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Fernando Pareja-Blanco^{1,2}; Julián Alcazar^{3,4}; Juan Sánchez-Valdepeñas¹;
Pedro J. Cornejo-Daza¹; Francisco Piqueras-Sanchiz¹; Raúl Mora-Vela¹;
Miguel Sánchez-Moreno⁵; Beatriz Bachero-Mena⁵; Manuel Ortega-Becerra^{1,2}; Luis M. Alegre^{3,4}

¹Physical and Athletic Performance Research Centre, Sports and Computers Sciences. Universidad Pablo de Olavide, Seville, Spain; ²Faculty of Sport Sciences. Department of Sports and Computers Sciences. Universidad Pablo de Olavide, Seville, Spain; ³GENUD Toledo Research Group, Universidad de Castilla-La Mancha, Toledo, Spain; ⁴CIBER of Frailty and Healthy Aging (CIBERFES), Madrid, Spain; ⁵Department of Physical Education and Sports, University of Seville, Seville, Spain

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Velocity Loss as a Critical Variable Determining the Adaptations to Strength Training

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¹Physical and Athletic Performance Research Centre, Sports and Computers Sciences. Universidad Pablo de Olavide, Seville, Spain; ²Faculty of Sport Sciences. Department of Sports and Computers Sciences. Universidad Pablo de Olavide, Seville, Spain; ³GENUD Toledo Research Group, Universidad de Castilla-La Mancha, Toledo, Spain; ⁴CIBER of Frailty and Healthy Aging (CIBERFES), Madrid, Spain; ⁵Department of Physical Education and Sports, University of Seville, Seville, Spain

Corresponding author: Fernando Pareja Blanco

Physical and Athletic Performance Research Centre, Pablo de Olavide University, Ctra. de Utrera, km 1, 41013 Seville, SPAIN.

email: fparbla@upo.es

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ABSTRACT:

Purpose: This study aimed to compare the effects of four resistance training (RT) programs with different velocity loss (VL) thresholds: 0% (VL0), 10% (VL10), 20% (VL20) and 40% (VL40) on sprint and jump performance, muscle strength, neuromuscular, muscle hypertrophy and architectural adaptations. **Methods:** Sixty-four young resistance-trained men were randomly assigned into four groups (VL0, VL10, VL20, and VL40) that differed in the VL allowed in each set. Subjects followed an RT program for 8 weeks (2 sessions per week) using the full-squat (SQ) exercise, with similar relative intensity (70-85% 1RM), number of sets (3) and inter-set recovery period (4-min). Before and after the RT program the following tests were performed: 1) muscle hypertrophy and architecture of the vastus lateralis (V_{LA}); 2) tensiomyography; 3) 20-m running sprint; 4) vertical jump; 5) maximal voluntary isometric contraction in SQ; 6) progressive loading test in SQ; and 7) fatigue test. **Results:** No between-group differences existed for RT-induced gains in sprint, jump and strength performance despite the differences in the total volume performed by each group. VL20 and VL40 showed significant increases ($P < 0.001$) in muscle hypertrophy (group \times time interaction, $P = 0.06$). However, only VL40 exhibited a significant slowing ($P < 0.001$) of the delay time in the V_{LA} muscle (group \times time interaction: $P = 0.05$). Moreover, VL40 showed a significant decrease in the early rate of force development ($P = 0.04$). **Conclusions:** Higher VL thresholds (i.e. VL20 and VL40) maximized hypertrophic adaptations, although an excessive VL during the set (i.e. VL40) may also induce negative neuromuscular adaptations. Therefore, moderate VL thresholds should be chosen to maximize strength adaptations and to prevent negative neuromuscular adaptations.

Keywords: resistance training, dose-response, neuromuscular adaptations, architectural adaptations, tensiomyography, muscle hypertrophy

INTRODUCTION

Resistance training (RT) is recognized as an effective method for improving overall fitness (1). In this regard, the manipulation of training variables such as relative intensity (%1RM), volume, exercise type and order, rest duration and repetition velocity is a critical factor in order to induce neural and morphological adaptations (2, 3). Notably, the dose-response relationship between training volume and athletic performance adaptations has been suggested to exhibit an inverted U-shaped curve (4-6). A recent study by Barbalho et al. (7) reported the existence of a plateau in strength gains and muscle hypertrophy after a threshold volume was reached (5-10 sets per muscle group per session). Further increases in training volume did not yield any gains and even led to declines in performance. However, most investigations have focused on the dose-response relationship between RT volume and RT-induced adaptations by manipulating the number of sets (2, 7-9), while other alternatives remain unexplored.

Among the variables that can be manipulated to configure training volume, the actual number of repetitions performed in a set in relation to the maximum number of repetitions that can be completed (i.e. 'level of effort') (10) seems to be another variable that should be considered when designing an RT program (10-12). Exercise sets are traditionally completed by performing every repetition in succession until the desired number of repetitions is reached (1, 3). However, since the number of repetitions that can be completed against a given %1RM has shown a large variability between individuals (13, 14), this traditional approach can lead to different levels of effort among individuals performing the same number of repetitions per set. It has been shown that the level of fatigue increases gradually as the level of effort during the set increases (10). In this regard, the gradual decrease in lifting velocity across repetitions performed within a set can be interpreted as evidence of impaired neuromuscular function, and its assessment may provide a

simple and objective means of quantifying levels of fatigue (10). Moreover, there is a strong positive relationship between the percentage of velocity loss (VL) induced during the set and the percentage of repetitions that can be completed before muscle failure ($R^2 = 0.93-0.97$) (14). Thus, the monitoring of repetition velocity and of relative VL during training provides real-time feedback on the level of effort exerted in the set, with considerable accuracy. This novel strategy allows the application of a more homogeneous stimulus across individuals, which might be useful in protocols aimed at studying adaptations to different levels of fatigue during RT sessions, since a standardized state of fatigue is induced.

A recent study (15) compared the effects of two squat training programs that only differed in the relative VL reached in each set: 20% (VL20), leading to the completion of approximately 50% of the possible repetitions per set; vs. 40% (VL40), leading to the completion of almost 100% of the possible repetitions per set (i.e. very close to muscle failure). The VL20 group achieved similar or even superior strength gains, especially in high-velocity actions (e.g. vertical jump), while the VL40 group experienced a higher hypertrophic response and a IIX-to-IIA shift in single muscle fiber phenotype, whereas the VL20 group did not display reductions in the IIX fiber-type pool (15). Another study comparing a relative VL of 15% (VL15) vs. 30% (VL30) reported similar results, pointing out the superiority of VL15 in terms of RT-induced strength and jumping gains (16). These findings may also suggest the existence of a volume plateau, beyond which further volume increases do not induce greater strength gains and can even induce suboptimal adaptations. However, further studies considering a wider spectrum of VL thresholds are needed. Therefore, the main goal of the present study was to compare the effects of four RT programs with different VL thresholds (0%, 10%, 20% and 40%) on sprint and jump performance, muscle strength, neuromuscular, muscle hypertrophy and architectural adaptations.

Materials and methods

Experimental design

A longitudinal research design was used to compare the effects of four RT programs that only differed in the magnitude of the VL induced during the set: 0% (VL0) vs. 10% (VL10) vs. 20% (VL20) vs. 40% (VL40). Subjects trained during an 8-week period, following a progressive lower-limb RT program comprising only the SQ exercise. The four groups trained at the same %1RM in each session. Sessions were performed in a research laboratory under the direct supervision of the investigators, at the same time of the day (± 1 h) and the same environmental conditions (20°C and 60% humidity) for each subject. Subjects were requested not to perform any other type of strenuous physical activity during the study period. All groups were measured on two occasions: 72 h before (Pre-training) and 72 h after (Post-training) the 8-week training intervention. A battery of tests was performed in two testing sessions (separated by 48 h). The first testing session consisted of: 1) ultrasound measurements of the vastus lateralis (V_{LA}) muscle; and 2) tensiomyography (TMG) of the V_{LA} and vastus medialis (V_{ME}) muscles. On the second testing session a battery of fitness tests was performed as follows: 1) 20-m running sprint; 2) vertical jump; 3) maximal voluntary isometric contraction (MVIC) in SQ exercise; 4) progressive loading test in SQ; and 5) fatigue test in SQ. Training compliance was 100% of all sessions for the subjects who completed the intervention.

