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Movement Velocity as a Determinant of Actual Intensity in Resistance Exercise

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ABSTRACT

This study aimed to analyze the acute mechanical, metabolic and EMG response to five resistance exercise protocols (REP) in the full squat (SQ) exercise performed with two velocity conditions: maximal intended velocity (MaxV) vs. half-maximal velocity (HalfV). Eleven resistance-trained men performed 10 REP (5 with each velocity conditions) in random order (72–96 h apart). The REP consisted of three sets of 8–3 repetitions against 45–65 % 1RM. The percent change in countermovement jump (CMJ) height, velocity attained with the load that elicited a ~1.00 $m \cdot s^{-1}$ (V1-load), surface EMG variables and blood lactate concentration were assessed pre- vs. post-exercise protocols. MaxV resulted in greater percent changes (Δ: 12–25 %) and intra-condition effect sizes (ES: 0.76–4.84) in loss of V1-load and CMJ height compared to HalfV (Δ: 10–16 %; ES: 0.65–3.90) following all REP. In addition, MaxV showed higher post-exercise lactate concentration than HalfV (ES: 0.46–0.83; $p < 0.05$). For EMG variables, only the Dimitrov index resulted in relevant changes after each REP, with MaxV showing greater magnitude of changes (23–38 %) than HalfV (12–25 %) across all REP. These results suggest that voluntary movement velocity is a key aspect to consider since it clearly determines the overall training intensity during resistance exercise.

Introduction

Manipulation of the acute exercise variables determines the type and magnitude of the stimuli faced during resistance training (RT) and, consequently, the neuromuscular response [1]. The acute and chronic effects of manipulating different RT variables (e. g. volume, relative load, rest periods, type and order of exercises, and training frequency) have been widely studied in the scientific literature [2, 3]. However, the effects of voluntarily manipulating movement velocity have been much less studied to date, despite the importance recently placed on this variable in relation to specific adaptations consequent to RT [4–6]. An analysis of the mechanical and metabolic responses to different resistance exercise protocols (REP), in which movement velocity is considered as the independent variable, can provide further insight into the mechanisms

underlying the adaptations that may occur following a training period under different velocity conditions. There is some evidence that the actual velocity at which loads are lifted during RT has a differential effect on the resulting neuromuscular adaptations [4, 6] which, in turn, may affect physical and sports performance.

Several studies have compared the acute kinetic, kinematic and physiological effects of resistance exercise performed at different movement velocities [7–9]. Most of these studies have observed greater oxygen uptake, heart rate, blood lactate and ammonia concentrations, as well as increased losses in vertical jump height when training was performed at "fast" versus "slow" velocities [4, 6–10]. Previous research has also provided evidence that: 1) both the neuromuscular demands and the training effect itself largely depend on the velocity at which loads are lifted; and 2) movement velocity depends on the load to overcome and the voluntary intent of the subject to move that load [4–6].

In order to isolate and compare the effect of lifting velocity on neuromuscular performance, it is necessary that all the other acute exercise variables (loading intensity, number of sets and repetitions, rests duration, etc.) remain constant or unmodified across the REP analyzed. However, this has not been the case with most studies to date which present methodological inconsistencies that prevent determining the real effect of movement velocity on the acute neuromuscular response. Some studies [11, 12] used different relative loads in order to manipulate repetition velocity (i. e. high loads for "slow" velocities vs. light loads for "fast" velocities). In addition, exercise sets in these studies were conducted to or very close to muscle failure, which involves performing a much greater number of repetitions per set for light loads compared to heavy load protocols [12, 13]. As a result, relative loads and training volumes were different for each velocity condition, making it difficult to clearly interpret the research findings. Other studies manipulated repetition velocity by imposing a specific lifting cadence using a metronome, or a fixed tempo for different movement phases (e. g. 4–1–4–1 seconds for concentric-isometric-eccentric-isometric successive actions) [7, 8, 10]. In this case, since the length of the lower and upper limbs is expected to exhibit high variability between subjects, imposing a predetermined tempo or lifting cadence will result in different movement velocities for each participant. Moreover, as loads get heavier and/or repetitions approach failure, following a fixed cadence becomes unfeasible. Finally, most studies comparing the response to RT under different velocity conditions failed to monitor and register actual repetition velocities during training [8, 10], which makes it impossible to ascertain whether the differences between exercise protocols are due to differences in movement velocity or respond to the manipulation of other variables, such as relative load or exercise volume.

To the best of our knowledge, only two studies have examined the effect of movement velocity as a true independent variable [4, 6]. In these studies, the effect of performing each repetition at two distinct velocity conditions: maximal intended (MaxV) vs. half-maximal (HalfV) concentric velocity against three relative loads (60 %, 70 and 80 % 1RM) was examined in the squat and bench press exercises [4, 6]. Pre-post changes in countermovement jump (CMJ) height and in the velocity developed against the load that elicited a ~1.00 $m \cdot s^{-1}$ mean propulsive velocity (MPV) were taken as mechanical indicators of muscle fatigue, while post-exercise blood lactate, ammonia and uric acid concentrations were measured to quantify metabolic stress. The results of these two studies showed a greater degree of fatigue for the MaxV condition compared to HalfV against all loads examined, and particularly against 60 and 70 % 1RM. The REP examined used moderate to heavy loads (60–80 % 1RM), leaving a broad range of loads unexplored. In many athletic and physically active populations, it is also common to use lighter loads in their training routines, and these loads demonstrate higher variability in terms of movement velocity. So it would be interesting to extend the analysis of the effect of velocity to a wider load spectrum. In addition, and considering the importance of neural factors in the process of muscle adaptation [14], it may be important to describe the changes in electromyographic (EMG) variables induced by REP under different velocity conditions. Therefore, the aim of the present study was to compare the acute mechanical, metabolic and EMG responses of REP performed at MaxV vs. HalfV against five different loads (45 %, 50 %, 55 %, 60 and 65 % 1RM) in the full squat (SQ) exercise.

