Monitoring Bar Velocity to Quantify Fatigue in Resistance Training

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ABSTRACT

We analyzed the effects of load magnitude and bar velocity variables on sensitivity to fatigue. Seventeen resistance-trained men (age = 25.7 ± 4.9 years; height = 177.0 ± 7.2 cm; body mass = 77.7 ± 12.3 kg; back-squat 1RM = 145.0 ± 33.9 kg; 1RM/body mass = 1.86) participated in the study. Pre- and post-exercise changes in the mean propulsive velocity (MPV) and peak velocity (PV) in the back-squat at different intensities were compared with variations in the countermovement jump (CMJ). CMJ height decreased significantly from pre- to post-exercise (Δ % = −7.5 to −10.4; $p < 0.01$; ES = 0.37 to 0.60). Bar velocity (MPV and PV) decreased across all loads (Δ % = −4.0 to −12.5; $p < 0.01$; ES = 0.32 to 0.66). The decrease in performance was similar between the CMJ, MPV (40 % and 80 % 1RM; $p = 1.00$), and PV (80 % 1RM; $p = 1.00$). The magnitude of reduction in CMJ performance was greater than MPV (60 % 1RM; $p = 0.05$) and PV (40 % and 60 % 1RM; $p < 0.01$) at the post-exercise moment. Low systematic bias and acceptable levels of agreement were only found between CMJ and MPV at 40 % and 80 % 1RM (bias = 0.35 to 1.59; ICC = 0.51 to 0.71; CV = 5.1 % to 8.5 %). These findings suggest that the back-squat at 40 % or 80 % 1RM using MPV provides optimal sensitivity to monitor fatigue through changes in bar velocity.

Introduction

Monitoring acute responses such as neuromuscular fatigue plays an important role in adaptations to training [1]. Neuromuscular fatigue is defined as a transient reduction in the ability to produce force or power induced by exercise, which results in a temporary decrease in performance [2]. The accumulated fatigue in the RT session increases metabolic stress and the recovery time of neuromuscular function [3, 4]. There are training periods in which it is desirable to attenuate the level of mechanical, metabolic, and psychobiological stress, as well as to avoid an exacerbated reduction in neuromuscular performance [5]. Therefore, fatigue monitoring tools are essential for adequate adjustments in the RT program configuration.

The CMJ test is one of the most popular protocols for monitoring neuromuscular status [6, 7]. CMJ assessment is a valid and reliable method for quantifying neuromuscular fatigue [8, 9]. A meta-analysis study demonstrated that CMJ height is sensitive to neuromuscular fatigue [10]. Several methods, such as force platforms, contact mats, video systems, and smartphone applications, are valid for accurately measuring CMJ performance [11–14]. However, some potential drawbacks may limit its utilization for strength and conditioning coaches. Force platforms and contact mats are considered the gold standard, but their relatively expensive cost can restrict usability in many practical contexts. Video systems and smartphone applications are low-cost, but the evaluation results are not available in real time. Video processing takes time because each jump is tracked manually, which can compromise its applicability for large groups.

Monitoring bar velocity in resistance exercise through linear encoders and accelerometers has emerged as a methodological alternative to control neuromuscular fatigue in RT [15]. Sánchez-Medina and González-Badillo [4] investigated whether the loss of bar velocity can be used as an optimal indicator of fatigue. The results showed significant reductions in bar velocity against a moderate load (~1 m/s^{-1}) and countermovement jump (CMJ) height pre-post exercise. Strong correlations were found between pre-post exercise in the velocity loss percentage and the velocity loss percentage over sets (r = 0.91–0.97), blood lactate (r = 0.97), and ammonia (r = 0.86). Additionally, the velocity loss percentage (pre-post) in the squat and CMJ height reduction were strongly correlated (r = 0.93).

Previous studies have also proposed that bar velocity monitoring can be applied in various ways to assess and control neuromuscular fatigue in RT [4, 16]. The magnitude of fatigue can be controlled in real-time using intra-set velocity loss thresholds to regulate the volume [17]. Another application involves daily monitoring of bar velocity changes against a baseline measure (i. e. load-velocity profile) to assess residual fatigue level, readiness, and recovery status [18–20]. Increased or maintained bar velocity against a given load (pre-session) compared to the baseline measurement indicates a low level or absence of fatigue, optimal recovery, and readiness to train [18–20]. Conversely, a bar velocity reduction suggests exacerbated residual fatigue levels and compromised readiness and recovery. Despite the practical importance of this approach, the effects of variables capable of interfering with bar kinematics and its sensitivity to fatigue have yet to be widely examined.

The load intensity (usually considered by the percentage of the one-repetition maximum (%1RM)) and the kinematic velocity variables (e. g. mean propulsive velocity, peak velocity, or mean velocity) must be defined to implement bar velocity monitoring daily. A strong inverse relationship between load and different velocity variables has been evidenced in various resistance exercises [21, 22]. The absolute bar velocity is load-dependent and changes according to the load intensity magnitude. Furthermore, a recent study reported moderate reductions in bar velocity in the back-squat (mean and peak velocity) from baseline to 24 h and 48 h following a strength-oriented session, but only when moderate and heavy squat loads were performed (≥60 % 1 RM) [18]. No decrease in the mean or peak velocity was observed at light loads (20 % and 40 % 1RM). These results suggest that load intensity and the kinematic velocity variable can modulate their sensitivity to fatigue.