Subjects

Sixty-four resistance trained and physically active men (age = 24.1 ± 4.3 years, height = 1.75 ± 0.06 m, body mass = 75.5 ± 9.7 kg) volunteered to take part in this study. All subjects had a training background ranging from 1.5 to 4 years (1-3 sessions per week) and were accustomed to

performing the SQ exercise using the correct technique. Subjects were randomly assigned to one of four groups, which differed only in the magnitude of VL allowed in each training set. A participant flow diagram is presented in **Figure 1**. After being informed of the purpose and testing procedures, subjects signed a written informed consent form prior to participation. The present study was approved by the Local Research Ethics Committee, in accordance with the Declaration of Helsinki. No physical limitations, health problems, or musculoskeletal injuries that could affect testing were found after a medical examination. Subjects reported to be free from taking drugs, medications or dietary supplements known to influence physical performance. Caffeine consumption was not permitted 12 h before the TMG trials.

Testing procedures

Ultrasonography

Muscle cross-sectional area (CSA) and the architecture of the V_{LA} muscle were assessed using B-mode ultrasonography (MyLab 25, Esaote Biomedica, Italy) with a 50-mm, 5-12 MHz linear array probe. Resting ultrasound images were collected with the participants lying in the supine position with the knees resting slightly flexed at 150° (180° = full knee extension). After 15 min in the described position, V_{LA} CSA and architecture were measured at 50% and 60%, respectively, of the distance between the superior border of the greater trochanter and the inferior border of the lateral condyle of the right leg. The extended field of view (EFOV) mode was used in the case of muscle CSA, whereas the alignment of the transducer in the fascicular plane was required in the case of the muscle architecture. Adhesive gaskets were placed on the skin at the proximal and distal boundaries of the transverse path to be measured to facilitate the application of the gel and the rectilinear path of the ultrasound linear array probe. The panoramic image was taken from medial

to lateral, passing carefully and at a constant velocity along the defined path, keeping the probe perpendicular to the surface of the skin and applying a minimum pressure not to compress the tissues that will be evaluated. Three images were recorded at each thigh length (i.e. 50 and 60%) and digitally analysed (ImageJ 1.51j8, NIH) by the same operator, who was blinded to subject allocation. Muscle CSA (cm^2) was measured by surrounding the bounds (aponeuroses) of the V_{LA} muscle (**Fig. 2A**). V_{LA} pennation angle (PA) and fascicle length (FL) were measured from the visible portion of two fascicles within the same image and linear extrapolation of fibres and aponeuroses when a portion of the fascicle extended off the field of view (**Fig. 2B**) (17). Two ultrasound images were assessed for each variable, and when a coefficient of variation (CV) greater than 5% was found, the third image was analysed. The average value from all the analysed images was considered for further analysis. Consistency in measurement sites across testing days was achieved by recording probe positions onto a transparent acetate and using easily identifiable infiltrations of fatty and connective tissues as landmarks. Test-retest CV for V_{LA} CSA was 3.8%, and CVs for muscle architecture measures using these procedures have been previously reported: 2.7% for fascicle length and 3.6% for pennation angle (18).

Tensiomyography

The V_{LA} and V_{ME} muscles' contractile properties were assessed by TMG (TMG-100 System electrostimulator, TMG-BMC, Ljubljana, Slovenia) as their response to an electrically-evoked contraction. The electric stimulus was induced through two self-adhesive electrodes (inter-electrode distance 5-cm) (Dura-Stick® premium, Cefar-Compex, Hanover, Germany), and the muscle mechanical response was measured with a digital Dc-Dc transducer Trans-TekR (GK 40, Ljubljana, Slovenia) placed perpendicular to the muscle belly and equidistant from the self-adhesive electrodes at a distance of 25-30-mm. Participants remained lying in the supine position

for 10 min before starting the TMG measurements data acquisition and the V_{LA} and V_{ME} were marked according to the SENIAM indications and location (19). Measurements were taken with the athletes in the supine position and the knee joint fixed at an angle of $\sim 140^\circ$ using a wedge cushion. Electrical stimulation was applied with a pulse duration of 1 ms and an initial current amplitude of 40 mA, which was progressively increased in 10 mA steps up to the stimulator's maximal output (100 mA). A 10-s rest period was allowed between each electrical stimulus to avoid fatigue or post-tetanic activation (20). The variables assessed in this study were the maximum radial displacement of the muscle belly (D_m), contraction time (T_c), and delay time (T_d). D_m was defined as the peak amplitude in the displacement–time curve of the tensiomyographical twitch response; T_c was obtained by determining the time interval from 10 to 90% of D_m ; and T_d was defined as the time between the electrical stimulus and 10% of D_m (21). All measurements were carried out by the same expert technician and only the curve with the highest D_m value was considered for further analysis. Test-retest reliability for the V_{ME} and V_{LA} muscles, respectively, was: D_m : CV = 5.5 and 5.0%; T_c : CV = 2.6 and 3.4%; and T_d : CV = 3.1 and 3.0%).

Running sprint and vertical jump tests

Subjects performed two maximal 20-m sprints on an indoor running track, separated by a 3-min rest between each sprint. Sprint times were measured using photocells (Witty, Microgate, Bolzano, Italy). Photocell timing gates were placed at 0, 10 and 20-m so that the times to cover the 0-10-m (T_{0-10}), 10-20-m (T_{10-20}) and 0-20-m (T_{0-20}) distances could be determined. A standing start with the lead-off foot placed 1-m behind the first timing gate was used. The warm-up protocol consisted of four 20-m running accelerations at 80%, 85%, 90%, 95% of perceived effort, and one

10-m sprint at 100% effort with 1-min rest periods between them. The test-retest reliability (CV values) ranged from 0.7 to 1.4%.

In the vertical jump test, subjects performed five maximal CMJs with 20-s rests between each jump. Before CMJ assessment, participants warmed-up by performing 2 sets of 10 squats without external load, 5 submaximal CMJs and 3 maximal CMJs. CMJ height was calculated from flight time values determined using an infrared timing system (OptojumpNext, Microgate, Bolzano, Italy). After discarding the highest and lowest CMJ heights, the resulting average was kept for further analysis. The CV was 1.6%.

Maximal voluntary isometric contraction test

Maximal isometric force (MIF) and maximal rate of force development (RFD_{max}) were measured during an MVIC in the SQ exercise with the participants standing with their knees flexed at 90° (180° = full extension). This test was performed on a Smith machine with height-adjustable movable supports, instrumented with an 80 x 80-cm dynamometric platform (FP-500, Ergotech, Murcia, Spain). The subjects were instructed to push with their legs on the force platform as fast and hard as possible after the cue “ready, set, go!” during two 5-s trials separated by 1 min of rest. External forces were collected at a sampling rate of 1000 Hz and processed with specific software (T-Force System, Ergotech, Murcia, Spain). RFD_{max} was calculated as the maximum slope in the force-time curve in 20-ms time intervals. Moreover, the average tangential slope of the force-time curve obtained over different time intervals (50, 100 and 150 ms from the onset of force production, RFD₀₋₅₀, RFD₀₋₁₀₀, and RFD₀₋₁₅₀, respectively) were calculated. The average value of each variable in the two attempts was recorded for further analysis. Test-retest reliability (CV values) for the MIF and RFD values respectively, was 4.3% and from 12.8 to 24.3%.

