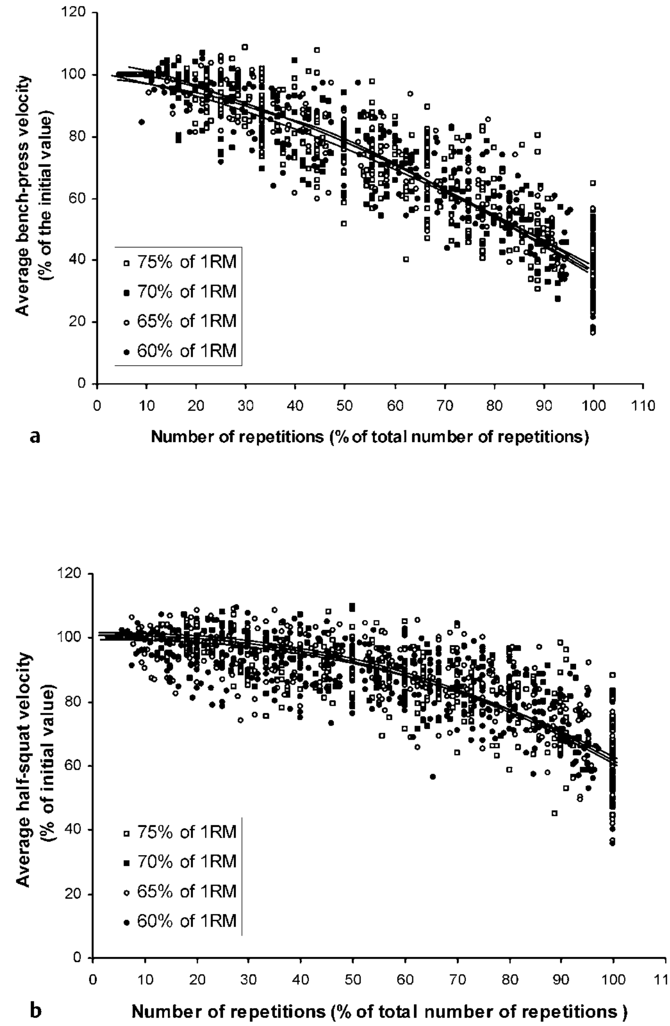

Fig. **3a** and **b** Relationship between the average velocity achieved during each repetition and the number of repetitions performed with different percentages of 1RM in a bench press (**a**) and parallel squat actions (**b**).

1RM, respectively. The average velocity attained during the last repetition performed during the sets at 75% ($0.17 \pm 0.04\,m \cdot s^{-1}$), 70% ($0.18 \pm 0.05\,m \cdot s^{-1}$), 65% ($0.18 \pm 0.05\,m \cdot s^{-1}$), and 60% ($0.17 \pm 0.06\,m \cdot s^{-1}$) of 1 RM_{BP} were not significantly different and ranged from 30% to 38% of the average velocity attained during the initial two repetitions. The average velocity attained with the load of one repetition maximum (1RM) was similar ($0.15 \pm 0.03\,m \cdot s^{-1}$) to that attained during the last repetition performed with all the loads tested in bench press action. For a given relative load ranging from 60% to 75% of 1RM, the shapes of the decline in the average relative velocity achieved during each repetition (expressed as a percentage of the initial value) and the relative number of repetitions performed (expressed as a percentage of the total number of repetitions performed), followed the same pattern (Fig. **3a**). The equation predicting the decline in average velocity (AV) from the percentage of the relative number of repetitions (PR) performed intensities ranging from 60% to 75% of 1RM was $-0.0032\,PR^2 - 0.331\,PR + 102.47$ (R 2 accounted for 83% of the variance, with a SEE of 0.09).

Parallel squat performance

The value of the 1 RM_{HS} was 200 ± 20 kg. A significantly ($p < 0.001$) different number of repetitions was performed during the sets performed at 75% (10.4 ± 1), 70% (14.2 ± 2), 65% (18.6 ± 2), and 60% (21.5 ± 2) of 1 RM_{HS}. Absolute average parallel squat velocity declined consistently during the sets performed with all percentages of 1RM tested (Fig. **2a**). When expressed as a percentage of the average velocity achieved during the initial two repetitions, significant declines ($p < 0.05 - 0.001$) in average relative velocity were observed at repetitions 5, 9, 11, and 15 during the sets performed at 75%, 70, 65, and 60% of 1 RM_{HS}, respectively (Fig. **2b**). The repetition at which a significant decrease in the initial relative velocity occurred corresponded to 48%, 63%, 59%, and 70% of the total number of repetitions achieved at 75%, 70%, 65%, and 60% of 1RM, respectively. The average absolute velocities attained during the last repetition performed during the sets at 75% ($0.31 \pm 0.05\,m \cdot s^{-1}$), 70% ($0.32 \pm .07\,m \cdot s^{-1}$), 65% ($0.31 \pm 0.06\,m \cdot s^{-1}$), and 60% ($0.33 \pm 0.07\,m \cdot s^{-1}$) of 1 RM_{HS} were not significantly different and ranged from 55% to 64% of the average absolute velocity attained during the initial repetition of each load. The average velocity attained with the load of one repetition maximum (1RM) was similar ($0.27 \pm 0.02\ m \cdot s^{-1}$) to that attained during the last repetition performed with all loads tested in parallel squat actions. The shapes of the decline in the relative average velocity achieved during each repetition (expressed as a percentage of the initial value) and the relative number of repetitions performed (expressed as a percentage of the total number of repetitions performed) followed the same pattern with all percentages of 1RM tested (Fig. **3b**). The equation predicting the decline in average relative velocity (AV) from the percentage of the relative number of repetitions (PR) performed at range intensities from 60% to 75% of 1RM was $-0.0044\,PR^2 + 0.1218PR + 96.758$ (R2 accounted for 63% of the variance, with a SEE of 0.09).