Three kinematic variables are often used for monitoring the bar velocity during the concentric exercise phase, which include mean propulsive velocity (MPV), mean velocity (MV), and peak velocity (PV). The kinematic variables measured depend on the type of device used to monitor the bar velocity (e. g. encoder, accelerometer, or smartphone application). Some technological devices only measure MV and PV or MPV and PV, while other equipment reports MPV, MV, and PV data. However, the kinematic variable used as a parameter for monitoring neuromuscular fatigue appears to be arbitrarily defined [18–20]. Pérez-Castilla et al. [23] compared the inter-session reliability of the MPV, MV, and PV variables measured by a linear encoder during a loaded vertical jump exercise. The results showed that MV, MPV, and PV presented acceptable test-retest reliability (ICC > 0.70 and CV < 10 %), but PV demonstrated greater reliability than MV and MPV. The findings of the study by Pérez-Castilla suggest that the kinematic velocity variable seems to be an important factor to be considered in monitoring protocols using encoders in the RT. However, to date it has not yet been determined whether the encoder's sensitivity to fatigue is influenced by the velocity variable measured by the encoder device used in the bar. Therefore, this study compared the acute responses of pre- to post fatigue exercise through CMJ height and bar velocity in free parallel back-squat against three load intensities (40 %, 60 %, and 80 % 1RM) using two kinematic variables (MPV and PV).

Materials and Methods

Experimental design

We implemented a repeated-measures randomized cross-over design to analyze the effects of load magnitude (40 %, 60 %, and 80 % 1RM) and bar velocity variables (MPV and PV) on sensitivity to neuromuscular fatigue. After familiarization (session 1) and 1RM assessment (session 2), the actual experimental trials took place in three visits to the laboratory, separated by 48 to 96 hours (sessions 3, 4, and 5). The participants completed a fatiguing protocol that consisted of three sets with maximum repetitions of back squat exercise at 75 % 1RM in each experimental session. The eccentric phase of back-squat was performed at a continuous and controlled cadence (2–3 s) with a momentary pause (~1.5 s) before starting the concentric phase [22]. The participants performed the concentric phase with maximum intentional velocity [4]. They also performed assessments of CMJ height (3 trials with 30 s of rest) and bar velocity (MPV and PV) during a back-squat exercise (1 set x 3 repetitions at 40 %, 60 %, or 80 % 1RM) before and after the intervention (-10 min, + 5 min, and + 20 min, respectively). The exercise load was randomized in the experimental sessions. The same evaluators conducted the tests at the same time of day (± 1 hour) under similar environmental conditions.

Participants

The estimated minimum sample size was 16 participants, considering a power of 0.80, alpha = 0.05, and effect size of 0.35. A total of 20 male university students aged 18 to 35 years old were recruited to participate in the study. After three subjects failed to complete the experimental sessions, the final sample consisted of 17 participants (age = 25.7 ± 4.9 years; height: 177.0 ± 7.2 cm; body mass = 77.7 ± 12.3 kg; strength training experience = 4.2 ± 2.5 years; back-squat 1RM = 145.0 ± 33.9 kg; relative strength ratio - 1RM/

body mass = 1.86). All the participants were recreationally trained with at least 12 months of experience in RT. The participants were physically active and had experience in RT ranging from 1.5 to 6 years (4.2 ± 2.5 years), with a weekly training frequency of three to five RT sessions per week in the last 12 months. They were accustomed to performing the back-squat exercise with correct technique in training routines. No recent musculoskeletal injuries were reported. Consent for participation in the study was obtained individually after the participants received information about the experimental procedures. The Institutional Research Ethics Committee approved the experimental protocol, and it was then carried out in conformity with the Declaration of Helsinki.

Procedures

Familiarization – session 1

The first session was used to familiarize participants with the Total Quality Recovery scale (TQR), OMNI-RES perceived exertion scale, CMJ, and back-squat exercise at maximal intended velocity in the concentric phase. Maximal intended velocity aimed to familiarize participants with lifting loads with different intensities (% 1RM) as fast as possible. We used the average and confidence interval of the bar velocity reported in a previous study as a reference to ensure the appropriate application of the maximal intended velocity [22]. We adopted anchoring procedures based on previous studies to ensure accuracy and consistency of responses when employing perceptive scales [24, 25]. Anchoring procedures consisted of teaching participants to report responses based on their sensations, perceptions and memory with maximum accuracy. Standardized instructions were used to differentiate the scale scores and their respective descriptors [26, 27]. Participants also received cues to facilitate the association of the score with the appropriate scale descriptor and possible sensations experienced.

Each participant completed a general warm-up, including dynamic stretching, joint mobility, light aerobic cycling, and 2 sets of 3 unloaded vertical jumps. Then, they completed 2 sets of 5 CMJ (10 s between attempts and 3 minutes rest between sets). The CMJ consisted of a maximal concentric movement preceded by a rapid eccentric movement to a knee flexion of approximately 90 °. After 5 minutes of rest, the participants performed a specific warm-up in the back-squat exercise (2 sets x 5 reps x 20 kg). Familiarization procedures for applying the maximal intended velocity were performed as previously described [22]. The participants completed three different back-squat protocols during familiarization as follows: a) 3 sets x 12 reps x 40 % 1RM estimated; b) 3 sets x 8 reps x 60 % 1RM estimated; and c) 3 sets x 5 reps x 80 % 1RM estimated. The interval between the sets was 2 minutes. The researchers provided verbal feedback on performance throughout the familiarization session.

