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Effects of velocity loss in the bench press exercise on strength gains, neuromuscular adaptations, and muscle hypertrophy

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Objective: This study aimed to compare the effects of four velocity-based training (VBT) programs in bench press (BP) between a wide range of velocity loss (VL) thresholds—0% (VL0), 15% (VL15), 25% (VL25), and 50% (VL50)—on strength gains, neuromuscular adaptations, and muscle hypertrophy.
Methods: Sixty-four resistance-trained young men were randomly assigned into four groups (VL0, VL15, VL25, and VL50) that differed in the VL allowed in each set. Subjects followed a VBT program for 8-weeks using the BP exercise. Before and after the VBT program the following tests were performed: (a) cross-sectional area (CSA) measurements of pectoralis major (PM) muscle; (b) maximal isometric test; (c) progressive loading test; and (d) fatigue test.
Results: Significant group x time interactions were observed for CSA ($P < .01$) and peak root mean square in PM (peak RMS-PM, $P < .05$). VL50 showed significantly greater gains in CSA than VL0 ($P < .05$). Only the VL15 group showed significant increases in peak RMS-PM ($P < .01$). Moreover, only VL0 showed significant gains in the early rate of force development (RFD, $P = .05$), while VL25 and VL50 improved in the late RFD ($P \leq .01$-$.05$). No significant group × time interactions were found for any of the dynamic strength variables analyzed, although all groups showed significant improvements in all these parameters.
Conclusion: Higher VL thresholds allowed for a greater volume load which maximized muscle hypertrophy, whereas lower VL thresholds evoked positive neuromuscular-related adaptations. No significant differences were found between groups for strength gains, despite the wide differences in the total volume accumulated by each group.

KEYWORDS
fatigue, neural adaptations, resistance training, structural adaptations, training prescription, velocity-based training

1 | INTRODUCTION

The effectiveness of resistance training (RT) for enhancing muscle strength and hypertrophy, movement velocity, power output, and muscular endurance is widely recognized.[1] Adaptations in response to RT may differ according to the manipulation of several variables, including training frequency, type and order of exercises, loading magnitude, volume (ie number of sets and repetitions), and repetition velocity.[2] Exercise intensity during RT has traditionally been determined as lifted load relative to the one-repetition maximum (%1RM) or using percentages of set and repetition combination maximums;[3] while RT volume has frequently been prescribed according to a theoretical maximum number of repetitions (MNR) per set that can be performed against a given %1RM up to muscle failure.[1,2] However, a relatively high interindividual variation has been reported for the MNR that can be completed under a given %1RM.[4-6] This issue may lead athletes to train at different levels of effort, defined as the relationship between the repetitions performed and the MNR that could be performed.[7]

Velocity-based training (VBT) has emerged as an objective method for real-time monitoring and prescription of RT intensity and volume.[7,8] Firstly, strong relationships (R^2 = .94-.98) between %1RM and movement velocity have been reported for exercises conducted on Smith machine such as bench press (BP),[8] prone bench pull,[9] pull-up,[10] and different squat variants.[11,12] Notably, it has also been reported that these relationships are not affected by individual strength levels or training background.[13,14] These strong relationships open up the possibility of prescribing exercise intensity on a daily basis by adjusting the absolute load (kg) to match the movement velocity associated with the %1RM that is scheduled for the training session.[8] Afterward, it has been shown that individual load-velocity relationships could provide more accurate predictions of %1RM from barbell velocity than general equations.[15,16] However, it should be noted that velocity-based predictions conducted on free-weight exercises are not always accurate.[17,18] Secondly, using only the velocity attained at a given %1RM is not a proper method to predict the MNR that can be completed with such load.[19] However, the velocity loss (VL) incurred within the set, calculated as the relative difference between the fastest repetition velocity and the last repetition velocity of the set,[7] has shown strong correlations (R^2 = .96) with the percentage of completed repetitions with respect to the MNR.[5,20] Accordingly, VL can be used to accurately determine the percentage of the MNR that has been completed in the set.[5] Therefore, VBT can be considered as an alternative method to monitoring RT intensity and volume by collecting repetition velocity.

VBT programs have been demonstrated to induce physiological adaptations in muscle function and structure and physical performance, these adaptations being dependent on the VL threshold.[21,22] Thus, several studies conducted on the lower limbs (squat exercise) showed that greater muscle hypertrophic responses can be observed with higher VL thresholds (40%),[21,22] although these VL thresholds may also induce negative neuromuscular adaptations,[21] while greater strength gains were reported when applying moderate VL thresholds (10%-20%).[21-24] However, it remains to be established whether these respective findings can be extrapolated to one of the most commonly prescribed upper-body RT exercises (ie the BP exercise). Therefore, the aim of the present study was to compare the effects of four BP VBT programs under different VL thresholds (0% vs 15% vs 25% vs 50%) on strength gains, neuromuscular adaptations, and muscle hypertrophy.

2 | MATERIAL AND METHODS

2.1 | Subjects

This study is an extension of our previous work (see Pareja-Blanco et al[21]). However, no variables or training interventions described here have been reported previously. Sixty-four resistance-trained young men (mean ± SD: age = 24.1 ± 4.3 years, height = 175.0 ± 5.5 cm, body mass = 75.5 ± 9.7 kg, relative 1RM BP = 0.90 ± 0.21 kg body mass), with at least 1.5 years of RT experience in the BP exercise, volunteered to take part in this study. Subjects were randomly assigned to one of the four training groups differed in the VL allowed during the set: 0% (VL0) vs 15% (VL15) vs 25% (VL25) vs 50% (VL50). Two subjects dropped out during the course of the study for reasons not related to the training intervention, so the remaining subjects per group were: VL0 (n = 15), VL15 (n = 16), VL25 (n = 15) and VL50 (n = 16). All subjects were informed about the purpose and test procedures and signed a written informed consent form before participating. The present study was approved by the Research Ethics Committee of "Hospitales Universitarios Virgen Macarena-Virgen del Rocío" (Reference: 1547-N-19), in accordance with the Declaration of Helsinki.

2.2 | Study design

An experimental research design was used to examine the effects of four RT programs that differed in the VL threshold during the set in the BP exercise: 0%, 15%, 25%, and 50%. Two sessions per week (48-72 hours apart) were performed over 8 weeks as part of a progressive RT program. Subjects were asked to abstain from other types of vigorous physical activity involving the upper body during the research period. Subjects were measured on two occasions: 72 hours before (Pre-training) and 72 hours after (Post-training) the 8-week training intervention. A battery of tests was performed in two testing sessions (separated by 48 hours). The first testing session consisted of cross-sectional area (CSA) measurements of the pectoralis major (PM) muscle. In the second testing session, a battery of tests was performed as follows: (a) isometric BP test; (b) progressive loading BP test; and (c) fatigue test, which consisted of performing repetitions to failure with the 70% of 1RM attained at Pre-training in the BP exercise. Training compliance was 100% for all sessions. Sessions were performed at the same time of the day for each subject (±1 hour) and under similar environmental conditions (~20°C and 60% humidity) in a research laboratory under the direct supervision of the researchers. Subjects were motivated to give maximal effort with strong verbal encouragement during all the test and training sessions.