Materials and Methods

Subjects

Eleven young healthy men (mean ± SD: age 23.5 ± 3.6 years, body mass 75.3 ± 7.4 kg, stature 1.77 ± 0.05 m) volunteered to take part in this study. Participants were physically active sports science students with a RT experience ranging from 1 to 2 years (2–3 sessions per week). Their initial estimated one-repetition maximum ($1RM_{est}$) for the SQ was 111.5 ± 14.2 kg (relative strength ratio: 1.52 ± 0.17). No physical limitations, health problems or musculoskeletal injuries that could affect testing were reported. None of the participants were taking drugs, medications, or dietary supplements known to influence physical performance. The present investigation met the ethical standards of this journal [15]. The study was also approved by the Local Ethics Committee, and conducted according to the Declaration of Helsinki. After being informed of the purpose and experimental procedures, the participants signed a written informed consent form before participation.

Study design

A cross-sectional research design was used to analyze the mechanical, metabolic, and EMG changes induced by REP that only differed in the voluntary velocity at which loads were lifted: maximal intended vs. half-maximal lifting velocity (MaxV vs. HalfV) in each repetition. These REP were performed against five different relative loads (45 %, 50 %, 55 %, 60 and 65 % 1RM) in the SQ exercise. In order to analyze the acute mechanical, metabolic and neural response to each session, participants underwent a battery of assessments before and immediately after each REP: (a) CMJ height, (b) the individually determined load that elicited a ~1.00 $m \cdot s^{-1}$ (± 0.03 $m \cdot s^{-1}$) MPV (V1-load) in the SQ while surface EMG signals of the vastus intermedius (V_{MI}) and vastus lateralis (V_{LA}) were recorded, and (c) blood lactate concentration. During a period of five weeks, each participant underwent 10 REP (2 per week), which were conducted on separate days with at least 72 h of recovery time between sessions (Monday

and Thursday, or Tuesday and Friday). All sessions were randomized for each participant to avoid the influence of potential confounding variables. Sessions took place at a performance research laboratory, and were performed at the same time of day for each participant (± 1 h) under similar environmental conditions (~20–22°C and 55–65 % humidity). Participants were required to refrain from any other type of intense physical activity or sports training (with the exception of some core-strengthening exercises) for the duration of the present investigation. During the two weeks preceding this study, four familiarization sessions were undertaken in order to emphasize proper exercise technique (SQ and CMJ) and get used to the particular assessment protocols used. The last familiarization session was used for anthropometric assessments, medical examination and assessment of estimated maximal strength in the SQ exercise.

Testing procedures

Progressive loading test in the SQ exercise

A detailed description of the SQ testing protocol has been provided elsewhere [16]. Testing was performed on a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain). The participants performed the SQ from an upright position, descending (eccentric phase) at a controlled velocity (~0.50–0.60 $m \cdot s^{-1}$) until the posterior thighs and calves made contact with each other; then they immediately reversed motion and ascended back (concentric phase) at maximal intended velocity. Initial load was set at 30 kg for all participants and was gradually increased in 10 kg increments. The test ended when the attained concentric MPV was slower than ~0.60 $m \cdot s^{-1}$, which corresponds to ~85 % 1RM in the SQ [16]. Three repetitions were performed for light (MPV ≥ 1.10 $m \cdot s^{-1}$), two for medium (1.10 $m \cdot s^{-1}$ > MPV ≥ 0.80 $m \cdot s^{-1}$), and only one for the heaviest (MPV < 0.80 $m \cdot s^{-1}$) loads. Only the best repetition (fastest MPV value) against each load was considered for subsequent analyses. Inter-set rests ranged from 3 (light) to 5 min (heavy loads). The 1RM was individually estimated for each participant from the MPV value attained against the heaviest load lifted in the progressive test, as follows: $(100 \cdot \text{load})/(-5.961 \cdot \text{MPV}^2 - 50.71 \cdot \text{MPV} + 117)$ [16].

Acute resistance exercise protocols

Each participant completed 10 sessions in which five different REP were examined under two velocity conditions (MaxV vs. HalfV). For each REP, three exercise sets with 4 min inter-set rests were performed. The same number of repetitions per set were completed in both MaxV and HalfV conditions. Descriptive characteristics of each REP are provided in ▶ **Table 1**. Relative loads were determined from the load-velocity relationship for the SQ exercise [16]. Thus, a target MPV value to be attained in the first (usually the fastest) repetition of the first set in each session was used as an estimation of %1RM, as follows: 1.24 $m \cdot s^{-1}$ (~45 % 1RM), 1.16 $m \cdot s^{-1}$ (~50 % 1RM), 1.09 $m \cdot s^{-1}$ (~55 % 1RM), 1.00 $m \cdot s^{-1}$ (~60 % 1RM), and 0.93 $m \cdot s^{-1}$ (~65 % 1RM). Once the absolute load (kg) for each participant and REP was determined, it was maintained for the three sets of the corresponding session. In the MaxV condition participants performed each repetition at maximal intended velocity. Conversely, in the HalfV condition, participants were required to intentionally reduce repetition velocity so that it corresponded to half the target MPV value established for each session. In all sessions, participants received immediate velocity feedback (visual and auditory) from the software of a linear velocity transducer. This real-time velocity feedback was key for the participants to adjust their concentric lifting velocity as required by each condition. This was practiced in the familiarization sessions. ▶ **Fig. 1** show an example of repetition velocity during a REP using three sets of 8 repetitions against the 45 % 1RM load for a representative participant under two velocity conditions: MaxV vs. HalfV. It is important to note that the MPV during each repetition in the HalfV condition was very similar to the proposed target velocity.

Warm-up

Warm-up for each session consisted of the following: 5 min of jogging at a self-selected easy pace, 5 min of lower-limb joint mobilization exercises, two 30 m running accelerations, two sets of 10 body weight squats and, finally, five CMJs at increasing intensity.