1RM assessment – session 2

A progressive load test was performed in session 2 to determine 1RM in the back-squat exercise from the individual load-velocity profile [20]. The participants completed a general and specific warm-up as previously described. The initial load was 30 kg for all participants, followed by gradual increments of 20 kg until reaching a mean propulsive velocity (MPV) < 0.9 m.s^{-1}, and then 15 to 5 kg until MPV was < 0.50 m.s^{-1}. Three, two and one repetitions for a given load were performed for light, moderate, and heavy loads, respectively. We considered only the fastest MPV repetition at each load for the load analyses [21]. Inter-set resting ranged from 2 to 3 min for light and moderate loads, and 5 min for heavy loads. Finally, the participants squatted down until their thighs were parallel with the floor (90-degree angle), pushing their hips backward and flexing their knees, and then they returned to the initial position. The execution technique was carefully supervised in all repetitions. The eccentric phase of the movement was performed in a controlled manner imposing a momentary pause (i. e. the bar was held on the ground for 1.5 s between the eccentric and concentric phases) [22]. Verbal encouragement and real-time velocity feedback were provided in every repetition.

Experimental trials – sessions 3–5

The experimental sessions involved assessments of neuromuscular fatigue (pre- and post-exercise) using the CMJ and back-squat bar velocity against three load intensities (40 %, 60 %, or 80 % 1RM). The experimental phase consisted of three sessions spaced 48 to 96 hours apart. The interval between sessions was evaluated to ensure that the participants were in the best recovery state between experimental tests. The experimental session only occurred when participants reported a minimum score of 15 points, equivalent to the “good recovery” descriptor on the TQR scale. During the experimental sessions, three subjects reported scores below the established criteria. In these particular circumstances, experimental sessions were rescheduled in order to guarantee sufficient recovery and equalization between the experimental conditions. All participants answered the TQR scale and performed the standardized warm-up before each experimental session. Then, assessments of neuromuscular fatigue using vertical jump (CMJ) and maximal concentric velocity (MCV) in the back-squat exercise were performed immediately after the warm-up (detailed in the next section). After 10 minutes, the participants were submitted to a fatiguing exercise protocol consisting of 3 sets with the maximum repetitions at 75 % 1RM and 3 min of rest in the back-squat exercise. The participants completed as many repetitions as possible until the MPV fell below the velocity corresponding to 1RM (0.30 m.s^{-1}) [22]. The maximum repetitions protocol with a load of 75 % 1RM was programmed to achieve a velocity loss percentage of approximately 50 % in each set. The percentage of velocity loss was established by the percentage difference between the maximum intended velocity for the load of 75 % 1RM (0.60 m.s^{-1}) and the velocity corresponding to 1RM (0.30 m.s-1) for the back-squat exercise [22]. Velocity loss thresholds above 40 % per set result in high magnitudes of mechanical and metabolic stress [17]. The repetitions were performed with the maximum intended velocity and verbal encouragement throughout the protocol. Neuromuscular fatigue was assessed again 5 and 20 minutes after fatiguing exercise. Finally, the participants reported their perceived exertion at the end of the experimental session. They were asked to maintain their sleep behavior, avoid alcohol consumption, and usual diet habits before each of the following experimental sessions. They were also requested to avoid caffeine consumption for 3 h before the experimental condition and consume a light meal 2 h before the experiment. Participants were instructed to interrupt their resistance training routines during the experimental period to minimize the potential effects of confounding variables. These data were self-reported before each experimental session. Moreover, we use the TQR responses to control for optimal readiness status before the experimental session, as previously described.

Neuromuscular fatigue assessment

The CMJ height and MCV in the back-squat exercise with sub-maximal loads were used as mechanical measures to assess neuromuscular fatigue in the experimental sessions. Mechanical measures to assess neuromuscular fatigue were obtained before (−10 min) and after (+5 min and +20 min) the fatiguing resistance exercise protocol. The participants completed a general warm-up prior to the start of testing, as previously described. After 2 minutes of rest, the participants performed three maximal CMJs interspersed by 10-second intervals. The mean of three jumps was used for analysis.

The evaluation of MCV in the back-squat against different load intensities started after 3 minutes of rest from the jump test. The load order (40 %, 60 %, and 80 % 1RM) was distributed randomly among the experimental sessions for each participant. The participants performed three repetitions of the back-squat with maximum intentional velocity in the concentric phase. The mean of three repetitions based on bar velocity variable (MPV and PV) was used in the analysis. Vertical jumps and MCV protocols followed the procedures described in previous studies [28, 29]. The researcher provided verbal encouragement during both tests.

Measurement equipment and data recording

CMJ height was assessed on a contact platform (Elite Jump; S2 Sports, São Paulo, Brazil). The height (h) was estimated from the flight time (t) in the system (i. e. $h = gt^2/8$). The validity and usability of this contact platform system have been previously reported [12]. A linear encoder (Vitruve, Madrid, Spain) was attached to the bar to measure the lifting kinematics for the MCV assessment. This system measures the cable displacement in response to changes in the bar position during the concentric phase at a sampling rate of 100 Hz [30]. Two velocity variables were used for analyses: 1) mean propulsive velocity (MPV) and 2) peak velocity (PV). The MPV was defined as a mean velocity value of the portion of the concentric phase during which barbell acceleration was greater than the acceleration due to gravity [31]. The PV was established as the maximum instantaneous velocity value reached during the concentric phase [23]. The Vitruve encoder (previously named Speed4Lifts) has been demonstrated to be valid and reliable to record movement velocity with an absolute error below the acceptable maximum error criterion (< 5 %) [30].