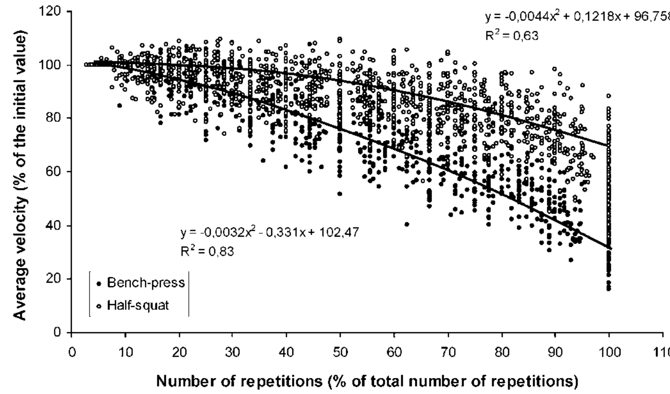

Fig. **4** Relationship between the average velocity achieved during each repetition and the number of repetitions performed with different percentages of 1RM in bench press and parallel squat performance.

Comparison between bench press and parallel squat performance

The average relative velocity achieved during each repetition (expressed as a percentage of the initial value) and the relative number of repetitions performed (expressed as a percentage of the total number of repetitions performed) decreased at a greater rate in bench press than in parallel squat performance (Fig. **4**). The total number of repetitions performed for a given percentage of 1RM was significantly higher ($p < 0.001$) in parallel squat than in bench press action. The average velocity attained during the last repetition performed during the sets at 75%, 70%, 65%, and 60% of 1RM was significantly higher in parallel squat ($0.32 \pm 0.06\ m \cdot s^{-1}$) than in bench press ($0.17 \pm 0.06\ m \cdot s^{-1}$) action (Figs. **1a** and **2a**). The significant declines observed in average relative velocity were observed at higher percentage of the total number of repetitions performed in parallel squat (48–69%) than in bench press (34–40%) actions (Figs. **1b** and **2b**).

Discussion

A unique approach in this study was to examine the impact of different loads on repetition and set velocity declines during high intensity upper and lower muscle actions. In agreement with previous studies, we found that over a set of repetitions until failure the speed of the repetitions slows naturally [13,15], whereby performance of repetitions became progressively more difficult as fatigue increases. The major finding in this study was that, for a given muscle action (bench press or parallel squat), the pattern of decline in the relative average velocity achieved during each repetition (expressed as a percentage of the initial value) and the relative number of repetitions performed (expressed as a percentage of the total number of repetitions performed) was the same with all percentages of 1RM tested. However, relative average velocity decreased at a greater rate in bench press than in parallel squat performance. Conceptually, this would indicate that for loads ranging from 60% to 75% of 1RM, one may predict the pattern of velocity decrease for a given exercise, so that a minimum repetition threshold to ensure maximal speed performance would be determined.

A different pattern of velocity declines in relative average velocity was observed when performing repetitions at different intensities between upper and lower extremity muscle actions. For all intensities tested, the average repetition velocity decreased at a greater rate in bench press than in parallel squat performance, so that in bench press performance the significant declines observed in the average repetition velocity (expressed as a percentage of the average velocity achieved during the initial repetition) occurred when the number of repetitions was over 34% of the total number of repetitions performed, whereas in parallel squat it was over 48%. In addition, it was interesting to observe that the velocity attained during the last repetition performed during the sets at 75%, 70%, 65%, and 60% of 1RM was significantly higher in half squat than in bench press performance.