2.3 | Testing procedures

2.3.1 | Ultrasonography

B-mode ultrasonography (MyLab 25, Esaote Biomedica), with a 50 mm, 5-12 MHz linear-array probe, was used to assess the CSA of the PM muscle. Before the collection of the images, subjects remained lying in the supine position for 15 minutes, with their arms resting at the sides of the trunk, and palms facing down. The CSA of the PM was recorded in the sagittal plane at an intermediate point between the sternum and the right areola mammae of the participants. This intermediate point was determined after an exploratory analysis as the most lateral point of the PM muscle while avoiding imaging of the pectoralis minor muscle. Then, a straight line was drawn with a pen over the participant's skin of from the most inferior (~5th rib) to the most superior (clavicle) portion of the PM muscle. Finally, the extended field of view mode was used to register three images of the CSA of the PM muscle. Ultrasound images were recorded and digitally analyzed (ImageJ 1.51j8, NIH) by the same operator, who was blinded to subject allocation. The CSA of the PM muscle was measured by surrounding the bounds (aponeuroses) of the muscle (Figure 1A). Two ultrasound images were initially assessed, and if the coefficient of variation (CV) exceeded 5%, the third image was analyzed. The average value from all the analyzed images was considered for further analysis. Consistency in measurement sites across testing days was achieved by recording the probe positions on a transparent acetate sheet and using easily identifiable infiltrations of fatty and connective tissues as landmarks. Test-retest reliability in a sub-group of 10 subjects evaluated 24 hours apart was: CV = 3.9%.

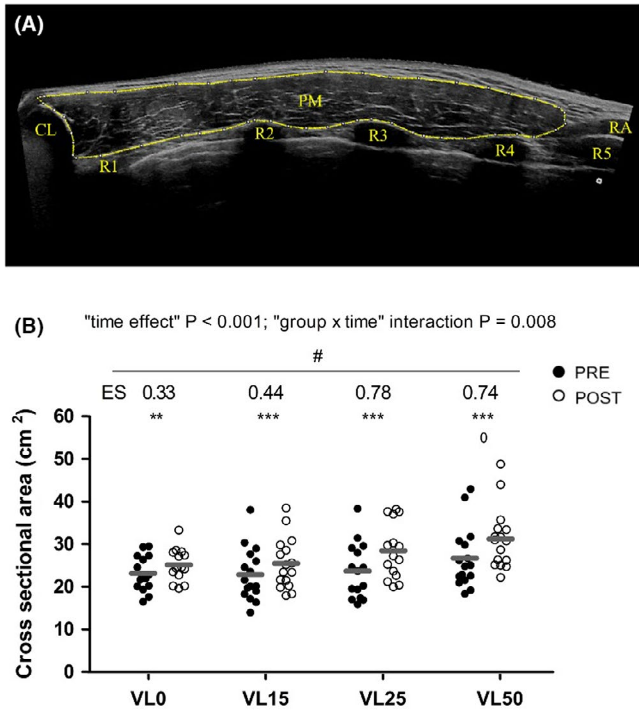

FIGURE 1 A, Ultrasound image obtained from the pectoralis major muscle of a standard subject. The cross-sectional area of the vastus lateralis muscle is surrounded by the yellow line. CL, clavicle; PM, pectoralis major; R, rib; RA, rectus abdominis. B, Changes produced on pectoralis muscle thickness, illustrated using ultrasound images from Pre- to Post-training for each group. N = 62. VL0, group that trained with a mean velocity loss of 0% in each set (n = 15); VL15, group that trained with a mean velocity loss of 15% in each set (n = 16); VL25, group that trained with a mean velocity loss of 25% in each set (n = 15); VL50, group that trained with a mean velocity loss of 50% in each set (n = 16); ES, within-group effect size from pre- to post-training. Intragroup significant differences from Pre- to Post-training: $^{**}P \leq .01$, $^{***}P \leq .001$. Statistically significant differences with VL0 group: $^{0}P \leq .05$. Significant group × time interaction: $^{\#}P \leq .05$

2.3.2 | Isometric bench press test

This test consisted of performing two 5 seconds maximal isometric contractions in the BP exercise, with a 1 minute rest between trials. The test was performed on a Smith machine (Fitness Line, Peroga) with the subjects placed in the supine position on top of a bench (Bench Fitness Line, Peroga) that was fitted onto a 0.8 × 0.8 m dynamometric platform (FP-500, Ergotech). The feet were positioned on the bench to record the force applied by the force platform. Before the test, the isometric position was individually adjusted with the bar placed 1 cm above the participant's chest through height-adjustable movable supports (elbow joint angle ~40°, considering full extension as 180°). A pronated grip at a width self-selected by the subject (approximately 150% of the biacromial distance) was used.

Individual bar height and width grip were recorded to be repeated at Post-training sessions. Subjects were instructed to push against the bar as fast and hard as possible after the cue "ready, set, go!" External forces were collected at a sampling rate of 1000 Hz. Raw force-time data were automatically processed (4th order low-pass Butterworth filter with no phase shift using a 200 Hz cutoff frequency) with specialized software (T-Force System, Ergotech). The following variables were measured during each attempt: (a) maximal isometric force (MIF); (b) maximal rate of force development (RFD_{max}), which was calculated as the maximum slope in the force-time curve in 20 ms time intervals; and (c) the average tangential slope of the force-time curve obtained over different time intervals (50, 100, 150, 200, and 400 ms from the onset of force production; RFD_{0-50}, RFD_{0-100}, RFD_{0-150}, RFD_{0-200}, and RFD_{0-400}, respectively). The average value of the two attempts for each variable was recorded for further analysis. The onset of the force signal was established at the point where the signal raised above 3 SDs the baseline signal. Test-retest CV values were: 5.7% and 17.7% for MIF and RFD_{max}, respectively. For RFD obtained over different time intervals, CV values were as follows: 21.1%, 14.3%, 10.3%, 9.5%, and 6.7% for RFD_{0-50}, RFD_{0-100}, RFD_{0-150}; RFD_{0-200}, and RFD_{0-400}, respectively.