Recovery status, perceived exertion and internal load

The level of perceived recovery was assessed through the Total Quality Recovery scale (TQR) before each experimental session [26]. TQR scores range from 6 to 20, in which a higher level of perceived recovery is related to higher scores. Participants reported their RPE 30 min after the end of each experimental session using the OMNI-RES scale [27]. All participants were familiarized with both scales in sessions 1 and 2 for the anchoring procedures. The same investigator obtained the perception variables individually during all sessions. The internal training load of each experimental condition was quantified using the session-RPE method [32]. The internal training load was the product of the RPE scale by the total number of repetitions completed in the fatiguing exercise.

Statistical analysis

The data are presented through mean and standard deviation. Percentual delta (pre-post) of the mechanical measures of neuromuscular performance was calculated for each test. We used the variation in CMJ performance as a reference measure for assessing bar velocity sensitivity during the MCV protocol. Normal distribution was confirmed by Shapiro-Wilk test ($p > 0.05$). Repeated-measures analysis of variance (ANOVA) compared the perceived recovery, perceived exertion, total of repetitions, volume load, and internal load between the experimental conditions. Changes in CMJ and MCV neuromuscular performance (40 %, 60 %, and 80 % 1RM) were compared at different time points (pre, post + 5 min, and post + 20 min) using two-way repeated measures ANOVA. The Bonferroni post hoc test was used to identify significant differences. Effect sizes (ES) were calculated using Cohen's d (mean difference divided by the SD of the change score) [33]. The ES magnitude was interpreted as trivial (< 0.2), small (0.21–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥ 2.0) [34]. Intraclass correlation coefficient (ICC), coefficient of variation (CV), and Bland-Altman plots with a 95 % confidence interval verified the agreement between CMJ and MCV protocols. The following criteria were used to interpret the ICC: poor (< 0.5), moderate (0.5–0.75), good (0.75–0.9), and excellent (> 0.9) [35]. CV values lower than 10 % were considered acceptable [36]. The statistical significance level was set at $p \leq 0.05$. All analyses were conducted in the Statistical Package for the Social Sciences program (SPPS version 21.0 for Windows).

Results

Neuromuscular performance changes in fatigue tests (CMJ and MCV) from pre-exercise to post-exercise (+5 min and +20 min) are shown in ▶ **Table 1** and ▶ **Fig. 1**. There was a significant decrease in CMJ height from pre- to post-exercise ($\Delta\% = -7.5$ to -10.4; $p < 0.01$; ES = 0.37 to 0.60). MPV reduced also significantly at 40 % 1RM ($\Delta\% = -7.5$ to -8.9; $p < 0.01$; ES = 0.43 to 0.60), 60 % 1RM ($\Delta\% = -5.3$ to -6.2; $p < 0.01$; ES = 0.35 to 0.39), and 80 % 1RM ($\Delta\% = -10.7$ to -12.5; $p < 0.01$; ES = 0.53 to 0.66) from pre- to post-exercise. Similarly, there was a decrease in PV at 40 % 1RM ($\Delta\% = -4.0$ to -4.5; $p < 0.01$; ES = 0.32 to 0.36), 60 % 1RM ($\Delta\% = -4.6$ to -4.9; $p < 0.01$; ES = 0.30 to 0.34), and 80 % 1RM ($\Delta\% = -9.2$ to -9.2 $p < 0.01$; ES = 0.43 to 0.47).

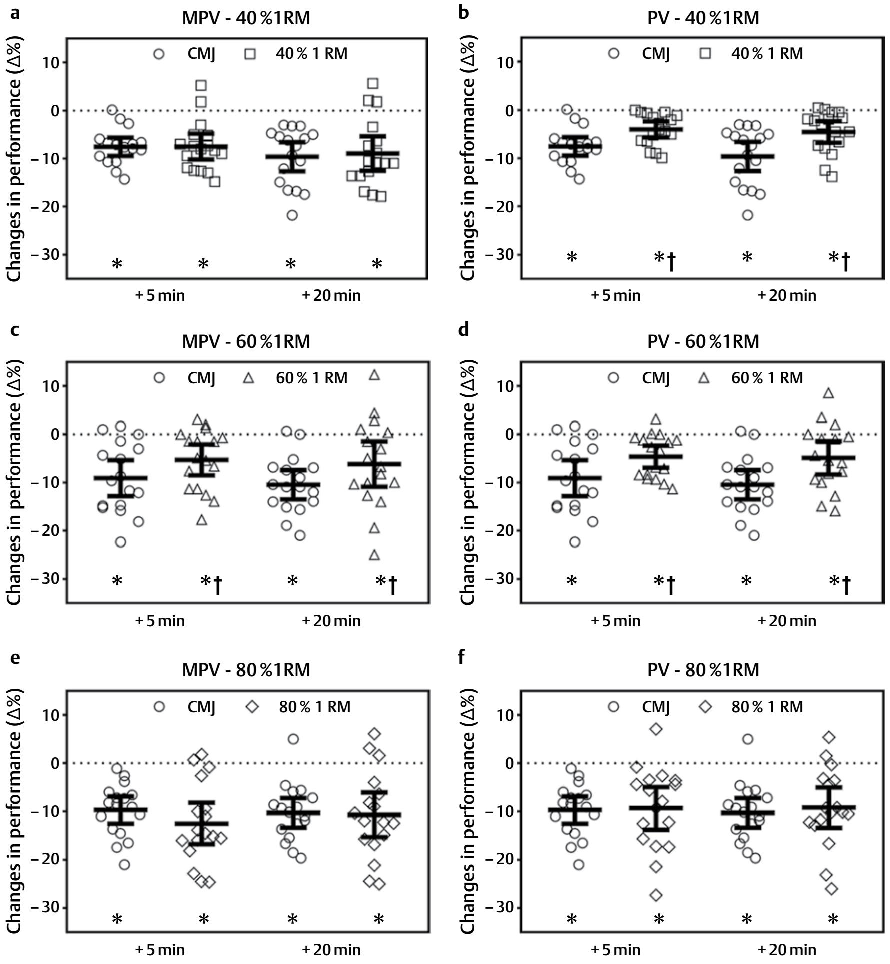
The decrease magnitude in neuromuscular performance was similar between the CMJ, MPV (40 % 1RM; and 80 % 1RM; $p = 1.00$), and PV (80 % 1RM; $p = 1.00$). However, the decrease in CMJ height percentage was higher than in MPV at 60 % 1RM ($p = 0.05$) and PV (40 % 1RM; $p = 0.05$ and 60 % 1RM; $p < 0.01$).