Pre- and post-exercise measurements

Following the warm-up, three maximal CMJs, separated by 20 s rests, were performed by each participant. The average jump height (cm) was taken as a pre-exercise reference value for each session. This was followed by the individual determination of the V1-load in the SQ. For this purpose, participants performed three sets of 6, 4 and 3 repetitions (3 min rests) with increasing loads up to the V1-load (± 0.03 $m \cdot s^{-1}$). The average velocity value of the three repetitions performed against the V1-load was also taken as a pre-exercise reference to calculate the pre-post velocity loss experienced following each REP [4, 17]. In addition, during the determination of the V1-load, the EMG signal of V_{MI} and V_{LA} was recorded. Following these measurements, adjustments in the proposed absolute load for each subject were made so that the velocity of the first repetition matched the programmed target MPV (± 0.03 $m \cdot s^{-1}$). Immediately after completing the last repetition of the third set, participants performed again three maximal CMJs, separated by 20 s rests. Next, each participant performed three repetitions against his V1-load (load was changed in less than 10 s with the help of trained spotters) with maximal voluntary effort. The CMJ and V1-load average values were taken as the immediate post-exercise measures.

Measurements of fatigue

Similarly to previous studies [18, 19], two different methods were used to quantify the extent of fatigue induced by each REP. The first method examined the change from pre- to post-exercise in MPV attained against the V1-load. The average MPV of the three pre-exercise repetitions was compared with the average MPV of the three post-exercise repetitions so that velocity loss was calculated as: $100 \cdot (\text{average MPV}_{post} - \text{average MPV}_{pre})/\text{average MPV}_{pre}$. The second method involved the calculation of percent change in CMJ height from pre- to post-exercise.

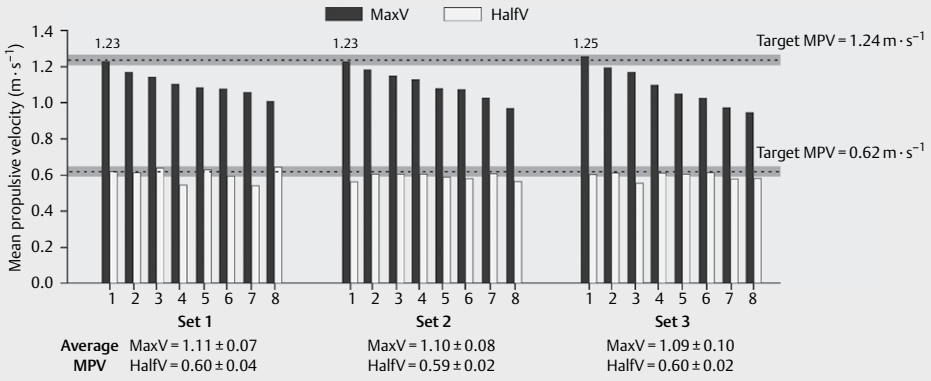
EMG measurements

Surface EMG during the determination of the V1-load in the SQ was recorded from the V_{LA} and V_{MI} muscles of the right leg via pairs of bipolar surface electrodes (Blue Sensor N-00-S, Medicotest) with a distance between the electrodes' centers of 22 mm. After careful

▶ **Table 1** Descriptive characteristics of the resistance exercise protocols (REP) analyzed.

Scheduled	**45 % RM**	**50 % RM**	**55 % RM**	**60 % RM**	**65 % RM**
Sets x reps	3 × 8	3 × 6	3 × 6	3 × 4	3 × 3
Target MPV ($m \cdot s^{-1}$)					
MaxV	~1.24 ± 0.02	~1.16 ± 0.02	~1.09 ± 0.02	~1.00 ± 0.02	~0.93 ± 0.02
HalfV	~0.62 ± 0.02	~0.58 ± 0.02	~0.54 ± 0.02	~0.50 ± 0.02	~0.47 ± 0.02
Actually Performed					
Reference MPV ($m \cdot s^{-1}$)					
MaxV	1.24 ± 0.02	1.16 ± 0.02	1.08 ± 0.02	1.00 ± 0.03	0.92 ± 0.02
	(~45 % 1RM)	(~50 % 1RM)	(~55 % 1RM)	(~60 % 1RM)	(~65 % 1RM)
HalfV	0.68 ± 0.02	0.63 ± 0.02	0.59 ± 0.02	0.56 ± 0.03	0.51 ± 0.03
MPV all reps ($m \cdot s^{-1}$)					
MaxV	1.09 ± 0.04***	1.02 ± 0.15***	0.95 ± 0.04***	0.90 ± 0.03***	0.84 ± 0.03***
HalfV	0.59 ± 0.01	0.56 ± 0.01	0.52 ± 0.01	0.49 ± 0.01	0.45 ± 0.01
Load (kg)					
MaxV	62 ± 10	69 ± 10	71 ± 12	78 ± 11	83 ± 14
HalfV	62 ± 10	69 ± 10	71 ± 12	78 ± 11	83 ± 14

Data are mean ± SD. Each participant performed the 5 REP in two different conditions: MaxV vs. HalfV. MaxV: each repetition was performed at maximal intended velocity; HalfV: each repetition was performed at half the maximal intended velocity. REP: Resistance exercise protocol; MPV: Mean propulsive velocity; reps: number of repetitions performed. See text for details.; Statistically significant differences between velocity conditions: ***$p < 0.001$.