2.3.3 | EMG signal acquisition

EMG signals were recorded continuously during the isometric test. Electrodes were placed over the PM and triceps brachii (TB) muscles of the right side according to surface EMG recommendations for non-invasive muscle evaluation.[25] Electrode positions were recorded onto a transparent acetate as well as different anatomic references and skin moles as landmarks in order to replicate the electrode positions at Post-training. EMG signals were collected using a parallel bar, bipolar, surface electromyographic sensor wireless Trigno™ EMG system (interelectrode distance of 10 mm, common mode rejection ratio >80 dB, and bandwidth filter between 20 and 450 Hz ± 10%) (Delsys Inc). The baseline noise was <5 μV peak-to-peak, and sampling rate was 1926 Hz. Raw EMG data were stored in digital format using EMG works Acquisition software (Delsys Inc) and smoothed by root mean square (RMS) calculation using a moving window of 100 ms with an overlap of 99 ms From each isometric trial, the highest averaged (over a 500 ms window) RMS value (peak EMG) and the integrated EMG (iEMG) of the RMS (normalized to peak EMG)-time curve over different time intervals (50, 100, 150, 200, and 400 ms from the onset of EMG activity, $iEMG_{0-50}$, $iEMG_{0-100}$, $iEMG_{0-150}$, $iEMG_{0-200}$, and $iEMG_{0-400}$, respectively) were calculated. The average value of each variable of the two maximal isometric contractions was recorded for analysis. The onset of the EMG signal was set at the point where the signal raised above 3 SDs the baseline signal. Test-retest CV values for peak EMG were 13.6% and 18.1% for PM and TB muscles, respectively.

2.3.4 | Progressive loading test

The individual load-velocity relationships and 1RM load in the BP exercise were determined using a Smith machine with no counterweight mechanism (Multipower Fitness Line, Peroga) and a linear velocity transducer (T-Force System Ergotech). The participants' position and grip were the same as reported during the isometric test. During each repetition, the subjects were required to perform the eccentric phase in a controlled manner and to maintain a static position for ~1 second at the end of this phase (ie bar resting on the chest) to minimize the contribution of the rebound effect and allow for more reproducible measurements.[26] Then, the bar was lifted at maximal intended velocity upon hearing the command. Throwing the bar at the end of the concentric phase was not allowed. The initial load consisted of one set of 3 repetitions with a rigid plastic bar (bar weight <0.2 kg) to assess the maximal unloaded velocity (V_0) in BP exercise. Then, a set of 3 repetitions with 20 kg was performed and the load was progressively increased in 10 kg increments until the attained MPV was ≤0.30 m/s. When the load was close to 0.3 m/s, the load was increased in smaller increments (5 down to 2.5 kg) to allow better adjustments. A total of 6.3 ± 1.3 increasing loads were used for each subject. Three repetitions were executed for light (>0.80 m/s), two for medium (0.80-0.60 m/s) and only one for heavy (<0.60 m/s) loads. Inter-set recovery periods ranged from 3 minutes (light) to 5 minutes (heavy loads). Warm-up consisted of two sets of 6 BP repetitions with 0.2 and 20 kg, respectively. Only the fastest repetition with each load was considered for subsequent analysis. The velocity measures used in this study correspond to the mean velocity of the propulsive phase of each repetition (ie mean propulsive velocity, MPV), defined as that portion of the concentric action during which the measured acceleration is greater than acceleration due to gravity (−9.81 m/s^2) (Sanchez-Medina, Perez, & Gonzalez-Badillo, 2010). In addition to 1RM strength and V_0, three other variables were analyzed: (a) average MPV attained against all absolute loads common to Pre- and Post-training (AV); (b) average MPV attained against absolute loads that were lifted faster than 0.8 m/s at Pre-training (AV > 0.8); and (c) average MPV attained against absolute loads that were lifted slower than 0.8 m/s at Pre-training (AV < 0.8). These variables were analyzed to examine the effects on the different parts of the load-velocity relationship (ie velocity developed against light vs heavy loads).

2.3.5 | Fatigue test

This test was performed with the same absolute load (kg) at Pre- and Post-training measurements, which corresponded to 70% of 1RM attained at Pre-training. The execution technique and devices used were the same as described in the progressive loading test. Subjects were required to complete as many repetitions as possible until muscle failure, performing each repetition at maximum intended velocity. The following variables were used for analysis: (a) maximal number of repetitions to failure (FT-MNR); and (b) average MPV attained against the same number of repetitions to Pre-training and Post-training (FT-AV). For example, if one subject performed 10 MNR at Pre-training and 15 MNR at Post-training, we evaluated the average MPV over the first 10 repetitions in both tests. This enabled assessment of the changes in MPV corresponding to the MNR at Pre-training. Fatigue testing began 5 minutes after subjects finished the BP progressive loading test.

2.4 | Resistance training program

The descriptive characteristics of the RT program are presented in Table 1. The technical execution was identical to that previously described in the Progressive loading test section (including similar width grip and pause between the eccentric and concentric phases). All groups performed each training session with the same relative intensity (from 70% to 85% 1RM), number of sets (3) and interset recovery

TABLE 1 Descriptive characteristics of the 8-wk velocity-based bench press training program performed by the four experimental groups

Scheduled	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8
Set × %1RM	3 × 70	3 × 70	3 × 70	3 × 70	3 × 70	3 × 75	3 × 75	3 × 75
Target velocity (m/s)	0.65 ± 0.07	0.65 ± 0.07	0.65 ± 0.07	0.65 ± 0.07	0.65 ± 0.07	0.57 ± 0.07	0.57 ± 0.07	0.57 ± 0.07

Scheduled	Session 9	Session 10	Session 11	Session 12	Session 13	Session 14	Session 15	Session 16
Set × %1RM	3 × 75	3 × 75	3 × 80	3 × 80	3 × 80	3 × 80	3 × 85	3 × 85
Target velocity (m/s)	0.57 ± 0.07	0.57 ± 0.07	0.49 ± 0.06	0.49 ± 0.06	0.49 ± 0.06	0.49 ± 0.06	0.41 ± 0.05	0.41 ± 0.05

Actually performed	Fastest MPV (m/s)	Slowest MPV (m/s)	MPV all reps (m/s)	Mean VL (%)	Total Rep	Total volume load (set × rep × %1RM)
VL0	0.53 ± 0.05	0.48 ± 0.05$^{15\ 25\ 50}$	0.51 ± 0.05^{50}	0.0 ± 0.0$^{15\ 25\ 50}$	48.0 ± 0.0$^{15\ 25\ 50}$	3621 ± 82$^{15\ 25\ 50}$
VL15	0.57 ± 0.05	0.43 ± 0.04$^{25\ 50}$	0.52 ± 0.05^{50}	16.3 ± 0.8$^{25\ 50}$	136.6 ± 17.8$^{25\ 50}$	10 666 ± 2627$^{25\ 50}$
VL25	0.57 ± 0.07	0.38 ± 0.05^{50}	0.50 ± 0.07^{50}	25.0 ± 0.7^{50}	191.1 ± 34.1^{50}	14 595 ± 3536^{50}
VL50	0.55 ± 0.07	0.21 ± 0.02	0.40 ± 0.05	51.9 ± 1.6	316.4 ± 65.1	22 687 ± 5734