Bland-Altman plots revealed low systematic bias in the different MCV protocols (▶ **Fig. 2**). However, the lowest systematic biases values were observed in the MPV with 40 % and 80 % 1RM. In addition, acceptable levels of agreement between CMJ and bar velocity post 5 min were only found in the MPV protocols at 40 % 1RM (ICC = 0.71, 95 %CI = 0.19–0.89; CV = 5.1, 95 %CI = 3.5–6.7) and 80 % 1RM (ICC = 0.58, 95 %CI = 0.65–0.84; CV = 8.5 %, 95 %CI = 6.2–10.7), but both were moderate (▶ **Table 2**). Moderate agreement was also

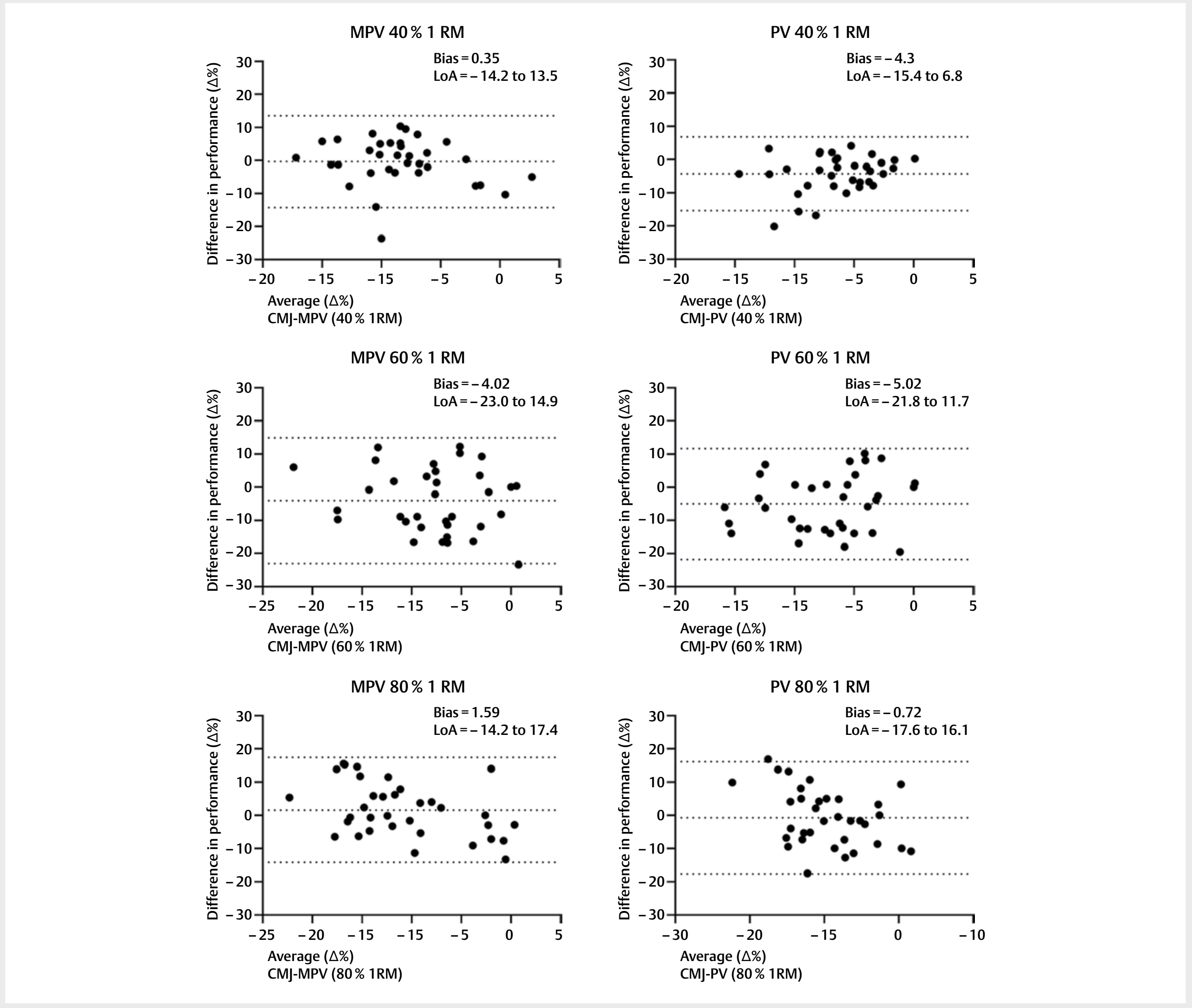
▶ **Table 1** Comparisons of neuromuscular performance within (pre- to post-exercise) and between experimental protocols. Data are presented in mean and standard deviation.