▶ **Fig. 1** Example of repetition velocity during a REP using 3 × 8 against the 45 % 1RM load for a representative participant under two velocity conditions: MaxV vs. HalfV. Horizontal dashed lines indicate target velocity for both velocity conditions.

preparation of the skin by shaving and cleaning with alcohol, surface electrodes were placed over the belly of the muscle, parallel to the presumed orientation of the muscle fibers of V_{LA} and V_{MI}, according to SENIAM (Surface EMG for Non-Invasive Assessment of Muscles) guidelines [20]. All electrode positions were carefully measured for each participant and were marked with henna dye to ensure identical recording sites throughout the 5-week period intervention to ensure reliable placement of electrodes during all sessions. The reference electrode was placed on the patella of the same limb. Skin-electrode impedance was assessed on each occasion to verify that it was maintained at a consistent level for each participant (within 0.5 MΩ) and at a value < 5 MΩ for all participants. EMG signals were recorded at 1000 Hz. During off-line analysis, the signals were band-pass filtered in both directions between 6 and 500 Hz using a second order Butterworth digital filter. The parameters analyzed in the present study corresponded to the first 500 ms of the concentric phase of the SQ exercise in both V_{MI} and V_{LA} muscles [18, 21, 22]. Thus, in order to analyze the neuromuscular changes, an average of the sEMG parameters of the three pre-exercise repetitions against the V1-load was compared with the average of the three post-exercise repetitions in each REP and velocity condition: 100 x (average EMG_{post} − average EMG_{pre})/average EMG_{pre} [18]. Thus, for each REP, the percent change obtained in the EMG variables evaluated for MaxV and HalfV was compared.

Analysis of blood lactate

Blood lactate concentration was used as an indicator of the metabolic stress induced by each REP. In each session, whole blood cap-

illary samples were drawn from the earlobe before the warm-up and again 1 min after completing the last repetition against the V1-load following each REP.

Measurement equipment and data acquisition

Stature and body mass were determined using a medical stadiometer and scale (Seca 710, Seca Ltd., Hamburg, Germany) with the participants in a morning fasting state and wearing only underclothes. Jump height was measured using an infrared timing system (Optojump Next, Microgate, Bolzano, Italy). A Smith machine (Multipower Fitness Line, Peroga, Spain) that ensures a smooth vertical displacement of the bar along a fixed pathway was used for all sessions. The Lactate Pro 2 LT-1730 (Arkray, Kyoto, Japan) portable lactate analyzer was used for lactate measurements. A dynamic measurement system (T-Force System, Ergotech, Murcia, Spain) automatically calculated the relevant kinematic parameters of every repetition, provided auditory and visual feedback in real-time, and stored data on disk for analysis. This system consists of a linear velocity transducer interfaced to a personal computer by means of a 14-bit resolution analogue-to-digital acquisition board and custom software (version 3.70). Instantaneous velocity was sampled at 1,000 Hz and subsequently smoothed by its software using a 4th order low-pass Butterworth filter with no phase shift and 10 Hz cut-off frequency. Reliability of this system has been reported elsewhere [17]. All velocity values reported in this study correspond to the MPV of the concentric phase of each repetition. The propulsive phase was defined as that portion of the concentric phase during which the measured acceleration (a) is greater than acceleration due to gravity (i. e. $a \geq -9.81\ m \cdot s^{-2}$) [23]. EMG data were collected using LabChart software version 7.0 (National Instruments Corporation. Austin, TX, USA), and data analysis was performed off-line using the MATLAB 2011a software environment (MathWorks Inc., Natick, Massachusetts, USA). The following EMG parameters were calculated: root mean square (RMS), integrated electromyography (iEMG), mean power frequency (F_{mean}), median power frequency (F_{median}), maximal power frequency (F_{max}), Dimitrov index (F_{Insm5}),[24] and discrete wavelet transform (DWT) [25]. Reliability of these EMG variables was previously reported [18].

Statistical analysis

Standard statistical methods were used for the calculation of means and standard deviations (SD). Differences in V1-load, CMJ, and lactate variables between both velocity conditions in each REP were assessed using a 2 (condition: MaxV vs. HalfV) x 2 (time: Pre vs. Post) factorial ANOVA with Bonferroni's adjustment. A paired samples t-test was used to compare the percent change between MaxV and HalfV in the sEMG variables in each REP. The intra-group effect sizes (ES) were calculated using Hedge's g, as follows: g = (mean Post − mean Pre)/Pooled SD. The ES for changes between the MaxV and HalfV conditions for each dependent variable was calculated as follows: g = (mean Pre-Post differences MaxV) − (mean Pre-Post differences HalfV)/Pooled SD. Threshold values for assessing magnitudes of standardized effects were 0.20, 0.60, 1.20, and 2.00 for small, moderate, large, and very large, respectively [26]. Statistical significance was accepted at $p < 0.05$. Analyses were performed using SPSS software version 22.0 (SPSS, Chicago, IL).

Results

Analysis of REP

Descriptive characteristics of the REP analyzed for the two velocity conditions are displayed in ▶ **Table 1**. Both scheduled and actually performed repetition velocities and number of repetitions are reported. No significant differences were found between the targeted MVP values and the fastest MPV values of each REP in any condition. No significant differences were observed in the absolute loads used in each REP between both velocity conditions. As expected, significant differences ($p < 0.001$) between MaxV and HalfV were observed in the average MPV value corresponding to each REP (▶ **Table 1**).

Acute mechanical and metabolic response

All variables were distributed normally, and homoscedasticity was assumed. No significant differences between REP were found at Pre for any variable. Average values and ES of mechanical and metabolic measurements following each REP are displayed in ▶ **Table 2**, whereas the changes in EMG variables are presented in ▶ **Table 3**. Post-exercise MPV attained against the V1-load, CMJ height and lactate concentration were significantly different ($p < 0.001$) from pre-exercise values following all REP in both velocity conditions (▶ **Table 2**). Significant "condition x time" interactions ($p < 0.05$–0.01) were observed for all variables for the REP performed against loads of 45 and 50 % 1RM, whereas for the REP against 55 and 60 % 1RM, significant "condition x time" interactions ($p < 0.05$) were only found for CMJ height and V1-load, respectively. The MaxV condition induced significantly greater changes than HalfV in V1-load, CMJ height and lactate following REP against 45 and 50 % 1RM (▶ **Table 2,** ▶ **Fig. 2**). In addition, significant differences between conditions were observed in CMJ following REP against 55 and 65 % 1RM, and in the V1-load following REP against 60 % 1RM. The MaxV condition resulted in greater percent changes (▶ **Fig. 2**) and intra-condition ES (▶ **Table 2**) compared to HalfV for all REP performed.