EMG signal acquisition

After skin preparation, surface EMG electrodes were placed over the V_{ME} and V_{LA} muscles of the right leg following SENIAM recommendations (19). Consistency in measurement sites across testing days was achieved by recording electrode positions onto a transparent acetate and using different anatomic references and skin moles as landmarks. EMG signals were recorded continuously during MVIC testing using a parallel-bar, bipolar surface electromyographic sensor Trigno™ wireless EMG system, with an inter-electrode distance of 10 mm, common mode rejection ratio >80 dB, and bandwidth filter between 20 and 450 Hz \pm 10% (Delsys Inc, MA, USA). Baseline noise was < 5 μ V peak-to-peak and sampling rate was 1926 Hz. The raw data from the EMG were stored in digital format using EMG works Acquisition software (Delsys Inc, MA, USA). Root mean square (RMS) values were calculated to identify changes in muscle excitation levels. The highest RMS during each MVIC was calculated using a moving window of 500 ms with an overlap of 490 ms. V_{ME} and V_{LA} muscle excitation values were averaged, and the average of the two MVICs was calculated for further analysis. The CV for the RMS signal was 9.3%.

Progressive loading test

Individual load-velocity relationship and 1RM load in the SQ exercise were determined using a progressive loading test in a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) with no counterweight mechanism. The SQ was performed with subjects starting from the upright position with the knees and hips fully extended, parallel feet and stance approximately shoulder-width apart, and the barbell resting across the back at the level of the acromion. Each subject descended in a continuous motion as low as possible (\sim 35-40° knee flexion), then immediately reversed motion and raised back to the upright position. Unlike the eccentric phase that was

performed at a controlled mean velocity ($\sim 0.50\text{-}0.65\text{ m}\cdot\text{s}^{-1}$), subjects were required to always execute the concentric phase at maximal intended velocity. Range of movement and velocity values of all repetitions were recorded at 1000 Hz with a linear velocity transducer (T-Force System Ergotech, Murcia, Spain), whose reliability has been reported elsewhere (10). Firstly, the participants warmed up by performing 6 repetitions with a 20 kg load. The initial load was set at 20 kg and was progressively increased in 10 kg increments until the mean propulsive velocity (MPV) was $\leq 0.50\text{ m}\cdot\text{s}^{-1}$. Then, the load was increased with smaller increments (2.5-5.0 kg) for better adjustment. A total of 8.5 ± 1.8 increasing loads were used for each subject. Three repetitions were executed for light loads ($\geq 1.00\text{ m}\cdot\text{s}^{-1}$), two for medium loads ($1.00\text{-}0.80\text{ m}\cdot\text{s}^{-1}$) and one for the heaviest loads ($\leq 0.80\text{ m}\cdot\text{s}^{-1}$). Inter-set recoveries ranged from 3 min (light loads) to 5 min (heavy loads). Only the best repetition (i.e. highest MPV) with each load was considered for subsequent analysis. The propulsive phase corresponds to the portion of the concentric action during which the measured acceleration is greater than acceleration due to gravity ($-9.81\text{ m}\cdot\text{s}^{-2}$) (22).

In addition to the individual load-velocity relationship and the corresponding 1RM load, we reported: a) average MPV attained against all absolute loads common to pre- and post-training (AV); b) average MPV attained against absolute loads that were moved faster than $1\text{ m}\cdot\text{s}^{-1}$ at pre-training (AV>1); and c) average MPV attained against absolute loads that were moved slower than $1\text{ m}\cdot\text{s}^{-1}$ at pre-training (AV<1). These variables were analyzed to examine the potential adaptations achieved in different areas of the load-velocity relationship.

Fatigue test

Five minutes after the SQ progressive loading test, the subjects were required to complete as many repetitions as possible with a load corresponding to 70% of 1RM until the MPV fell below 0.50 m·s⁻¹. The test was repeated after the completion of the study using the same absolute load as in the baseline examination (i.e. 70% of baseline 1RM). The execution technique and devices used were those described for the progressive loading test. Subjects were encouraged to perform each repetition at maximal intended velocity. The total number of repetitions being performed was used for further analysis.

Resistance training program

The descriptive characteristics of the RT program are presented in **Table 1**. The four groups trained twice a week (training sessions being 48-72 h apart) for eight weeks with the same exercise (full SQ), relative intensity (increasing from 70% to 85% 1RM), number of sets (3) and inter-set recovery (4 min). The only difference between groups was the VL threshold allowed in each set. Hence, the VL0 group performed only 1 repetition per set (0% of VL) while the other groups (VL10, VL20 and VL40) stopped their sets when the corresponding VL threshold (10%, 20% and 40% of VL, respectively) was exceeded. All repetitions for all participants during all sessions were recorded using a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain). Relative loads were determined from the individual load-velocity relationship obtained from the progressive loading test in the SQ exercise for each subject ($R^2 = 0.99 \pm 0.01$). Therefore, for each training session, individual loads were adjusted to ensure the corresponding MPVs matched ($\pm 0.03 \text{ m} \cdot \text{s}^{-1}$) the prescribed % 1RM. In addition, subjects received immediate velocity feedback while being encouraged to perform each repetition at maximal intended velocity during each training session. A standardized warm-up preceded each training

session: i) 5 min of jogging at a self-selected easy pace; ii) 2×10 repetitions of SQ (own body weight); iii) 4×6-6-4-3 repetitions of SQ (20 kg, 40%, 50% and 60% of 1RM, respectively); and iv) 1×2 repetitions of SQ at 70% of 1RM (only in sessions 6-16) plus 1x1 repetition of SQ at 80% of 1RM (only in sessions 15-16).

Statistical analysis

Values are reported as mean ± standard deviation (SD). Sample size was calculated (using GPower Version 3.1.9.2) introducing the following parameters: effect size index (1.05 for a 10% increase in 1RM based on previous data (15)); and α error probability (0.05) and power (0.95), which resulted in a sample size of 12 subjects per group. The CV was measured to observe the test-retest absolute reliability. Normality and homoscedasticity were verified with Shapiro-Wilk and Levene's tests, respectively. Data were analyzed using a 4×2 factorial ANOVA with Bonferroni's *post-hoc* comparisons using one between-group factor (VL0 vs. VL10 vs. VL20 vs. VL40) and one within-group factor (Pre- vs. Post-training). Statistical significance was established at the $P \leq 0.05$ level. All statistical analyses were performed using SPSS software version 20.0 (SPSS Inc., Chicago, IL).

Results

Attrition and compliance

Nine subjects dropped out during the course of the study; thus, the final sample was composed of 55 subjects as follows: VL0 (n = 14), VL10 (n = 14), VL20 (n = 13) and VL40 (n = 14) (**Fig. 1**). Compliance was 100% for all subjects. No significant differences between groups were observed at pre-training for any of the variables analyzed.

Muscle CSA and architecture

RT-induced adaptations in V_{LA} muscle CSA, pennation angle and fascicle length are shown in Figure 2. A tendency to a group \times time interaction was observed for V_{LA} muscle CSA ($P = 0.06$), with a significant time effect ($P < 0.001$). The VL20 and VL40 groups showed significant improvements in muscle CSA (+7.0% and +5.3%, respectively; both $P < 0.001$), whereas no significant changes were observed for VL0 and VL10 (**Fig. 2C**). No significant group \times time interactions were observed for V_{LA} PA or FL, with a significant time effect for FL ($P = 0.04$). With regard to PA values, only the VL10 group exhibited significant changes in PA (+6.0%, $P = 0.02$) (**Fig. 2D**); while FL increased significantly only in VL20 (6.8%, $P = 0.05$) and VL40 (7.4%, $P = 0.02$) (**Fig. 2E**).

Tensiomyography

A significant group \times time interaction ($P = 0.05$) and a main effect of time ($P = 0.004$) were observed for Td in the V_{LA} muscle (V_{LA} -Td), although only the VL40 group exhibited a significant increase ($P < 0.001$) (**Table 2**). No significant group \times time interactions were found for the rest of variables (**Table 2**). A significant main effect of time was also noted for V_{ME} -Dm ($P = 0.008$), with significant decreases being observed only in the VL0 ($P = 0.04$) and VL10 ($P = 0.02$) groups. No significant changes were observed in Tc, V_{LA} -Dm, or V_{ME} -Td.