Protocols	Variables	Pre	Post 5 min	Post 20 min	Δ % Post 5 min	ES Post 5 min	Δ % Post 20 min	ES Post 20 min
40 % 1RM	CMJ (cm)	40.4 ± 6.34	37.3 ± 5.64	36.5 ± 6.07	−7.5 ± 3.7*	0.37 (S)	−9.6 ± 6.0*	0.46 (S)
	MPV ($m.s^{-1}$)	0.95 ± 0.12	0.88 ± 0.11	0.86 ± 0.09	−7.5 ± 5.3*	0.43 (S)	−8.9 ± 7.0*	0.60 (M)
	PV ($m.s^{-1}$)	1.68 ± 0.15	1.61 ± 0.16	1.60 ± 0.16	−4.0 ± 3.3*†	0.32 (S)	−4.5 ± 4.4*†	0.36 (S)
60 % 1RM	CMJ (cm)	40.6 ± 6.40	36.9 ± 4.24	36.2 ± 5.15	−9.1 ± 7.3*	0.60 (M)	−10.4 ± 5.9*	0.54 (S)
	MPV ($m.s^{-1}$)	0.74 ± 0.08	0.70 ± 0.08	0.69 ± 0.10	−5.3 ± 6.2*†	0.35 (S)	−6.2 ± 9.2*†	0.39 (S)
	PV ($m.s^{-1}$)	1.42 ± 0.14	1.36 ± 0.14	1.35 ± 0.15	−4.6 ± 4.5*†	0.30 (S)	−4.9 ± 6.7*†	0.34 (S)
80 % 1RM	CMJ (cm)	40.5 ± 7.07	36.5 ± 5.43	36.3 ± 6.50	−9.7 ± 5.4*	0.45 (S)	−10.2 ± 5.9*	0.52 (S)
	MPV ($m.s^{-1}$)	0.52 ± 0.08	0.45 ± 0.07	0.46 ± 0.08	−12.5 ± 8.3*	0.66 (M)	−10.7 ± 9.0*	0.53 (S)
	PV ($m.s^{-1}$)	1.19 ± 0.17	1.08 ± 0.16	1.08 ± 0.19	−9.2 ± 8.6*	0.47 (S)	−9.2 ± 8.1*	0.43 (S)

Note: CMJ: there was a decrease in countermovement jump; MPV: mean propulsive velocity; PV: peak velocity; ES: effect size; S: small effect size; M: moderate effect size; *Significant difference to pre-exercise (p ≤ 0.05). †Significant difference to CMJ (p ≤ 0.05).



▶ **Fig. 1** Comparison of changes in performance dext-linkng post-exercise (+ 5 min and + 20 min) versus pre-exercise (baseline) between the assessment of fatigue in the CMJ protocol and maximum concentric velocity in the back-squat using different loads (40 %, 60 %, and 80 % 1RM) and kinematic variables (MPV and PV). The data are presented in mean and 95 %CI. Note: CMJ: countermovement jump; MPV: mean propulsive velocity; PV: peak velocity. *Significant difference to pre-exercise (p ≤ 0.05). †Significant difference to CMJ (p ≤ 0.05).



▶ **Fig. 2** Bland-Altman plots for the changes in performance (Δ %) between CMJ performance (reference measure) and bar velocity assessment (MPV and PV). Note: CMJ = countermovement jump; MPV = mean propulsive velocity; PV = peak velocity; SD = standard deviation; LoA = limits of agreement.

observed at the post-20 min moment between CMJ and bar velocity at 80 % 1RM (ICC = 0.58, 95 %CI = 0.65–0.84), while the CV was not acceptable (CV = 12.1, 95 %CI = 8.7–15.4).

The total quality recovery, total of number repetitions, load volume, perceived exertion, and internal training load from the fatigue protocol are shown in ▶ **Table 3**. There were no statistical differences between experimental condition sessions (p > 0.05).

Discussion

Previous studies have proposed the use of bar velocity during resistance exercise as a method of monitoring neuromuscular fatigue [4, 18–20]. However, no study to date has investigated whether load magnitude and the mechanical velocity variable influence the sensitivity to fatigue. To our knowledge, this is the first study to compare the effects of the load magnitude of resistance exercise and bar velocity kinematics variables on sensitivity to fatigue. Our findings revealed an acute reduction in neuromuscular performance during post-session in both CMJ and back-squat exercise at MCV, independent of load intensity (40 %, 60 %, and 80 % 1RM) and variable kinematic velocity (MPV or PV). Furthermore, our results indicated greater agreement and similarity in the acute decrease pattern of neuromuscular performance between CMJ and back-squat exercise using MPV at intensities of 40 % and 80 % 1RM during fatigue monitoring by bar velocity.