Actually performed	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	Average Training Intensity (%1RM)
VL0	1.0 ± 0.0$^{15\ 25\ 50}$	1.0 ± 0.0$^{15\ 25\ 50}$	1.0 ± 0.0$^{15\ 25\ 50}$	1.0 ± 0.0$^{15\ 25\ 50}$	1.0 ± 0.0$^{15\ 25\ 50}$	75.2 ± 1.7
VL15	2.9 ± 0.4$^{25\ 50}$	3.4 ± 0.3$^{25\ 50}$	2.9 ± 0.5$^{25\ 50}$	2.5 ± 0.5$^{25\ 50}$	2.0 ± 0.4^{50}	74.3 ± 0.8
VL25	4.0 ± 0.7^{50}	5.0 ± 0.9^{50}	4.1 ± 0.7^{50}	3.4 ± 0.8^{50}	2.6 ± 0.7^{50}	74.3 ± 0.9
VL50	6.6 ± 1.4	8.3 ± 1.7	6.7 ± 1.4	5.5 ± 1.5	4.2 ± 1.2	74.3 ± 0.9

Note: Data are mean ± SD. Only one exercise (bench press) was used in training.

Abbreviations: Average rep per set in all sessions, average number of repetitions performed in each set; Average training intensity, average relative intensity attained during the training program calculated as total volume load/total repetitions; Fastest MPV, average of the fastest repetitions measured in each session (this value represents the average intensity, %1RM, achieved during the training program); Mean velocity loss, average velocity loss attained during the entire training program; MPV all reps, average MPV attained during the entire training program; MPV, mean propulsive velocity; 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); Slowest MPV, average of the slowest repetitions measured in each session; Target velocity, velocity associated with the scheduled %1RM; Total rep, Total number of repetitions performed during the training program; Total volume load, sets × reps × %1RM; VL0, group that trained with a mean velocity loss of 0% in each set (n = 15); VL15, group that trained with a mean velocity loss of 15% in each set (n = 16); VL25, group that trained with a mean velocity loss of 25% in each set (n = 15); VL50, group that trained with a mean velocity loss of 50% in each set (n = 16); 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.

Statistically significant differences with VL15 protocol: $^{15}P \le .05$. Statistically significant differences with VL25 protocol: $^{25}P \le .05$. Statistically significant differences with VL50 protocol: $^{50}P \le .05$.

(4 minutes) in the BP exercise. Relative loads were determined from the individual load-velocity relationship obtained from the progressive loading test for each subject (R^2 = .996 ± .004). Therefore, the absolute load (kg) was individually adjusted according to the individual velocity (±0.03 m/s) associated with the %1RM that was set for that session. We used a range of 0.03 m/s since it has recently been shown that the smallest detectable change in MPV when using the T-Force System is 0.03 m/s in BP exercise.[27] The four groups differed in the VL threshold allowed in each set (0% vs 15% vs 25% vs 50%). VL0 performed only one repetition per set in order to induce the least possible fatigue. The rest of the groups finished their sets when the corresponding targeted VL threshold was exceeded. All repetitions during all sessions were recorded using a linear velocity transducer (T-Force System, Ergotech). The warm-up preceding each training session was standardized for all training groups, as follows: 5 minutes of jogging at a self-selected easy pace, a set of 6 BP repetitions with 20 kg, followed by 3 sets of 6, 4 and 3 repetitions with loads of 40%, 50%, and 60% 1RM, respectively, for sessions 1-5 (in which the training load was 70% 1RM). An additional set of two repetitions with 70% 1RM was added for sessions 6-14 (in which the training load was 75%-80% 1RM), and a final set of one repetition with 80% 1RM was added for sessions 15 and 16 (in which the training load was 85% 1RM). A 3 minutes rest between the warm-up sets was always used. The total volume load (ie sets × reps × %1RM) and average training intensity (ie (total volume load/total repetitions) were calculated.[3]

2.5 | Statistical analysis

Data are reported as mean ± SD. Test-retest absolute reliability was measured by the standard error of measurement (SEM), which was expressed in relative terms through CV. The SEM was calculated as the root mean square of the intrasubject total mean square. Normality and homoscedasticity were verified with the 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 VL15 vs VL25 vs VL50) and one within-group factor (Pre- vs Post-training). A one-way ANOVA with Bonferroni post-hoc adjustments was performed to analyze differences between groups in the training variables analyzed. Statistical significance was established at the $P \leq .05$ level. In addition, effect size (ES) values were calculated using Hedge's g on the pooled SD[28] using a purpose-built spreadsheet. The rest of statistical analyses were performed using SPSS software version 20.0 (SPSS Inc). Figures were designed using SigmaPlot 12.0 (Systat Software Inc).

3 | RESULTS

No significant differences between groups were observed at Pre-training for any of the variables analyzed.

3.1 | Muscle cross-sectional area

A significant group × time interaction was observed for PM muscle CSA (P = .008, Figure 1B). After completing the RT program, all groups obtained significant increases in muscle CSA (P < .001-.01). However, VL50 showed significantly greater gains than VL0 (P = .04) and almost significantly higher gains than VL15 (P = .06). No significant differences were reported between VL25 and VL50 or between any of the other groups (all P > .05).

3.2 | Isometric test

No significant group × time interactions were observed for the isometric strength parameters analyzed, but significant overall time effects were observed for MIF, $RFD_{0\text{-}150}$, $RFD_{0\text{-}200}$ and $RFD_{0\text{-}400}$ (P < .001-.05). All groups showed significant gains in MIF (P < .001-.05). RT-induced changes in RFD parameters for each group are depicted in Figure 2. The VL0 intervention induced significant gains in $RFD_{0\text{-}50}$ (P = .05), and VL25 improved in $RFD_{0\text{-}400}$ (P < .05), whereas VL50 showed significant increases in $RFD_{0\text{-}150}$ and $RFD_{0\text{-}400}$ ($P \leq$ .01-.05).

With regard to neuromuscular adaptations, a significant group × time interaction was observed for peak EMG-PM (P = .03) and there was an almost significant group × time interaction (P = .06) for peak EMG-TB. Only the VL15 group showed significant increases in peak EMG-PM (P < .01), while no significant changes were observed for peak EMG-TB for any group (Table 2). For normalized values, VL15 showed a significant decrease for iEMG400ms-PM (P < .05). No significant changes were detected for the rest of the parameters analyzed.