Running sprint and vertical jump tests

No significant group \times time interactions were found for any of the variables analyzed. A significant main effect of time ($P < 0.001$), coupled with significant increases in CMJ height, was found in VL0 (+5.6%), VL10 (+8.0%), VL20 (+5.4%) and VL40 (+6.1%) ($P < 0.001$ -0.01). A significant time effect was observed for T10-20 ($P < 0.001$). However, no significant changes were detected

in any group for sprint-related variables, except for T10-20 performance, which improved in the VL10 group (-1.8%; $P = 0.002$).

MVIC- and EMG-derived outcomes

Figure 3 displays the main findings regarding MVIC- and EMG-derived outcomes. No significant group \times time interactions were noted. Significant time effects were observed for MIF ($P < 0.001$), RFDmax ($P = 0.03$), and RFD₀₋₁₅₀ ($P = 0.04$). All groups showed significant improvements in MIF ($P < 0.001-0.05$, **Fig. 3A**). Moreover, VL0 showed significantly greater RFDmax values than VL10 at Post-training ($P = 0.04$, **Fig. 3B**) and VL40 showed significant decreases in RFD₀₋₅₀ ($P = 0.04$, **Fig. 3C**). No significant intra-group changes were observed in RFD₀₋₁₀₀, RFD₀₋₁₅₀ and averaged V_{LA} and V_{ME} muscle excitation (RMS) values (**Fig. 3D**).

Individual load-velocity relationship, 1RM and fatigue

RT-induced adaptations noted in dynamic SQ performance are shown in **Table 2**. No significant group \times time interactions were found for any variable, although significant time effects were observed for all these variables (all $P < 0.001$). 1RM values increased significantly in VL0 (+13.7%), VL10 (+18.1%), VL20 (+14.9%) and VL40 (+12.3%), as did velocity-related outcomes obtained from the individual load-velocity relationship (AV , $AV > 1$ and $AV < 1$) (all $P < 0.05$). **Figure 4A** shows the evolution of the RT-induced gains in 1RM values estimated from the individual load-velocity relationships. All four groups significantly improved with regard to the number of repetitions performed in the fatigue test ($P < 0.001-0.01$).

Training program

The main kinematic characteristics of the RT programs are reported in **Table 1**. No between-group differences were noted for the averaged fastest MPV during each session, while registered relative VL differed significantly among groups: 0% for VL0, $10.6 \pm 0.9\%$ for VL10, $20.3 \pm 1.5\%$ for VL20, and $41.9 \pm 1.4\%$ for VL40 (all $P < 0.05$). Thus, the average MPV attained during the training program decreased as the VL increased ($P < 0.05$). Moreover, the total number of repetitions and the average number of repetitions per set (total and for each %1RM) increased as relative VL increased ($P < 0.05$). The total repetitions performed at different velocity ranges by each VL group are shown in **Figure 4B**.

DISCUSSION

The main findings derived from this study comparing four RT programs differing in VL threshold induced during the set were: i) no between-group differences existed for RT-induced gains in sprint and jump performance, individual load-velocity relationship, MVIC and neuromuscular adaptations, despite the considerable differences in the reps per set performed by each group (VL0: 1.0 ± 0.0 ; VL10: 3.0 ± 0.8 ; VL20: 3.5 ± 1.0 ; VL40: 6.4 ± 1.7); and ii) higher VL thresholds (i.e. VL20 and VL40) promoted an increased muscle hypertrophy response, although an excessive VL during the set may also induce negative neuromuscular adaptations (i.e. longer V_{LA-Td} and decrease in RFD_{0-50} only in VL40). Therefore, our data suggest that once an upper VL threshold is achieved a further increase in VL does not elicit additional strength gains and may even lead to negative neuromuscular adaptations

All groups showed significantly increased SQ performance in terms of 1RM, MIF, AV, $AV < 1$, and $AV > 1$, although greater percentage changes were noted when applying moderate VL

thresholds (i.e. VL10 and VL20). Thus, only one repetition per set (VL0) may not be enough to maximize strength gains, while a high VL threshold (VL40) does not provide further strength or velocity gains. A recent review concluded that a single set of 6-12 reps at 70-85% 1RM to muscle failure, 2-3 times per week for 8-12 weeks may be the minimum training dose required to increase 1RM strength (23). In this regard, an even lower training dose, as induced by VL0, which consisted of 3 sets of 1 rep at 70-85% 1RM twice a week for 8 weeks, produced suboptimal yet significant increases in 1RM strength. Likewise, a previous study showed increased gains in 1RM strength derived from VL20 vs. VL40 (18.0 vs. 13.4%, respectively) (15). Additionally, the VL20 group showed significant gains in high-velocity actions (i.e. AV>1) while VL40 did not (6.2 vs. 1.0%, respectively) (15). However, previous studies on this topic only analyzed two VL thresholds (15, 16), thus the dose-response relationship between RT-induced adaptations and the whole spectrum of relative velocity losses (i.e. from no VL (0%) to muscle failure (~40%)) remained to be investigated. Moreover, the VL10 and VL20 groups experienced earlier significant improvements in 1RM strength (noted at sessions 2 and 3, respectively) compared to the VL0 (noted at session 6) and VL40 (noted at the end of the RT program) groups (c.f. **Figure 4**), which might be of particular relevance in sport disciplines that require the maintenance of a high strength performance level throughout the entire season.

Although it has been traditionally suggested that a high number of repetitions per set during RT should be performed to maximize gains in local muscular endurance (3, 24), the four training groups all significantly improved with regard to the maximal number of repetitions achieved during the fatigue test (VL0: 70.9%; VL10: 100.2%; VL20: 103.8%; VL40: 96.3%), despite VL40 performing higher total volumes. Previous research showed greater gains in localized muscular endurance (total repetitions with 75% of 1RM) in bench press after an 11-week training program

to failure compared to non-failure training, although there were no differences in the squat exercise (25), which suggests that the effects of level of effort during the set on endurance performance may be exercise-dependent. Accordingly, our findings suggest that muscular endurance gains in SQ exercise, assessed by completing as many repetitions as possible with 70% of 1RM until the MPV fell below $0.50 \text{ m} \cdot \text{s}^{-1}$, do not seem to depend exclusively on the training volume accumulated.

In contrast, it was under moderate-to-high VL values (i.e. VL20 and VL40) that significant positive adaptations in V_{LA} muscle CSA were provoked. A previous study showed that both VL20 and VL40 increased quadriceps volume, but VL40 training elicited greater muscle hypertrophy than VL20 (15). It has been reported that protocols with higher levels of effort during the set (i.e. higher VL) induce higher mechanical and metabolic stress (10), along with greater hormonal responses and muscle damage (11, 12), which have been postulated as precursors of hypertrophic adaptations (26). It is therefore conceivable that the hypertrophic response is influenced by the level of effort attained during the set, and in this sense, both 0% and 10% of VL seemed to be insufficient to induce such adaptations. Moreover, the increases in muscle CSA in the VL20 and VL40 groups were accompanied by significant increases in fascicle length, whereas the pennation angle only increased significantly in the VL10 group. A further analysis in our participants showed a small but significant relationship ($r = 0.28$; $P = 0.038$) between the combined changes in fascicle length and pennation angle and those reported in muscle CSA. Importantly, muscle CSA and muscle architecture were measured at different muscle sites, which coupled with possible differences in regional muscle adaptations induced by RT (27, 28), may explain discrepancies between the sets of measures. Our findings suggest that unlike changes in muscle function, structural muscle adaptations rely on higher levels of fatigue and training volume, as supported by previous investigations (29, 30).