Similar to previous studies [18–20], we found meaningful reductions in MPV and PV during the back-squat at 40 %, 60 % and, 80 % 1RM after fatiguing exercise. These findings provide additional evidence that supports the use of monitoring changes in bar velocity as a simple, practical, and valid alternative to assess exercise-

▶ **Table 2** Intraclass correlation coefficients and coefficients of variation with 95 % confidence intervals of the agreement of fatigue assessment between CMJ and bar velocity protocols with different loads (40 %, 60 %, and 80 % 1RM) and kinematic variables (MPV and PV).

Protocols vs CMJ	**ICC**	**CV (%)**	**ICC**	**CV (%)**
	Post 5 min	**Post 5 min**	**Post 20 min**	**Post 20 min**
MPV (40 % 1RM)	0.71 (0.19–0.89)	5.1 (3.5–6.7)	0.09 (−1.76–0.68)	5.4 (3.8–7.1)
MPV (60 % 1RM)	0.10 (−1.36–0.62)	5.4 (3.7–7.1)	0.23 (−0.81–0.70)	5.5 (4.0–6.9)
MPV (80 % 1RM)	0.58 (−0.65–0.84)	8.5 (6.2–10.7)	0.51 (−0.40–0.82)	12.1 (8.7–15.4)
PV (40 % 1RM)	0.37 (−0.29–0.73)	2.8 (2.2–3.3)	−0.08 (−1.34–0.56)	3.1 (2.0–4.2)
PV (60 % 1RM)	−0.27 (−1.77–0.48)	4.8 (2.4–4.8)	0.21 (−0.53–0.66)	4.5 (1.9–7.0)
PV (80 % 1RM)	0.43 (−0.65–0.80)	8.2 (5.5–11.0)	0.38 (−0.77–0.78)	10.3 (6.3–14.3)

Note: CMJ: countermovement jump; MPV: mean propulsive velocity; PV: peak velocity; ICC: intraclass correlation coefficients; CV: coefficients of variation.

▶ **Table 3** Perceived recovery, characterization of the fatigue protocol, and perceived exertion in the three experimental conditions.

Variables	**40 % 1RM**	**60 % 1RM**	**80 % 1RM**
TQR	17.0 ± 2.1	17.0 ± 1.7	18.0 ± 1.4
Total of RMs	27.0 ± 6.0	28.0 ± 8.6	28.0 ± 9.1
Volume load (kg)	2960 ± 1029	3104 ± 1278	3101 ± 1220
RPE	7.0 ± 1.0	7.0 ± 1.4	8.0 ± 1.7
Internal load (AU)	189 ± 50	196 ± 89	224 ± 95

Note: TQR: total quality recovery; RMs: sum of the maximum number of repetitions in the 3 sets of the fatigue protocol (75 % 1RM); RPE: rating of perceived exertion; AU: arbitrary units.

induced neuromuscular fatigue [4, 18–20], which can be used as an alternative to other protocols such as isometric maximal force measurement, electromyography, voluntary muscle activation, motor evoked potential, and vertical jumps [10, 37]. Neuromuscular fatigue results in a temporary reduction in the capacity of the neuromuscular system to produce force and power [2]. The gradual development of fatigue affects central and peripheral mechanisms, which results in a reduction in shortening velocity, an increase in relaxation time, and a decrease in the efficiency of the contractile capacity of muscle fibers [2]. Regardless of the load magnitude, the acute post-exercise decreases in both kinematic measurements of bar velocity (MPV and PV) in the back-squat exercise can be thought of as a behavioral manifestation of impaired central and peripheral mechanisms involved in muscle contraction resulting from fatigue.

Based on delta percentage magnitude, our results revealed that MPV was more sensitive than PV during fatigue monitoring using bar velocity in back-squat exercise. These findings can be interpreted as a result of the greater sensitivity of the MPV to discriminate the fatigue level during the concentric phase of the movement. The concentric phase of the movement can be subdivided into two portions: 1) propulsive (F > 0) and braking (F < 0) [31]. The hip and knee extensor muscles work collectively to produce high levels of force to break inertia and accelerate the bar throughout the propulsive phase of the back-squat. During the concentric phase of the back-squat from a static position, the initial velocity of the movement is zero, achieves peak velocity at the final part of the propulsive portion of the lift, and returns to zero velocity at the end of braking [31]. The presence of neuromuscular fatigue impairs muscle contractile function and, consequently, the capacity of the neuromuscular system to produce force and velocity in the propulsive portion of the concentric phase [2]. Thus, a measure with high sensitivity to fatigue is one that is able to detect the impairment degree of neuromuscular function accurately during the propulsive portion of movement. MPV is a kinematic velocity variable representative of the entire propulsive portion of the movement. Conceptually, MPV is a mean velocity value arising from the portion of the concentric phase in which the bar acceleration is higher than gravity. In contrast, PV is a measurement derived from a single value equivalent to the maximum instantaneous velocity reached in the bar's acceleration phase [31]. Additionally, the ability of muscle fibers to generate force depends on the length-tension relationship [38, 39]. Force generation is enhanced when the length of the sarcomere provides an optimal overlap between the actin and myosin filaments for the formation of cross-bridges [38, 39]. Given that MPV is a measure that depicts the force application across the propulsive phase, its increased amplitude of capture of variations in force production of the muscle groups in various length-tension relationships during the back-squat may explain why it is more sensitive to fatigue. Therefore, it is possible that MPV showed greater sensitivity to fatigue because it encompasses more information about the application of force to lift the bar during the propulsive portion of the concentric phase.