To the best of the authors' knowledge a paucity of data have examined the differences in the pattern of decline in relative intensity between the upper and lower extremity actions. This may be partly explained by differences in the deceleration phases between the upper and lower type of movements performed. The deceleration phase is an important part of the lift, in which bar velocity decreases because it is intentionally decelerated by the performer [11,14]. During bench press, with a load of 45% of 1RM, the deceleration phase was shorter (40% of the concentric movement time) [14] compared to the slow bench press with heavy loads (51.7% of the concentric movement time with a load of 81% of 1RM) [4]. Furthermore, Newton and coworkers [14] also showed that for a given load of 45% of 1RM bench press action involves a longer deceleration phase (40% of the movement) compared with a bench throw condition (4% of the concentric movement time). It is also suggested that when attempting to perform a powerful press movement and maximize bar velocity, the subject reduces the length of this deceleration phase [4,14]. In the present study, it was interesting to observe that performing high-velocity repetitions with free weights at different intensities (60% to 75% of 1RM) from parallel squat position may have a longer deceleration phase than in the bench press exercise. Thus, during parallel squat performance the load could not be maximally accelerated through the full range of motion as much as in bench press performance. This suggests that, during parallel squat performance, the shorter length of the concentric effort phase attained during completion of each repetition may induce a less relative repetition intensity and therefore explain the average velocity decrease at a lower diminished rate in parallel squat than in bench press performance.

The shape of the power and velocity curve at different loads during bench press has been also previously reported to differ from that observed during parallel squat performance. Thus, it has been shown that the velocity that elicited the maximal power in the lower extremities was lower ($\approx 0.75\ m \cdot s^{-1}$) than that occurring in the upper extremities ($\approx 1\ m \cdot s^{-1}$) [9]. Similarly, when performing repetitions to failure with different intensities, a possible explanation for the different pattern of decline in average velocity between the upper and lower extremity muscle actions may be also associated with extremity-related differences in maximal strength, muscle cross-sectional area, fiber type distribution [12], muscle mechanics (i.e. length and muscle pennation angle) of the upper and lower limbs, together with functional differences according to the joint position and geometry of the joints and levers [5]. It is likely that the repetition-velocity relationship may vary between different muscle groups, for example, in relation to fiber type distribution and/or biomechanical characteristics of the open and closed upper/lower kinetic chains.

Finally, another possible explanation that might account for the differences observed between bench press and half squat actions in the pattern of velocity declines when performing repetitions to failure with different intensities, may be related to differences in the coordination and postural control, as well as the number and size of the muscle groups responsible for the upper and lower extremity muscle actions. It has recently been observed that the time to task failure (time a task can be sustained) may be influenced by the amount of activity that is necessary in accessory muscles to produce the required position [8]. Thus, the faster declines observed in the average repetition velocity of the upper extremity muscles when performing repetitions to failure may be also related to the lower coordination and postural control required to fatigue, as well as to the lower amount of muscles involved in bench press performance. To what extent different patterns of velocity-reduction could be observed during a more controlled lower extremity action (i.e. from leg press position) requiring less muscle coordination needs to be further examined. Hoeger and coworkers [7] also demonstrated that the lower the percentage the higher the number of repetitions. However, this was affected by the amount of muscle used in the exercise, with large muscle groups requiring higher percentages to elicit lower RM values. The findings of this study indicate that a given percent of 1RM will not always elicit the same number of repetitions when performing different lifts. Furthermore, it should also be taken into consideration that one could squat slightly more weight in parallel squat (thigh parallel to floor) as opposed to full range of motion [13] and thus the subjects will be lifting a heavier weight for the 60 – 75% protocols compared to a full squat protocol. This observation may also suggest that the number of repetitions performed to failure, as well as the time to starting exercise failure (which was higher for the half squat) may be slightly inflated because only a partial range of motion was used.

An interesting finding was that the average velocity attained during the last repetition performed with different intensities (60%, 65%, 70%, and 75% of 1RM) and that attained with the 1RM were similar for a given muscle action. This feature suggests that a minimum velocity threshold, and thus force application, would be needed to further perform a successful individual repetition across a set of repetitions to failure, as well as with different loading intensities (% of 1RM). These observations may have important practical relevance for optimizing the control of relative training intensity related to different loads and optimal number of repetitions.

The present results indicate a consistent and similar pattern of decline in repetition speed during the repetitions performed at maximal intentional speed with all percentages of 1RM tested in both upper and lower extremity muscle actions. For all intensities tested, the decrease in the speed of movement in bench press action was significant when the number of repetitions was over one third (34%) of the total number of repetitions performed, whereas in half squat it was nearly one half (48%). It is concluded that, for the range of intensities tested, in order to guarantee a maximal training velocity and to avoid a decline in the repetition speed, the number of repetitions performed in a set should not exceed one third and one half of the performed maximum number of repetitions to failure, respectively, in bench press and parallel squat actions. This maximal velocity threshold corresponds to an approximate 13% and 8% decrease of the velocity achieved during the first repetition for bench press and half squat muscle actions, respectively. The present results may be of use in evaluating the optimal training number of repetitions required to ensure optimal maintenance of the maximal performance velocity with different percentages of maximum strength.

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