3.3 | Progressive loading test and fatigue test

Changes in the selected performance variables from Pre- to Post-training for each group are reported in Table 3. No significant group × time interactions were found for any of the dynamic strength variables analyzed, but significant overall time effects were observed for all these parameters. All groups showed significant gains in 1RM strength (P < .001). With regard to the changes in the load-velocity relationship, all groups showed significant increases in AV, AV < 0.8, and AV > 0.8 (P < .001). However, only the VL15 group showed

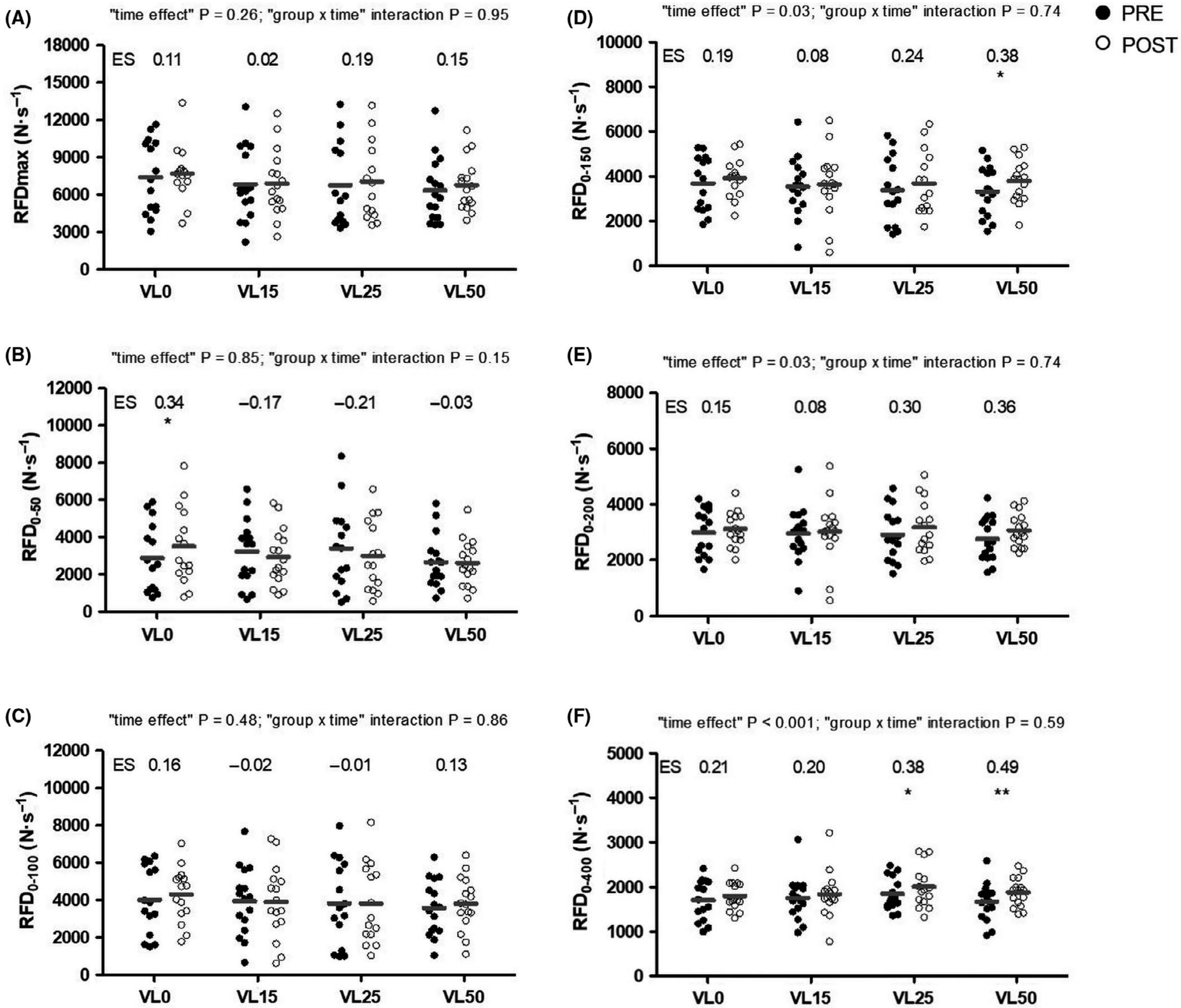

FIGURE 2 A, Changes produced in maximal rate of force development (RFD_{max}) from Pre- to Post-training for each group. B, Changes produced in 0-50 ms rate of force development ($RFD_{0\text{-}50}$) from Pre- to Post-training for each group. C, Changes produced in 0-100 ms rate of force development ($RFD_{0\text{-}100}$) from Pre- to Post-training for each group. D, Changes produced in 0-150 ms rate of force development ($RFD_{0\text{-}150}$) from Pre- to Post-training for each group. E, Changes produced in 0-200 ms rate of force development ($RFD_{0\text{-}200}$) from Pre- to Post-training for each group. F, Changes produced in 0-400 ms rate of force development ($RFD_{0\text{-}400}$) from Pre- to Post-training for each group. N = 62; VL0, group that trained with a mean velocity loss of 0% in each set (n = 15); VL15, group that trained with a mean velocity loss of 15% in each set (n = 16); VL25, group that trained with a mean velocity loss of 25% in each set (n = 15); VL50, group that trained with a mean velocity loss of 50% in each set (n = 16); ES, within-group effect size from Pre- to Post-training. Intragroup significant differences from Pre- to Post-training: $^{*}P \leq .05$, $^{**}P \leq .01$, $^{***}P \leq .001$

a significant improvement ($P = .03$) in the maximal unloaded velocity (V_0). With regard to muscular endurance performance, the four groups showed significant enhancements in the fatigue test (FT-MNR and FT-AV, $P < .001$).

3.4 | Training program

The average of the fastest repetitions measured in each session, which represents the %1RM lifted in each training session, was similar for all groups (Table 1). Likewise, no significant differences were observed in the average training intensity actually performed during the training program by each group. The mean velocity (MPV all reps) attained during the training program became slower as the VL threshold increased ($P < .05$, Table 1). Furthermore, the training volume (ie total volume load, total number of repetitions performed, the repetitions per set, and the repetitions performed with each %1RM) was higher as the VL threshold increased ($P < .05$, Table 1). The repetitions performed in the different

TABLE 2 Changes in selected EMG parameters from Pre- to Post-training for each group