EMG response

There were significant "condition x time" interactions in DWT4 against 45 % 1RM and F_{max} against 65 % 1RM ($p < 0.05$). No significant differences between MaxV and HalfV were observed for any variable, except for F_{mean} and F_{Insm5} against 45 % 1RM and F_{max} against 65 % 1RM. Intra-condition comparisons showed significant differences for F_{Insm5} and F_{mean} following all REP for both velocity conditions, with a tendency to greater percent changes for MaxV compared to HalfV (▶ **Table 3**). In addition, F_{median} presented statistically significant changes ($p < 0.05$–0.001) in both velocity conditions following REP against 45, 50 and 60 % 1RM. HalfV resulted in significant pre-post differences in iEMG following REP against 45, 50, 55 % 1RM whereas for MaxV this difference was significant only following the REP against 65 % 1RM. DWT increased significantly for MaxV following the REP against 55 % 1RM. The rest of the variables did not show significant changes following any REP.

Discussion

The purpose of the present study was to describe and compare the acute response to five REP performed against moderate loads (45–

▶ **Table 2** Changes in mechanical (V1-load and CMJ) and metabolic (lactate) variables from pre- to post-exercise following each REP in each velocity condition (MaxV vs. HalfV).

REP_45 % RM							
	MaxV			HalfV			
	Pre	Post	ES_{INTRA}(95 % CI)	Pre	Post	ES_{INTRA}(95 % CI)	ES_{INTER}(95 % CI)
V1-load ($m \cdot s^{-1}$) ##	0.96 ± 0.02	0.77 ± 0.08**	3.36 (1.80–4.92)	0.96 ± 0.02	0.84 ± 0.05	2.94 (1.53–4.35)	0.18 (⁻0.65–1.02)
CMJ (cm) ##	36.3 ± 5.0	30.1 ± 4.8**	1.26 (0.64–1.87)	36.8 ± 5.2	32.8 ± 5.0	0.79 (0.43–1.14)	4.85 (3.13–6.57)
Lactate ($mmol \cdot l^{-1}$) #	1.1 ± 0.2	6.0 ± 2.3*	3.00 (1.66–4.35)	1.2 ± 0.2	4.1 ± 1.4	2.90 (1.52–4.27)	0.83 (−0.04–1.70)
REP_50 % RM							
	MaxV			HalfV			
	Pre	Post	ES_{INTRA}(95 % CI)	Pre	Post	ES_{INTRA}(95 % CI)	ES_{INTER}(95 % CI)
V1-load ($m \cdot s^{-1}$) ##	0.96 ± 0.03	0.76 ± 0.08*	3.32 (1.79–4.85)	0.95 ± 0.04	0.84 ± 0.05	2.48 (1.21–3.75)	0.18 (−0.66–1.02)
CMJ (cm) ###	37.0 ± 4.9	32.0 ± 4.8	1.03 (0.57–1.49)	38.3 ± 4.8	34.8 ± 4.7	0.74 (0.41–1.08)	5.09 (3.30–6.87)
Lactate ($mmol \cdot l^{-1}$) #	1.2 ± 0.2	5.3 ± 2.2*	2.61 (1.40–3.81)	1.1 ± 0.2	3.6 ± 1.4	2.47 (1.18–3.75)	0.69 (−0.18–1.55)
REP_55 % RM							
	MaxV			HalfV			
	Pre	Post	ES_{INTRA}(95 % CI)	Pre	Post	ES_{INTRA}(95 % CI)	ES_{INTER}(95 % CI)
V1-load ($m \cdot s^{-1}$)	0.95 ± 0.02	0.78 ± 0.05	4.84 (2.58–7.11)	0.96 ± 0.03	0.83 ± 0.04	3.91 (1.96–5.86)	0.18 (−0.66–1.02)
CMJ (cm) #	36.6 ± 4.8	31.9 ± 4.3*	1.03 (0.57–1.49)	38.2 ± 4.7	34.1 ± 4.8	0.85 (0.47–1.23)	5.01 (3.25–6.77)
Lactate ($mmol \cdot l^{-1}$)	1.0 ± 0.2	5.5 ± 2.6	2.41 (1.18–3.63)	1.1 ± 0.1	4.1 ± 1.8	2.33 (1.20–3.45)	0.67 (−0.19–1.53)
REP_60 % RM							
	MaxV			HalfV			
	Pre	Post	ES_{INTRA}(95 % CI)	Pre	Post	ES_{INTRA}(95 % CI)	ES_{INTER}(95 % CI)
V1-load ($m \cdot s^{-1}$) #	0.95 ± 0.02	0.77 ± 0.06*	3.92 (2.03–5.81)	0.97 ± 0.04	0.84 ± 0.06	2.47 (1.28–3.65)	0.18 (−0.66–1.02)
CMJ (cm)	38.1 ± 5.9	33.7 ± 5.6	0.77 (0.42–1.11)	38.8 ± 6.1	34.9 ± 6.1	0.66 (0.35–0.97)	4.44 (2.83–6.06)
Lactate ($mmol \cdot l^{-1}$)	1.1 ± 0.1	4.6 ± 2.3	2.12 (0.95–3.29)	1.1 ± 0.2	3.5 ± 1.7	2.59 (1.14–4.05)	0.62 (−0.24–1.48)
REP_65 % RM							
	MaxV			HalfV			
	Pre	Post	ES_{INTRA}(95 % CI)	Pre	Post	ES_{INTRA}(95 % CI)	ES_{INTER}(95 % CI)
V1-load ($m \cdot s^{-1}$)	0.96 ± 0.01	0.82 ± 0.05	4.12 (2.13–6.11)	0.96 ± 0.04	0.85 ± 0.08	1.73 (0.83–2.63)	0.17 (−0.66–1.01)
CMJ (cm)	38.6 ± 6.1	33.9 ± 6.0*	0.77 (0.41–1.13)	39.4 ± 6.1	35.6 ± 5.6	0.65 (0.36–0.94)	4.56 (2.92–6.20)
Lactate ($mmol \cdot l^{-1}$)	1.0 ± 0.2	4.1 ± 1.9	2.31 (1.06–3.56)	1.1 ± 0.2	3.3 ± 1.5	2.04 (1.03–3.06)	0.46 (−0.39–1.31)