To our knowledge, this is the first study to assess longitudinal adaptations of contractile properties to systematic RT using simple, noninvasive and selective TMG. TMG has been validated for the assessment of in-vivo passive muscle contractile properties in response to single-twitch stimulation (31). Based on our findings, it appears that the tested VL thresholds induced different adaptive responses in contractile properties, since only VL0 and VL10 showed significant decreases in V_{ME-Dm} , while VL40 showed a longer V_{LA-Td} at the end of the RT program. In this regard, plyometric training has previously been shown to produce decreases in Dm in both young active men (32) and seniors (33), which has been interpreted as an increase in muscle stiffness (21, 34). Moreover, Pisot et al. (34) reported an inverse relationship ($r = -0.71$) between change in Dm and decrease in muscle thickness after 35 days of bed rest. On the other hand, Td is recognized as a measure of muscle responsiveness (21), and has been found to be lower in power athletes compared to endurance athletes and to be negatively associated with CMJ height (35). Furthermore, a previous research found a positive relationship between the proportion of myosin heavy chain I and Td ($r = 0.61$) (36). Therefore, higher Td values may indicate negative neuromuscular adaptations. Likewise, VL40 showed significant impairment in the early RFD (RFD_{0-50}), although no significant changes were observed for RMS during MVIC for any group. Resistance exercise with high VL thresholds (i.e. VL40) is characterized by accumulated higher training volumes accompanied by large impairments in force production (10, 11), which induce a reduction of IIX fiber-type percentage, whereas moderate VL thresholds (i.e. VL20) preserve this pool (15). In this regard, a positive relationship ($r = 0.61$) has been shown between the changes in early RFD (<100 ms) and changes in the area percentage of IIX fiber-type (37). Thus, it is suggested that moderate VL thresholds ($\leq 20\%$) should be established as maximal, in order to avoid the negative neuromuscular adaptations observed in VL40.

Finally, of more functional relevance for coaches and practitioners were our results on RT-induced adaptations in CMJ and sprint performance. With regard to sprint performance, no significant changes were observed in any group for sprint-related variables, except for the flying phase (from 10 to 20 m), which improved in the VL10 group. By contrast, all groups improved significantly CMJ height, however, the lower VL threshold the higher training efficiency, since all groups obtained similar CMJ improvements but accumulating substantially different total training volume. The lower VL thresholds seemed to be more efficient and they do not evoke the high levels of discomfort and fatigue typically experienced in training routines characterized by high VL thresholds (11).

Several study limitations should be considered when interpreting our results. Firstly, there was no control of energy or protein intake during the study, which can influence RT-induced adaptations. Secondly, the study was carried out in the SQ exercise, and it should be noted that VL in a multi-joint exercise such as the SQ may involve peripheral fatigue in one or more muscles at different joints. Thus, the findings may not be generalizable to single joint exercise, where fatigue necessarily only manifests in muscles of an isolated joint. Moreover, the findings may not be generalizable to upper-limb exercises as well. Thirdly, no control group or control period without training before the start of the training intervention (e.g. -2 week and week 0) was included and as a consequence the influence of environmental variables cannot be ruled out. Fourthly, RFD findings should be interpreted with caution since the reliability values observed in RFD measurements were limited (CV from 12.8 to 24.3%). Lastly, various fitness tests were performed on day 2 (1: running sprint; 2: vertical jump; 3: MVIC in SQ; 4: progressive loading test in SQ; and 5: fatigue test in SQ), which may have induced fatigue in the subjects. Although all groups

would have been affected similarly by this fact, it still raises the possibility that the tests themselves may not be as accurate in determining the intended outcomes as a result.

CONCLUSIONS

The main findings of the current study were that higher VL thresholds (i.e. VL20 and VL40) maximized hypertrophic adaptations, although an excessive level of effort during the set (i.e. VL40) may also induce negative neuromuscular adaptations. Moreover, no differences between groups were observed for RT-induced gains in squat and jump performance, despite the considerable differences in the total volume accumulated by each group. Therefore, setting a moderate VL threshold (i.e. VL20) during RT might serve to avoid performing fatiguing repetitions, which does not elicit additional benefits in terms of muscle strength and might evoke negative neuromuscular adaptations.

PRACTICAL APPLICATIONS

The results of the present study contribute to improving our knowledge about RT design and prescription. By monitoring repetition velocity, a VL threshold should be chosen beforehand, depending on the specific training goal being pursued. Moderate-to-high VL thresholds (i.e. VL20 and VL40) should be used with the aim of maximizing muscle hypertrophy, although an excessive VL during the set (i.e. VL40) should be avoided to prevent negative neuromuscular adaptations. Further, moderate VL thresholds (i.e. VL10 and VL20) should be chosen to maximize athletic performance, since VL0 seemed to induce levels of fatigue that were too low to maximize adaptations, while VL40 did not produce further strength gains compared to VL10 and VL20. Therefore, moderate VL thresholds should be chosen to maximize strength adaptations and to prevent negative neuromuscular adaptations.

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The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine. This study has no conflicts of interest to declare. This study was not funded.

ACCEPTED

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FIGURE CAPTIONS

FIGURE 1. Participant flow diagram

FIGURE 2. Ultrasound images obtained from the vastus lateralis (V_{LA}) muscle of a standard subject: A) the cross-sectional area is surrounded by a thick line; B) thick lines indicate the superior and inferior aponeuroses of the V_{LA} muscle; dashed lines indicate the visible portions of muscle fascicles; and arched lines indicate angles formed between the visible muscle fascicles and the inferior aponeurosis. Non-visible portions of muscle fascicles were estimated using linear extrapolation of fibers and aponeuroses in order to estimate fascicle length. *Note:* FL, fascicle length. θ , pennation angle. Changes produced from pre- to post-training for each group in: C) cross-sectional area; D) pennation angle, and E) fascicle length of V_{LA} obtained from ultrasound images. Data are mean \pm SD, N = 55. VL0: group that trained with a mean velocity loss of 0% in each set (n = 14); VL10: group that trained with a mean velocity loss of 10% in each set (n = 14); VL20: group that trained with a mean velocity loss of 20% in each set (n = 13); VL40: group that trained with a mean velocity loss of 40% in each set (n = 14). Δ (%): relative change from pre- to post-training. Intra-group significant differences from pre- to post-training: * P < 0.05, *** P < 0.001.

FIGURE 3. Changes produced from Pre-to Post-training for each group in: A) maximal isometric force (MIF); B) maximal rate of force development (RFD_{max}); C) rate of force development from the onset of force production to 50 ms (RFD₀₋₅₀); and D) root mean square (RMS) averaged from the vastus medialis and vastus lateralis muscles. Data are mean \pm SD, N = 55. VL0: group that trained with a mean velocity loss of 0% in each set (n = 14); VL10: group that trained with a mean velocity loss of 10% in each set (n = 14); VL20: group that trained with a mean velocity loss of

20% in each set (n = 13); VL40: group that trained with a mean velocity loss of 40% in each set (n = 14). Δ (%): relative change from pre- to post-training. Intra-group significant differences from pre- to post-training: * P < 0.05, ** P < 0.01, *** P < 0.001. Between-groups significant differences (P < 0.05) with respect to VL10: 10.

FIGURE 4. A) Evolution of the 1RM strength in the squat exercise in each training session expressed as a percentage of the initial Pre-training level for each experimental group. 0, 10, 20 or 40 indicate the session from which the respective group attained significant improvements (P < 0.05) in 1RM strength compared to their Pre-training values. B) Number of repetitions performed in each velocity range, and total number of repetition completed by each training group. Between-groups significant differences (P < 0.05) with respect to: VL0: 0; VL10: 10, and VL20: 20. Data are mean \pm SD, N = 55. VL0: group that trained with a mean velocity loss of 0% in each set (n = 14); VL10: group that trained with a mean velocity loss of 10% in each set (n = 14); VL20: group that trained with a mean velocity loss of 20% in each set (n = 13); VL40: group that trained with a mean velocity loss of 40% in each set (n = 14).