	VL0			VL15			VL25			VL50			*P*-value	*P*-value
	Pre	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**	**Pre**	**Post**	**ES**	**time effect**	**group × time**
Pectoralis major														
Peak RMS (mV)	0.220 ± 0.146	0.196 ± 0.109	−0.21	0.150 ± 0.092	0.209 ± 0.113**	0.52	0.224 ± 0.145	0.217 ± 0.083	−0.06	0.166 ± 0.094	0.190 ± 0.106	0.21	.20	.03
iEMG (%)														
0-50 ms	1.6 ± 0.9	1.4 ± 0.7	−0.28	1.1 ± 0.5	1.0 ± 0.6	−0.14	1.2 ± 0.7	1.4 ± 1.1	0.28	1.1 ± 0.5	1.2 ± 0.7	0.14	.96	.45
0-100 ms	4.8 ± 2.4	4.5 ± 2.1	−0.15	3.7 ± 1.5	3.2 ± 2.0	−0.25	3.5 ± 2.1	4.0 ± ± 3.1	0.25	3.5 ± 1.1	3.9 ± 1.8	0.20	.86	.39
0-150 ms	8.9 ± 3.6	8.5 ± 3.7	−0.12	7.5 ± 2.7	6.1 ± 3.4	−0.41	6.3 ± 3.4	7.1 ± 5.0	0.24	6.8 ± 2.2	7.5 ± 3.0	0.21	.89	.28
0-200 ms	12.9 ± 4.4	12.5 ± 4.6	−0.09	11.5 ± 3.7	9.3 ± 4.5	−0.50	9.0 ± 4.2	10.0 ± 6.3	0.23	10.3 ± 3.1	11.1 ± 3.7	0.18	.69	.22
0-400 ms	28.4 ± 7.2	27.1 ± 6.3	−0.18	28.0 ± 6.9	23.3 ± 8.1*	−0.64	22.3 ± 7.7	22.4 ± 11.4	0.01	25.2 ± 4.6	25.8 ± 5.2	0.08	.22	.30
Triceps braquial														
Peak RMS (mV)	0.305 ± 0.220	0.277 ± 0.217	−0.15	0.238 ± 0.193	0.299 ± 0.188	0.32	0.367 ± 0.213	0.303 ± 0.116	−0.33	0.281 ± 0.170	0.312 ± 0.189	0.16	.99	.06
iEMG (%)														
0-50 ms	0.9 ± 0.9	1.1 ± 0.7	0.31	0.9 ± 0.5	0.8 ± 0.5	−0.16	1.4 ± 0.9	1.2 ± 0.7	−0.31	0.8 ± 0.4	0.9 ± 0.4	0.16	.97	.45
0-100 ms	2.9 ± 2.2	3.4 ± 1.6	0.26	2.9 ± 1.6	2.6 ± 1.6	−0.15	4.5 ± 3.1	3.6 ± 1.9	−0.46	2.7 ± 1.5	2.7 ± 1.3	0.00	.62	.37
0-150 ms	5.8 ± 3.2	6.4 ± 2.6	0.17	5.9 ± 3.1	5.2 ± 2.9	−0.20	8.8 ± 6.2	6.7 ± 3.3	−0.61	5.6 ± 2.8	5.5 ± 2.3	−0.03	.31	.36
0-200 ms	9.1 ± 3.9	9.8 ± 3.3	0.15	9.4 ± 4.5	8.1 ± 3.9	−0.28	12.9 ± 8.6	10.0 ± 4.5	−0.62	9.1 ± 4.1	8.8 ± 3.2	−0.06	.22	.43
0-400 ms	22.5 ± 6.6	25.3 ± 6.5	0.36	25.5 ± 7.8	22.2 ± 7.0	−0.43	26.6 ± 10.3	24.0 ± 9.1	−0.34	24.0 ± 6.5	25.0 ± 6.4	0.13	.66	.25

Note: Data are mean ± SD, N = 62.

Abbreviations: VL0, group that trained with a mean velocity loss of 0% in each set (n = 15); VL15, group that trained with a mean velocity loss of 15% in each set (n = 16); VL25, group that trained with a mean velocity loss of 25% in each set (n = 15); VL50, group that trained with a mean velocity loss of 50% in each set (n = 16). PM: pectoralis major muscle; TB, triceps brachii muscle; Peak RMS, maximal root mean squared value registered during the maximal voluntary isometric contraction for the corresponding muscle; iEMG, integrated EMG values of the root mean square-time curve over different time intervals from the onset of EMG activity. These parameters are normalized to the maximal RMS registered during the maximal voluntary isometric contraction; ES, within-group effect size from Pre- to Post-training.

Intragroup significant differences from Pre- to Post-training:

*$P < .05$;

**$P < .01$.

velocity ranges are shown in Figure 3A. Figure 3B shows the evolution of the estimated 1RM strength (expressed as percentage of the Pre-training values) in each training session for all groups, based on the individual load-velocity relationship ($R^2 = .996 \pm .004$) for each subject.

4 | DISCUSSION

This is the first study to analyze the effects of four different BP VBT programs (0% vs 15% vs 25% vs 50%) on strength gains, neuromuscular adaptations, and muscle hypertrophy of resistance-trained men. The main finding of this study was that the VL threshold in the set was a determining factor in modulating the muscle hypertrophic and neuromuscular adaptations that occur during RT. Higher VL thresholds (ie VL50), which accumulated remarkably higher volume load (Table 1) by performing more fatiguing and slower repetitions (Figure 3A), resulted in more muscle hypertrophy than lower VL thresholds (ie VL0), and only moderate VL thresholds (ie VL15) showed an increase in maximal neuromuscular excitation. In contrast, no group × time interactions were observed for RT-induced adaptations in muscle strength and endurance. It should be noted that these similar adaptations in BP strength levels were accompanied by very large differences in the total volume accumulated by each group throughout the study period (Table 1).

After an 8-week VBT program, the four VL groups significantly improved their maximal dynamic and isometric strength levels (ie 1RM and MIF) and load-velocity relationship-related adaptations (ie AV, AV < 0.8; and AV > 0.8). In agreement with our findings, previous VBT studies carried out using lower body exercises (ie squat) have shown that higher VL thresholds do not induce further 1RM strength gains than lower VL thresholds.[21,22,24] Moreover, all groups showed improvements in muscular endurance performance (ie FT-MNR and FT-AV), although the VL25 and VL50 groups attained the highest ES values. Supporting this finding, Izquierdo et al[29] observed greater BP muscular endurance following a training program to failure compared with non-failure training, although there were no differences in the squat exercise. It should be noted that the VL0 group showed the lowest percentage improvements in all physical performance parameters. Accordingly, a certain minimal VL threshold and training volume seems to be necessary to elicit strength gains, although once a certain VL threshold is achieved, performing additional repetitions does not seem to elicit further strength gains.