Data are mean ± SD. Significant differences between pre- and post-exercise for all variables in all REP: $p < 0.001$. MaxV: each repetition was performed at maximal intended velocity; HalfV: each repetition was performed at half maximal velocity; REP: resistance exercise protocol; V1-load: load that elicited a ~1 $m \cdot s^{-1}$ mean propulsive velocity at Pre; CMJ: countermovement jump; ES_{INTRA}: Intra-condition effect size; ES_{INTER}: Inter-condition effect size; CI: Confidence interval. Significant "condition x time" interaction: # $p < 0.05$; ## $p < 0.01$; ### $p < 0.001$. Significant inter-condition differences: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

65 % 1RM) under two distinct velocity conditions, MaxV vs. HalfV, in each repetition. The main finding was that performing repetitions at MaxV resulted in greater fatigue and metabolic stress compared to HalfV following all REP under study. In addition, more pronounced changes in EMG variables were observed in the MaxV condition, suggesting greater neural effects. These findings seem to confirm that the actual velocity at which loads are lifted influences the acute neuromuscular response to resistance exercise and, probably, also affect medium- and long-term performance adaptations [4–6]. Consequently, the intended lifting velocity should be considered as a critical variable when determining the overall intensity during RT sessions.

One of the novel aspects of our research was that all REP were carefully controlled in both velocity conditions. Thus, by monitoring movement velocity during all repetitions in each REP and establishing a target velocity for all participants in all sessions, the actual effort undertaken closely corresponded to that intended (%1RM). This methodology allowed us to ascertain the differences in average training velocity between the MaxV and HalfV conditions following each REP (▶ **Table 1**). Furthermore, unlike most previous studies [7–10], all variables except lifting velocity remained identical for the two conditions examined. Thus, it is reasonable to suggest that the differences in the neuromuscular response and metabolic stress observed between MaxV and HalfV were actually due to the distinct lifting velocities used during each REP, as the relative load (%1RM), the number of sets and repetitions per set, and inter-set rests were the same for both conditions. Previous studies analyzing the acute mechanical and metabolic effects of voluntary movement velocity used different relative loads, repetitions per set or a fixed lifting cadence [5, 7, 8, 10] for the different groups. As a consequence, the differences observed in these inves-

▶ **Table 3** Percentage of changes in selected sEMG variables from pre- to post-exercise following each REP in each velocity condition (MaxV vs. HalfV).

	45 %1RM		50 %1RM		55 %1RM		60 %1RM		65 %1RM	
	MaxV	HalfV	MaxV	HalfV	MaxV	HalfV	MaxV	HalfV	MaxV	HalfV
RMS	−3.1 ± 10.6	−10.7 ± 7.0*	0.2 ± 8.7	−5.9 ± 14.5	0.5 ± 7.1	−2.6 ± 10.0	−1.4 ± 9.8	−3.3 ± 6.7	−2.7 ± 10.6	−2.8 ± 10.6
iEMG	−6.5 ± 11.6	−6.9 ± 6.8*	−0.9 ± 9.0	−6.5 ± 17.3*	−4.6 ± 10.4	−7.8 ± 9.9*	−4.2 ± 9.9	−6.3 ± 7.2	−9.0 ± 10.4*	−4.1 ± 8.1
F_{median}	−6.7 ± 3.7***	−4.5 ± 4.2**	−4.2 ± 4.2*	−6.2 ± 5.4***	−3.1 ± 4.1	−2.4 ± 6.6	−5.7 ± 2.1***	−4.1 ± 3.6***	−2.5 ± 3.8	−2.4 ± 6.0
F_{mean}	−6.8 ± 2.8***	−4.9 ± 3.3†***	−5.2 ± 2.7***	−4.8 ± 2.6***	−4.3 ± 3.3***	−3.3 ± 3.9**	−4.8 ± 2.4***	−3.1 ± 3.2**	−3.5 ± 2.2**	−2.7 ± 3.9*
F_{max}	−14.1 ± 11.3**	−2.6 ± 13.3	−6.1 ± 10.3	−13.5 ± 16.1**	0.6 ± 14.2	−5.7 ± 17.3	−0.9 ± 25.4	−6.0 ± 10.6	−0.7 ± 13.3#†	−10.4 ± 4.6
F_{insm5}	38.6 ± 26.2†***	25.8 ± 19.4**	31.5 ± 16.9***	22.6 ± 12.7***	25.0 ± 13.5**	18.5 ± 14.6**	26.7 ± 21.3***	14.5 ± 13.5*	23.8 ± 13.7***	12.5 ± 13.7*
DWT 7	6.9 ± 15.6	2.4 ± 12.7	−1.3 ± 15.5	−4.0 ± 23.3	27.1 ± 21.6**	9.4 ± 22.9	12.5 ± 20.9	6.0 ± 27.5	11.5 ± 15.2	13.4 ± 17.0
DWT 6	7.3 ± 20.0	−1.2 ± 17.9	2.9 ± 13.3	−2.8 ± 25.9	15.7 ± 14.7*	9.4 ± 20.7	5.5 ± 14.0	10.3 ± 22.0	8.8 ± 15.5	9.8 ± 10.9
DWT 5	5.8 ± 13.5	−5.3 ± 11.5	6.2 ± 8.5	−2.1 ± 18.0	14.9 ± 20.1*	−1.4 ± 14.4	0.9 ± 18.7	3.1 ± 16.8	7.1 ± 13.2	−1.5 ± 8.6
DWT 4	8.7 ± 13.9#	−2.6 ± 10.1	11.8 ± 14.0	0.9 ± 19.3	16.4 ± 19.6**	5.1 ± 12.7	4.7 ± 15.1	6.5 ± 18.4	7.8 ± 11.0	3.2 ± 7.9
DWT 3	6.4 ± 13.5	−2.7 ± 10.1	11.4 ± 12.5	−0.5 ± 18.6	10.4 ± 12.4*	3.4 ± 12.5	3.2 ± 12.4	3.2 ± 15.9	5.8 ± 9.2	2.1 ± 8.0
DWT 2	1.5 ± 11.9	−4.0 ± 9.8	5.5 ± 10.5	−5.7 ± 20.0	4.5 ± 14.0	2.7 ± 15.2	2.1 ± 11.9	1.7 ± 16.5	5.3 ± 9.5	0.5 ± 7.4