The results of the current study suggest that the load magnitude of resistance exercise affect the agreement of bar velocity-based protocols with CMJ to detect neuromuscular fatigue. The post-exercise performance reduction profile (+ 5 min and + 20 min) during the CMJ showed higher concordance (based on ICC) with the back-squat at 40 % and 80 % 1RM than 60 % 1RM. These effects can be attributed to the different load intensities of the back-squat since the experimental sessions were similar in relation to the recovery status, volume, intensity, effort, and internal load measures (▶ **Table 3**). The biomechanical similarity between the back-squat at 40 % 1RM and CMJ may have been decisive for its high sensitivity to fatigue. The force application to perform the CMJ occurs under low external load conditions, similarly to the back-squat execution at a light load. Both exercises are characterized by the predominance of velocity from a mechanical point of view of the force-velocity profile [40]. In contrast, we also observed high sensitivity to fatigue of the protocol employing MPV during the back-squat at 80 % 1RM. The participants completed three sets with the maximum repetitions at 75 % 1RM in the RT program to induce fatigue. Resistance exercise of maximum repetitions with moderate-heavy load (i. e. 75 % 1RM) can predominantly cause fatigue of high-threshold motor units. Contractions against heavy loads preferentially recruit high-threshold motor units [41], which may explain the high sensitivity to fatigue of the back-squat exercise in the 80 % 1RM protocol. It is relevant to note that the measures used in the current study are limited to providing strong explanations of why the 60 % 1RM load did not produce similar results to the 40 % and 80 % 1RM. It is possible that this result was a chance event because we did not use a direct measure of fatigue in this study. New studies with direct measurements of fatigue may clarify this issue.

Our findings have important practical implications for fatigue management and load control in resistance training. Strength and conditioning coaches can implement bar velocity monitoring protocols (MPV or PV) in the back-squat at 40 % or 80 % 1RM before the start of the training session. A reduction in bar velocity indicates an impairment of neuromuscular function due to fatigue, which can be used to establish an optimal volume for the session, adjust the training dose, and minimize the risk of injury. Despite the practical implications of our findings, the present study has some limitations. The fatigue assessments through bar velocity monitoring only involved a single lower limb exercise (back-squat exercise) after a session with the same exercise. Fatigue assessment protocols involved two kinematic measurements of bar velocity (MPV and PV). The sensitivity to fatigue tests with different bar velocity monitoring protocols occurred acutely (+ 5 min and + 20 min post-exercise). Finally, the study sample only included resistance-trained men. Therefore, generalizing our results applies to contexts with similar characteristics to those described above. Future studies should investigate the fatigue sensitivity of protocols using bar velocity in other resistance exercises, with delayed acute (+ 24 h) and accumulated fatigue induced by different training programs and other populations (e. g. elite athletes, women, young athletes).

The CMJ test was employed as a reference in this study because it has biomechanical properties akin to the back-squat [41–43] and is assumed to be a valid indicator of neuromuscular fatigue [8–10]. Mechanical and neuromuscular factors linked to the capacity to generate and transmit vertical force are comparable between the two exercises. For example, both exercises show similarities in the recruitment pattern of lower limb muscles, such as quadriceps, hamstrings, and glutes [41–43]. There is also a similarity in the kinematic pattern of movement that includes flexion and extension of the hip, knee, and ankle joints [41–43]. Although vertical jump assessment is an applicable method for monitoring neuromuscular fatigue, the cost of some devices (e. g. force platforms and contact mats) and the impossibility of accessing real-time results when using video systems can restrict or make its use difficult for most strength and conditioning coaches. Nevertheless, there is a growing popularity of portable devices (i. e. linear encoders) among strength and conditioning coaches due to their applicability, accuracy, and relatively low cost [44, 45]. Linear encoders allow monitoring bar velocity in real time, which makes it possible to manipulate the volume and intensity of resistance training in an objective, precise and practical way [15]. Additionally, previous studies have proposed using movement velocity as an alternative method to monitor neuromuscular fatigue [18–20]. However, the best choice of velocity variables and the optimal load to detect changes in neuromuscular status have not yet been defined. Based on the results of this study, strength and conditioning coaches can quantify neuromuscular fatigue resulting from RT by monitoring MPV or PV during the back-squat exercise, regardless of the load magnitude. However, using the MPV variable and loads equivalent to 40 % 1RM and 80 % 1RM in the back-squat allows greater consistency in the CMJ results to detect the neuromuscular fatigue.

Conclusion

In conclusion, our findings showed that MCV back-squat exercise, regardless of the load intensity (40 %, 60 % and 80 % 1RM) and the kinematic variable velocity (MPV or PV), can be used to monitor acute fatigue caused by RT. However, the back-squat exercise at 40 % or 80 % of 1RM using MPV provides higher sensitivity for monitoring fatigue through changes in bar velocity. Therefore, strength and conditioning coaches can use the MPV and light (40 % 1RM)or heavy (80 % 1RM) loads to accurately manage neuromuscular fatigue during RT.

Conflict of Interest

The authors declare that they have no conflict of interest.

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