In an attempt to monitor strength evolution throughout the 8-week VBT, the 1RM was estimated in each training session from the individual load-velocity relationships of each subject. In this regard, all groups showed similar improvements in 1RM during the training program (Figure 3B). This result is very relevant for those athletes who are required to attain high strength levels during the entire season, with competitions every weekend or even every 3-4 days. It has been shown that RT protocols with large VL thresholds require longer recovery times (up to 48 hours post-exercise), whereas low VL thresholds show faster rates of recovery.[30,31] Therefore, including RT protocols with lower VL thresholds during in-season periods with congested calendars could produce significant strength adaptations while maximizing recovery, compared with higher VL thresholds that may be detrimental to muscle recovery.

Although training volume increased as VL threshold increased, this volume increment was due to accumulated slow and fatiguing repetitions (Figure 3A). These extra repetitions performed in the higher VL protocols may explain the different structural adaptations observed in the different groups. Although all training protocols induced muscle hypertrophy, higher VL thresholds (ie VL25-50) showed a greater hypertrophic response than lower VL thresholds (ie VL0-15). In agreement with our findings, it has been postulated that high training volumes[32] and levels of effort (ie reaching or approaching muscle failure) are important factors in maximizing muscle growth.[33,34] In this regard, a previous VBT study using the squat exercise also showed higher hypertrophy in the vastus lateralis muscle following an RT with higher VL (20%-40%) compared with lower VL (0%-10%).[21] The higher exercise-induced metabolic and mechanical stress,[7] the greater secretion of growth-promoting hormones and muscle damage, along with the higher total volume load observed in RT protocols with high VL thresholds[30] could be responsible for the greater hypertrophic adaptations observed with these protocols.[34,35] In addition, increased ribosomal biogenesis has recently been found to be behind the higher hypertrophic adaptations observed in high-volume RT programs.[36]

In contrast, a lower VL threshold seems to be required to induce positive neuromuscular adaptations, since only VL15 showed enhanced peak PM muscle excitation. Neuromuscular adaptations may be related to increased motor unit firing frequency, increased incidence of discharge doublets, and changes in fiber types and sarcoplasmic reticulum calcium kinetics.[37-39] In addition, only VL15 showed improved maximal unloaded (<0.2 kg) velocity (V_0). A faster muscle fiber phenotype has been reported to provide an advantage, especially under low loads or unloaded conditions.[40,41] This phenomenon is related to type II fibers having faster cross-bridge cycling rates than type I fibers.[42] Moreover, in the present study only the VL0 intervention induced improvements in the early RFD (ie RFD_{0-50}). A significant association ($r^2 = .49$) has previously been reported between vastus lateralis type II fiber area and knee extensor RFD_{0-50} in young men.[43] Specific RT-induced adaptations were found by Pareja-Blanco et al,[22] who reported

TABLE 3 Changes in selected performance variables from Pre- to Post-training for each group

	VL0			VL15			VL25			VL50			*P*-value time effect	*P*-value group × time
	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES	Pre	Post	ES		
MIF (N)	849 ± 172	934 ± 190**	0.43	853 ± 235	939 ± 246**	0.44	945 ± 155	1065 ± 173***	0.61	866 ± 198	995 ± 164***	0.66	<.001	.62
1RM (kg)	65.5 ± 9.6	73.1 ± 11.5***	0.50	64.5 ± 17.4	74.0 ± 14.2***	0.62	68.4 ± 18.5	80.8 ± 17.1***	0.81	70.0 ± 16.9	80.8 ± 13.5***	0.71	<.001	.15
V_0 (m/s)	2.31 ± 0.16	2.30 ± 0.14	−0.05	2.18 ± 0.14	2.27 ± 0.13*	0.48	2.27 ± 0.22	2.32 ± 0.23	0.26	2.23 ± 0.23	2.31 ± 0.22	0.42	.02	.30
AV (m/s)	0.70 ± 0.08	0.83 ± 0.08***	1.49	0.69 ± 0.09	0.84 ± 0.07***	1.72	0.71 ± 0.09	0.87 ± 0.10***	1.83	0.72 ± 0.09	0.86 ± 0.08***	1.60	<.001	.74
AV > 0.8 (m/s)	1.13 ± 0.08	1.21 ± 0.08***	1.15	1.09 ± 0.07	1.20 ± 0.06***	1.59	1.10 ± 0.05	1.21 ± 0.07***	1.58	1.12 ± 0.06	1.22 ± 0.07***	1.44	<.001	.62
AV < 0.8 (m/s)	0.44 ± 0.05	0.64 ± 0.08***	2.92	0.44 ± 0.05	0.65 ± 0.07***	3.07	0.43 ± 0.06	0.67 ± 0.08***	3.50	0.45 ± 0.04	0.67 ± 0.09***	3.21	<.001	.70
FT-MNR (rep)	11.7 ± 2.1	15.8 ± 4.3***	1.22	11.3 ± 1.5	16.9 ± 4.3***	1.67	11.2 ± 1.9	17.5 ± 3.6***	1.87	11.6 ± 1.6	18.6 ± 4.9***	2.08	<.001	.21
FT-AV (m/s)	0.43 ± 0.03	0.58 ± 0.09***	1.70	0.44 ± 0.04	0.60 ± 0.10***	1.82	0.44 ± 0.06	0.63 ± 0.13***	2.16	0.43 ± 0.05	0.59 ± 0.13***	1.82	<.001	.65

Note: Data are mean ± SD, N = 62.

Abbreviations: VL0, group that trained with a mean velocity loss of 0% in each set (n = 15); VL15, group that trained with a mean velocity loss of 15% in each set (n = 16); VL25, group that trained with a mean velocity loss of 25% in each set (n = 15); VL50, group that trained with a mean velocity loss of 50% in each set (n = 16); MIF, maximal isometric force; 1RM, one-repetition maximal in bench press exercise; V_0, maximal unloaded velocity; AV, average MPV attained against all absolute loads common to Pre- and Post-training; AV > 0.8, average MPV attained against absolute loads that were moved faster than 0.80 m/s at Pre-training; AV < 0.8, average MPV attained against absolute loads that were moved slower than 0.80 m/s at Pre-training; FT-MNR, maximal number of repetitions in the fatigue test; FT-AV, average MPV attained against the same number of repetitions to Pre-training and Post-training; ES, within-group effect size from Pre- to Post-training.