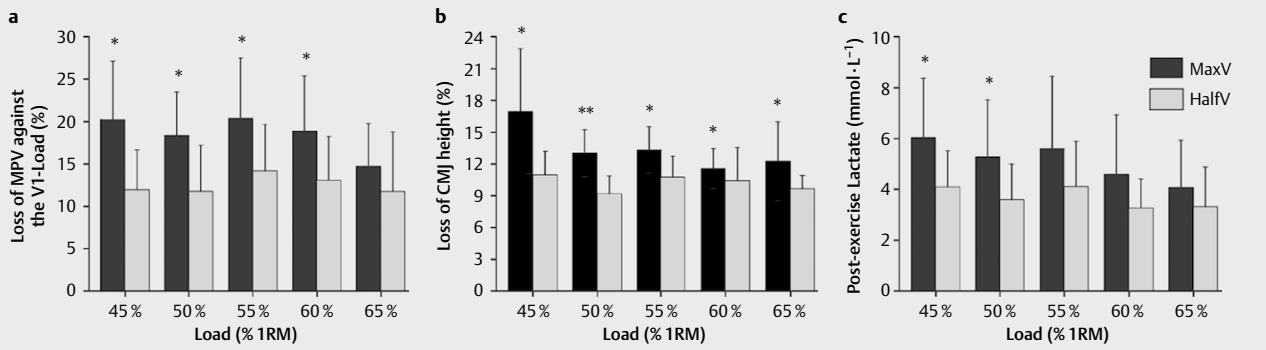
Data are mean ± SD. sEMG: Surface electromyography; MaxV: each repetition was performed at maximal intended velocity; HalfV: each repetition was performed at half maximal velocity; REP: resistance exercise protocol; RMS: root mean square; iEMG: integrated electromyography; F_{median}: median power frequency; F_{mean}: mean power frequency; F_{max}: maximal power frequency; F_{insm5}: Dimitrov index; DWT: discrete wavelet transform. Significant "condition x time" interaction: # $p<0.05$; Inter-condition significant differences: † $p<0.05$; †† $p<0.01$; Intra-condition significant differences from pre- to post-exercise: $p<0.05$; ** $p<0.01$; *** $p<0.001$.

tigations cannot be attributed solely to the effect of movement velocity.

The results of the present study showed that MaxV resulted in greater losses in mechanical variables (velocity against the V1-load and CMJ height) and higher metabolic stress (lactate concentration) compared to HalfV following all REP analyzed (▶ **Table 2**, ▶ **Fig. 2**). Contrary to our findings, one previous study showed no effect of velocity conditions on lactate [8], while another [9] found that a slow velocity protocol (~2 s concentric phase) resulted in higher lactate values compared to maximal lifting velocity. However, these studies [7–9] revealed that the maximal velocity condition induced a greater increase in the rate of energy expenditure, peak heart rate and oxygen uptake than slow-velocity contractions, suggesting greater exercise intensity for fast contraction modes, which appears to conflict with the lower lactate concentrations observed. The fact that lifting velocities were controlled by a metronome in these studies implies that subjects actually performed the repetitions at different velocities, as the displacement was different for each individual. This could explain the differences found in the post-exercise lactate concentrations with the present results. On the other hand, our results are in agreement with those previously observed in two studies that used similar exercise protocols and assessment methods [4, 6]. In these studies, repetition velocity was also carefully monitored and it served as a guide to ensure that the loads used in each REP were the ones intended. In agreement with the present study, the results of these two studies showed greater lactate levels as well as losses in the velocity against the V1-load and CMJ height for the MaxV compared to the HalfV condition. However, changes in the variables used to quantify the acute fatigue were of lesser magnitude for both velocity conditions in the study by Pareja-Blanco et al. [4] compared to the present study, despite the fact that in that previous study, REP were conducted using the same number of sets and repetitions per set, but against heavier loads (60–80 % 1RM), which should have led to a higher degree of fatigue [17, 27]. These discrepancies may be due to differences in the protocols used to measure the variables selected to quantify neuromuscular fatigue.

Differences in the mechanical and metabolic response between the MaxV and HalfV conditions could be due to (a) greater tension in the muscle fibres, and (b) increased muscle activation as a result of the greater motor unit recruitment and/or firing frequency that occurs when a load (%1RM) is lifted as fast as possible in each repetition [5, 10, 28, 29], as suggested by our EMG results. Therefore, since the REP used in the present study were not conducted to muscle failure, it is likely that lifting loads at maximal intended velocity stimulated and activated type II fibres to a greater extent [30, 31], and resulted in greater degrees of fatigue and metabolic stress [32, 33] compared to performing repetitions deliberately slower (HalfV condition). This type of RT (i. e. performing repetitions at maximal intended velocity and ending each set well ahead of muscle failure) seems to provide better conditions to induce neuromuscular adaptations aimed at increasing strength and RFD [4, 5, 34].