Figure 1

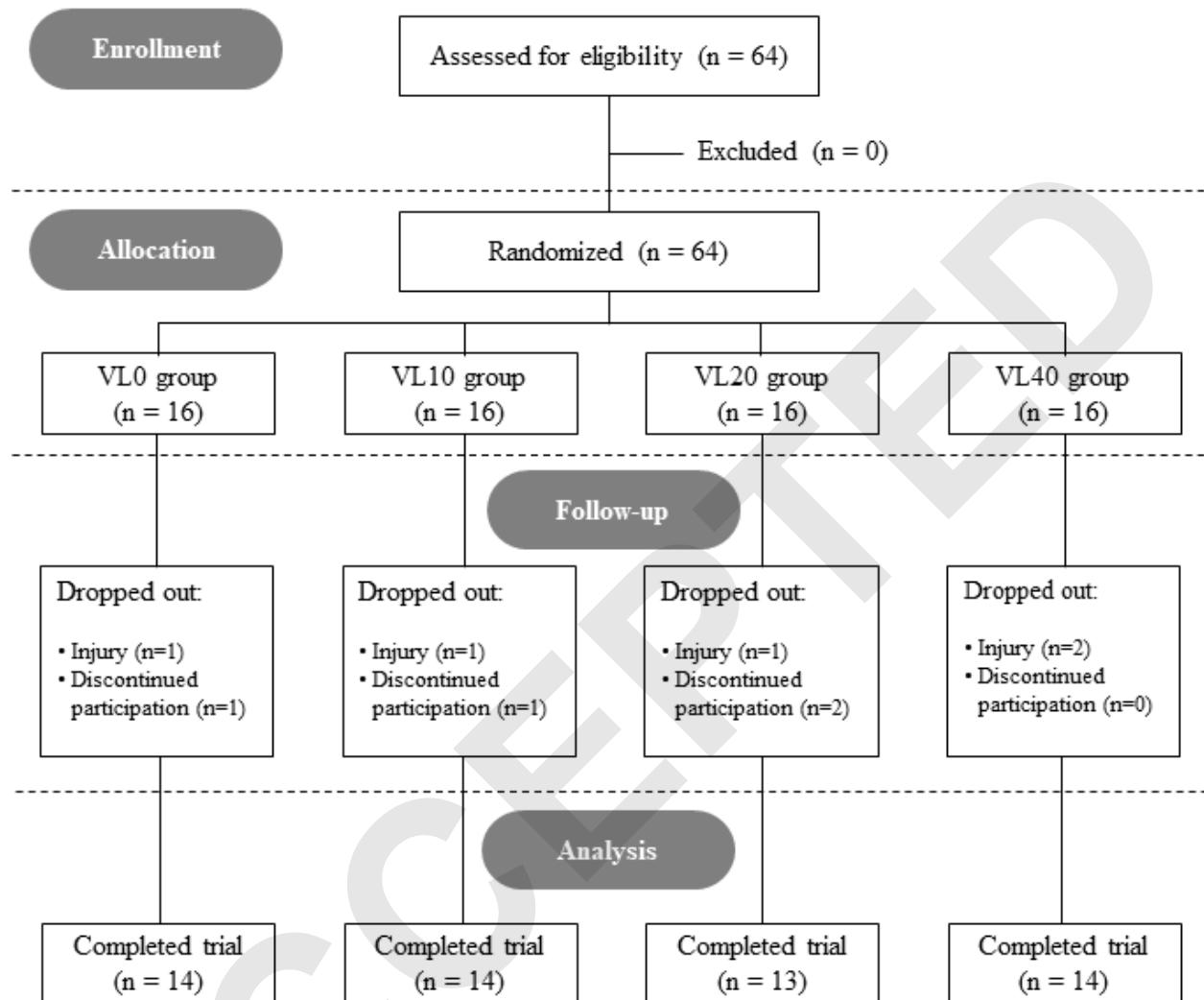


Figure 2

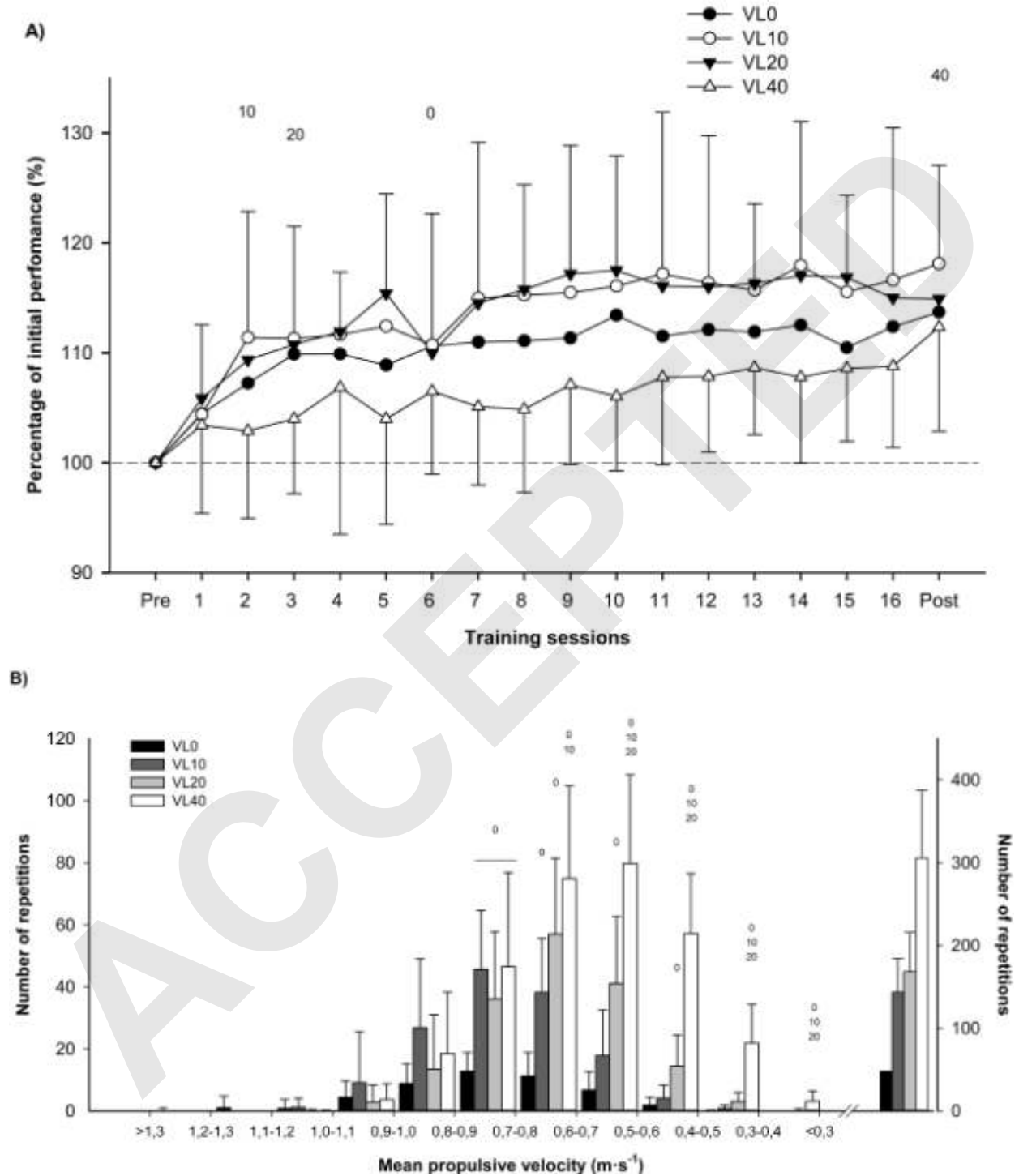


Figure 3

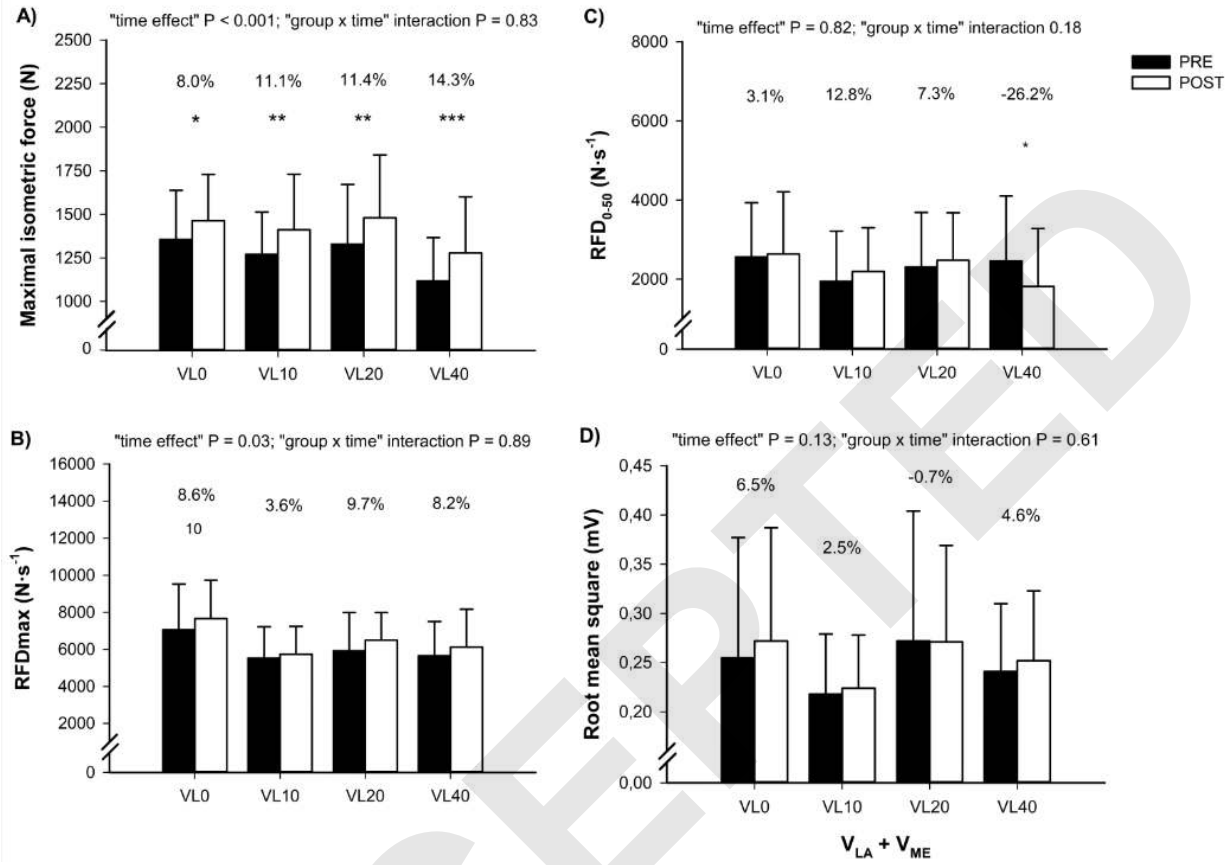


Figure 4

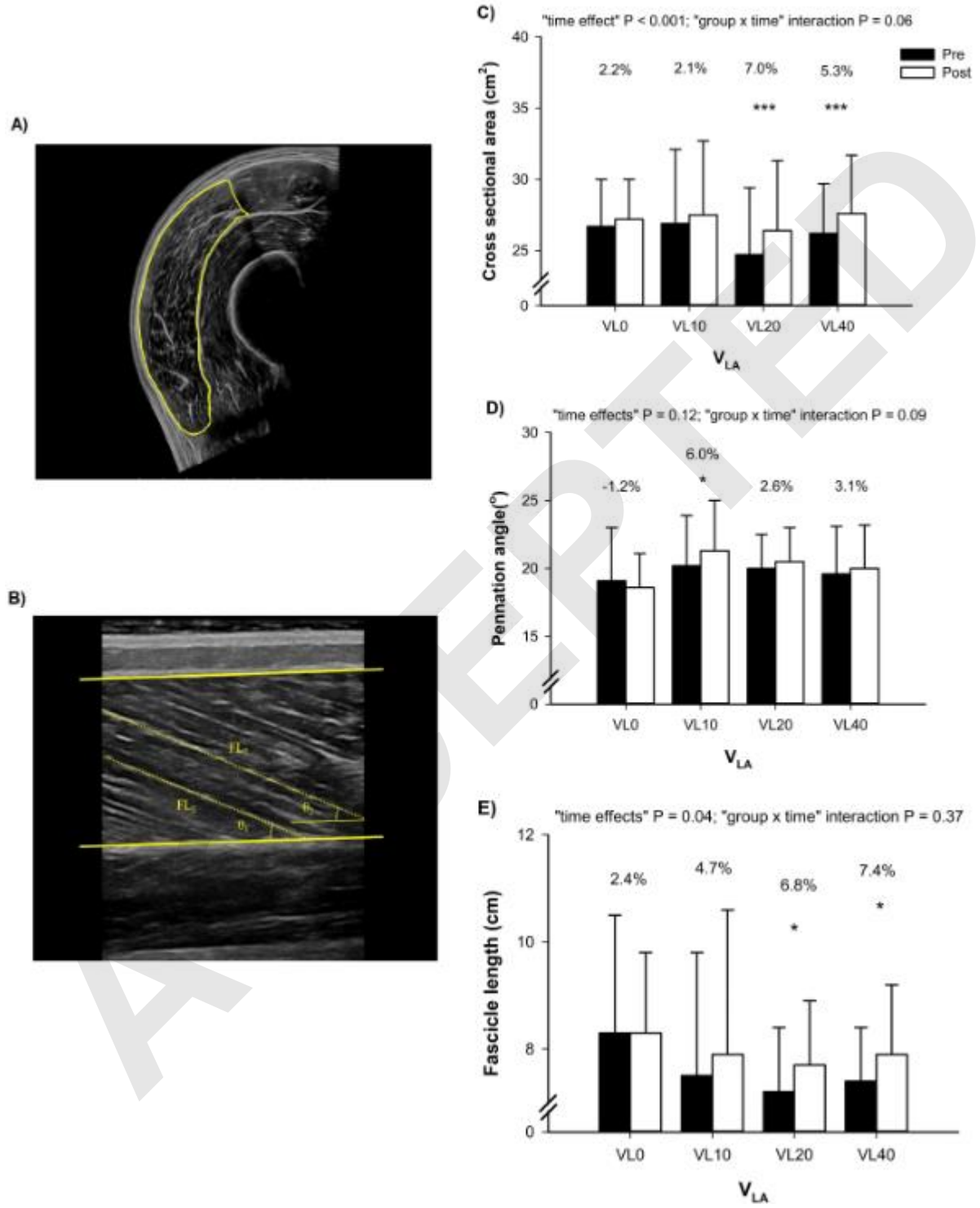


Table 1. Descriptive characteristics of the 8-week velocity-based squat training program performed by the four experimental groups

SCHEDULED								
<i>Training Sessions</i>	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8
Set x %1RM	3 x 70	3 x 70	3 x 70	3 x 70	3 x 70	3 x 75	3 x 75	3 x 75
<i>Training Sessions</i>	Session 9	Session 10	Session 11	Session 12	Session 13	Session 14	Session 15	Session 16
Set x %1RM	3 x 75	3 x 75	3 x 80	3 x 80	3 x 80	3 x 80	3 x 85	3 x 85
ACTUALLY PERFORMED								
Training Group	Fastest MPV (m·s⁻¹)¹⁾	Slowest MPV (m·s⁻¹)	MPV all reps	Mean VL	Total Rep			
VL0	0.77 ± 0.11	0.70 ± 0.12 ^{10 20 40}	0.74 ± 0.11 ^{20 40}	0 ± 0.0 ^{10 20 40}	48.0 ± 0.0 ^{10 20 40}			
VL10	0.76 ± 0.08	0.61 ± 0.08 ^{20 40}	0.71 ± 0.07 ⁴⁰	10.6 ± 0.9 ^{20 40}	143.6 ± 40.2 ⁴⁰			
VL20	0.73 ± 0.07	0.51 ± 0.06 ⁴⁰	0.64 ± 0.06	20.3 ± 1.5 ⁴⁰	168.5 ± 47.4 ⁴⁰			
VL40	0.75 ± 0.07	0.37 ± 0.05	0.58 ± 0.06	41.9 ± 1.4	305.6 ± 81.7			