Intragroup significant differences from Pre- to Post-training:

*$P < .05$,

**$P < .01$,

***$P < .001$.

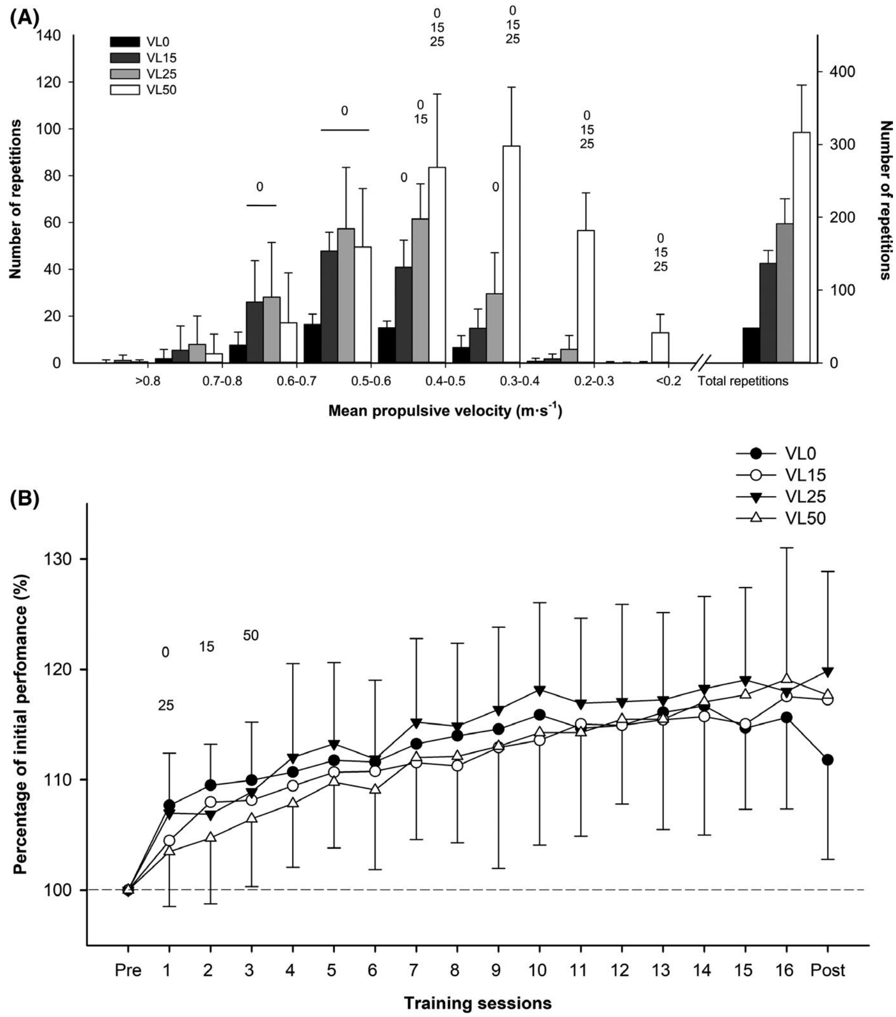

FIGURE 3 A, Number of repetitions in the BP exercise performed in each velocity range, and total number of repetitions completed by four training groups. B, Evolution of the estimated 1RM strength in the bench press exercise in each training session expressed as a percentage of the initial Pre-training level for four experimental groups. Data are mean ± SD, N = 62. VL0, group that trained with a mean velocity loss of 0% in each set (n = 15); VL15, group that trained with a mean velocity loss of 15% in each set (n = 16); VL25, group that trained with a mean velocity loss of 25% in each set (n = 15); VL50, group that trained with a mean velocity loss of 50% in each set (n = 16). Statistically significant differences with VL0 group: $^{0}P \leq .05$. Statistically significant differences with VL15 group: $^{15}P \leq .05$. Statistically significant differences with VL25 group: $^{25}P \leq .05$

a reduction in the percentage of type IIX fibers after completing an RT program using a 40% VL, whereas a 20% VL maintained the type IIX fiber pool. Likewise, Carroll et al[44] showed greater improvements in vertical jump, RFD and maximal strength when a non-failure training was compared with training to failure. By contrast, only higher VL thresholds (25%-50%) improved the force development when longer time periods to apply force were available (ie late RFD: RFD_{0-150} and RFD_{0-400}). It has been suggested that both the ability to activate muscles at high force levels,[45] which is not necessarily related to the capacity to rapidly activate muscles at force onset,[46] and muscle hypertrophy[47] may be pivotal to improving late RFD. These data suggest that lower VL thresholds would lead to a greater preservation of the fast muscle fiber phenotype and greater neural adaptations compared with higher VL thresholds, which due to the extra, slow and fatiguing repetitions, would induce a greater hypertrophic response. Finally, these distinct mechanisms would produce similar adaptations in BP strength.

Several study limitations should be considered when interpreting our results. Firstly, although all participants were resistance-trained men, they were not athletes, which may limit the extrapolation of the current findings to other populations, especially athletes. Secondly, the study was carried out in BP exercise with a narrow intensity range (70%-85% 1RM), thus, the findings may not be generalizable to other exercises or intensity ranges. Thirdly, researchers and coaches should take into consideration the filtering conditions (a 4th order low-pass Butterworth filter with no phase shift using 200 Hz cutoff frequency) when interpreting and comparing our force-time results. Fourthly, it should be acknowledged that daily 1RM estimations may not be accurate.[18] Lastly, it has recently been shown that unaccustomed resistance exercise can cause errors in ultrasound-based measures 72 hours post-exercise.[48] However, it should be noted that our participants were previously accustomed to the resistance exercise and we assessed a different muscle (pectoralis major) than the one assessed by Rowe et al[48] (biceps brachii), which likely limited the impact of this issue on our findings. Thus, whether a 72 hours post-exercise ultrasound measure of the pectoralis major muscle can be affected by the acute effect of resistance exercise in previously accustomed subjects should be assessed in future studies.

5 | PERSPECTIVES

Monitoring the VL threshold attained during the set can provide valid, accurate, and objective information for determining the degree of fatigue that induces specific functional, neuromuscular and structural adaptations. Resistance exercise with larger VL thresholds (ie VL25-VL50), and as consequence, with higher volume load and more fatiguing repetitions, maximizes muscle hypertrophy. However, in order to develop better neuromuscular adaptations, lower VL thresholds should be prescribed, since only low VL thresholds in this study showed positive neuromuscular adaptations (VL15: peak EMG-PM). Moreover, RFD improvements are influenced by the VL thresholds, since only the VL0 intervention improved the ability to develop force rapidly (ie early RFD, $RFD_{0\text{-}50}$) while only higher VL thresholds (25%-50%) improved the late RFD (ie $RFD_{0\text{-}150}$ and $RFD_{0\text{-}400}$). Lastly, although all four VL groups improved their BP strength levels significantly, the VL0 group demonstrated the lowest percentage changes in all strength variables. Consequently, a minimal VL threshold should be achieved to elicit strength gains in resistance-trained men. However, a threshold beyond a moderate VL (>VL25) does not appear to induce further strength benefits in this population. Further studies are warranted to confirm or refute these findings and assess the long-term consequences of different VBT approaches in highly trained subjects (eg professional athletes). Lastly, in order to isolate the effects of VL threshold from the influence of total volume load on structural and neural adaptations, further studies should examine the effects of different VL thresholds with work-matched training regimens.

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