Another novelty of this study was that the changes in EMG variables were analyzed in an attempt to understand the neural mechanisms underlying the changes in mechanical and metabolic variables following the REP performed at the two distinct velocity conditions. Since alterations in EMG variables can be related to the



▶ **Fig. 2** (**a**) Percent loss in mean propulsive velocity against the V1-load from pre- to post-exercise in the SQ exercise; (**b**) loss of CMJ height from pre- to post-exercise; (**c**) post-exercise lactate concentration following each REP in the two velocity conditions (MaxV vs. HalfV) analyzed. Statistically significant differences between MaxV and HalfV: *p<0.05, **p<0.01.

degree of fatigue, several studies have focused on analyzing changes in these variables during and after RT protocols [10, 18, 35–37]. However, few studies have compared the EMG response to REP that differed in voluntary lifting velocity [10] where, in any case, only a limited number of variables (RMS) was analyzed. Our results revealed that F_{Insm5} was the variable showing the greatest change both for MaxV (23–28 %) and HalfV (12–25 %) conditions following all REP under study. These findings are similar to those observed in previous studies analyzing the changes in F_{Insm5} to assess neuromuscular fatigue [18, 35, 36]. In addition, the magnitude of change of this variable was higher for MaxV compared to HalfV following all REP, with a higher change observed for both velocity conditions in the REP that used lower relative loads. This behavior in F_{Insm5} matched the changes observed in the mechanical variables and post-exercise lactate concentration. Therefore, our results seem to confirm that this variable has greater sensitivity for assessing muscle fatigue during concentric dynamic actions than the other EMG variables analyzed [18].

On the other hand, and in agreement with our results, some studies showed that RMS and iEMG remained unaltered or slightly decreased during or following different REP [18, 38, 39]. In contrast, the only known study comparing changes in RMS during REP with different velocity contraction modes [10] reported a slight increase in this variable between the first and the last repetition of sets conducted to muscle failure, regardless of the relative load used (40, 50, 60, 70 and 80 % 1RM), the voluntary lifting velocity and the muscle assessed (pectoralis, deltoid and triceps). However, it should be taken into account that in the present study, REP were characterized by the completion of less than half of the possible repetitions in each set. Therefore, the lower degree of fatigue experienced in each REP could explain the different EMG responses observed between that study [10] and the present one. With regard to EMG frequency variables, similarly to our results, previous studies have revealed progressive decrements in F_{mean}, F_{median} and F_{max} during or following exercise sets conducted to muscle failure [18, 36–39]. However, despite these modifications in the EMG amplitude (RMS and iEMG) and frequency (F_{mean}, F_{median} and F_{max}) variables, the observed changes were of low magnitude, not statistically significant and, most importantly, they did not allow to discriminate between the two velocity conditions. Thus, our results suggest that these variables have a relatively low sensitivity for identifying losses in mechanical variables (muscle strength and power output) and increments in metabolic stress, at least against REP in which the exercise sets end well ahead of reaching failure.

Finally, all frequency domains of DWT resulted in increments following all REP performed at MaxV, although significant changes were only found in the REP performed against 55 % 1RM (▶ **Table 3**). In contrast, changes for the HalfV condition were less consistent and depended on the relative load used (▶ **Table 3**). In addition, as observed in previous studies [18, 25], there was a tendency to show higher percent changes for lower frequency ranges (DWT_{4-7}) when repetitions were performed at maximal intended velocity. To the best of our knowledge, no previous studies have analyzed changes in DWT following REP performed with different voluntary velocities. Therefore, based on our results, it appears that the MaxV condition induces greater changes than HalfV in these variables, although, as occurs with the EMG amplitude and frequency variables, the differences do not seem to be sufficient to discriminate between the two velocity conditions.

Conclusions

In brief, our results showed that MaxV induced greater mechanical (loss in velocity against the V1-load and CMJ height) and metabolic (post-exercise lactate) stress compared to HalfV following all REP analyzed. In addition, performing each repetition at MaxV resulted in more pronounced changes in EMG variables, particularly in F_{Insm5}, than performing repetitions deliberately slower, at HalfV.

Practical Applications

The results of the present study clearly showed that for a given exercise protocol, performing repetitions at MaxV vs. HalfV considerably impacts the degree of fatigue experienced and the neuromuscular (EMG) response, regardless of the relative loads used. Thus, the main practical application that can be drawn from this study is that

voluntary movement velocity is a key aspect to consider since it clearly determines the overall training intensity. Movement velocity appears to have a direct influence on the type and magnitude of the training stimuli and, very likely, on the resulting adaptations. Thus, coaches and strength and conditioning professionals could manipulate this variable to modify the degree of fatigue incurred during training and the short-term responses. Moreover, it is important that athletes understand the benefits of performing repetitions at maximal intended velocity when implementing RT programs. On the other hand, considering that the losses of MPV against the V1-load and CMJ height similarly reflect the neuromuscular fatigue induced by REP performed at different velocity conditions, the monitoring of CMJ is recommended to quantify the degree of fatigue experienced during squat training. Monitoring of CMJ height is easier to apply, more practical, and less expensive than measuring changes in the velocity developed against the V1-load. Another practical application is that, in order to analyze the neural changes induced by different REP, it is recommended to focus on F_{Insm5} because this seems to be the EMG variable that best reflects the degree of fatigue.

Conflicts of Interest

The authors have no conflicts of interest to disclose with any outside institution, company, or manufacturer. The results of this study are presented clearly, honestly, and without fabrication, or inappropriate data manipulation.

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