Training Group	Average rep per set in all sessions	Rep per set with 70% 1RM	Rep per set with 75% 1RM	Rep per set with 80% 1RM	Rep per set with 85% 1RM
VL0	1.0 ± 0.0 ^{10 20 40}	1.0 ^{10 20 40}	1.0 ^{10 20 40}	1.0 ^{10 20 40}	1.0 ^{10 20 40}
VL10	3.0 ± 0.8 ⁴⁰	3.7 ± 0.9 ⁴⁰	3.1 ± 0.8 ⁴⁰	2.5 ± 0.9 ⁴⁰	2.2 ± 0.9 ⁴⁰
VL20	3.5 ± 1.0 ⁴⁰	4.2 ± 1.2 ⁴⁰	3.8 ± 1.2 ⁴⁰	2.9 ± 0.8 ⁴⁰	2.3 ± 0.8 ⁴⁰
VL40	6.4 ± 1.7	7.6 ± 2.5	7.0 ± 2.3	5.3 ± 1.5	4.3 ± 1.5

Data are mean ± SD. Only one exercise (FULL squat) was used in training. VL0: Group that trained with a mean velocity loss of 0% in each set (n = 14); VL10: Group that trained with a mean velocity loss of 10% in each set (n = 14); VL20: Group that trained with a mean velocity loss of 20% in each set (n = 13); VL40: Group that trained with a mean velocity loss of 40% in each set (n = 14). VL: Magnitude of velocity loss expressed as percent loss in mean repetition velocity from the fastest (usually first) to the slowest (last one) repetition of each set; MPV: Mean Propulsive Velocity; Fastest MPV: Average of the fastest repetitions measured in each session (this value represents the average intensity, %1RM, achieved during the training program); Slowest MPV: Average of the slowest repetitions measured in each session; MPV all reps: Average MPV attained during the entire training program; Mean Velocity Loss: Average velocity loss attained during the entire training program; Total rep: Total number of repetitions performed during the training program; Average rep per set in all sessions: average number of repetitions performed in each set; Rep per set with a given %1RM: average number of repetitions performed in each set with each of the loads used (70, 75, 80 or 85%1RM). Statistically significant differences

with VL10 protocol: ¹⁰P < 0.05. Statistically significant differences with VL20 protocol: ²⁰P < 0.05. Statistically significant differences with VL40 protocol: ⁴⁰P < 0.05.

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Table 2. Changes in muscle contractile properties and squat performance from Pre- to Post-training for each group.

<i>TMG</i> <i>parameters</i>	VL0			VL10			VL20			VL40			P-value	P-value
	Pre	Post	Δ (%)	Pre	Post	Δ (%)	Pre	Post	Δ (%)	Pre	Post	Δ (%)	time effect	group x time
V_{LA}-Tc (ms)	22.5 ± 3.4	21.8 ± 3.1	-2.8	21.3 ± 3.3	20.8 ± 3.0	-1.8	22.3 ± 2.6	21.1 ± 1.6	-4.6	21.6 ± 5.8	21.8 ± 4.1	3.4	0.19	0.70
V_{LA}-Td (ms)	22.9 ± 1.8	23.3 ± 2.1	1.8	22.6 ± 1.7	23.2 ± 1.3	3.0	23.6 ± 1.4	23.6 ± 1.4	0.3	22.1 ± 2.5	23.8 ± 2.6 ^{***}	8.4	0.004	0.05
V_{LA}-Dm (mm)	5.37 ± 1.51	5.48 ± 1.76	2.3	6.01 ± 2.85	5.57 ± 1.94	-0.5	5.35 ± 1.33	4.95 ± 1.67	-7.7	4.93 ± 1.67	5.60 ± 2.05	17.5	0.94	0.24
V_{ME}-Tc (ms)	21.8 ± 2.1	22.0 ± 2.3	1.2	21.8 ± 2.0	21.5 ± 2.3	-1.8	20.8 ± 2.1	20.4 ± 1.4	-1.5	21.7 ± 2.6	21.4 ± 3.0	-1.3	0.24	0.58
V_{ME}-Td (ms)	21.4 ± 1.2	22.1 ± 1.4	3.4	21.8 ± 1.5	21.7 ± 1.0	-0.9	21.2 ± 1.6	21.1 ± 1.5	-0.5	21.3 ± 1.5	21.9 ± 1.5	3.0	0.20	0.30
V_{ME}-Dm (mm)	7.58 ± 1.75	6.81 ± 1.46 [*]	-6.7	8.00 ± 2.01	7.14 ± 2.28 [*]	-11.3	6.71 ± 1.73	6.09 ± 1.52	-6.9	6.95 ± 1.79	7.19 ± 1.60	5.8	0.008	0.12
Squat performance	VL0			VL10			VL20			VL40			P-value	P-value
	Pre	Post	Δ (%)	Pre	Post	Δ (%)	Pre	Post	Δ (%)	Pre	Post	Δ (%)	time effect	group x time

1RM (kg)	99.9 ±	112.9 ±	13.7	96.7 ±	113.6 ±	18.1	97.8 ±	110.9 ±	94.5 ±	105.6 ±	12.3	<0.001	0.27	
	19.1	19.9***		15.3	15.6***		23.2	19.6***	17.5	18.5***				
AV (m·s ⁻¹)	0.99 ±	1.08 ±	9.5	0.97 ±	1.11 ±	14.3	0.97 ±	1.11 ±	0.96 ±	1.06 ± 0.13***	10.5	<0.001	0.34	
	0.11	0.12***		0.09	0.09***		0.05	0.08***	0.09					
AV>1 (m·s ⁻¹) 1)	1.30 ±	1.35 ± 0.13*	4.5	1.29 ±	1.38 ±	6.6	1.26 ±	1.36 ±	1.26 ±	1.33 ± 0.08**	5.2	<0.001	0.52	
	0.09			0.06	0.09***		0.06	0.07***	0.09					
AV<1 (m·s ⁻¹) 1)	0.67 ±	0.80 ±	20.5	0.67 ±	0.85 ±	27.3	0.68 ±	0.86 ±	0.68 ±	0.80 ±	17.7	<0.001	0.28	
	0.05	0.11***		0.05	0.09***		0.03	0.09***	0.05	0.09***				
MNR (rep)	9.2 ± 2.5	14.2 ± 6.0**	70.9	10.0 ± 3.2	19.7 ± 7.9***	100.2	8.4 ± 2.3	17.1 ± 7.2***	103.8	8.4 ± 2.8	16.1 ± 7.5***	96.3	<0.001	0.19

Data are mean ± SD, N = 55. VL0: group that trained with a mean velocity loss of 0% in each set (n = 14); VL10: group that trained with a mean velocity loss of 10% in each set (n = 14); VL20: group that trained with a mean velocity loss of 20% in each set (n = 13); VL40: group that trained with a mean velocity loss of 40% in each set (n = 14). V_{LA}: vastus lateralis muscle; V_{ME}: vastus medialis muscle; T_c: contraction time; T_d: delay time; D_m: muscle displacement; 1RM: one-repetition maximal in full squat exercise; AV: average MPV attained against all absolute loads common to Pre- and Post-training; AV > 1: average MPV attained against absolute loads that were moved faster than 1 m·s⁻¹ at Pre-training; AV < 1: average

MPV attained against absolute loads that were moved slower than $1 \text{ m}\cdot\text{s}^{-1}$ at Pre-training; MNR: maximal number of repetitions in the fatigue test.

Δ (%): relative change from Pre to Post-training. Intra-group significant differences from Pre to Post-training: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.