Acute Mechanical, Neuromuscular, and Metabolic Responses to Different Set Configurations in Resistance Training

Francisco Piqueras-Sanchiz,[1] Pedro J. Cornejo-Daza,[1] Juan Sánchez-Valdepeñas,[1,2] Beatriz Bachero-Mena,[3] Miguel Sánchez-Moreno,[3] Saúl Martín-Rodríguez,[4] Óscar García-García,[5] and Fernando Pareja-Blanco[1,2]

[1]Department of Sports and Computers Sciences, Physical Performance & Sports Research Center, Pablo de Olavide University, Seville, Spain; [2]Department of Sports and Computers Sciences, Faculty of Sport Sciences, Pablo de Olavide University, Seville, Spain; [3]Department of Physical Education and Sports, University of Seville, Seville, Spain; [4]Department of Physical Education, University of the Gran Canarian Palms, The Gran Canarian Palms, Spain; and [5]Laboratory of Sports Performance, Physical Condition and Wellness, Faculty of Education and Sport Sciences, University of Vigo, Pontevedra, Spain

Abstract

Piqueras-Sanchiz, F, Cornejo-Daza, PJ, Sánchez-Valdepeñas, J, Bachero-Mena, B, Sánchez-Moreno, M, Martín-Rodríguez, S, García-García, Ó, and Pareja-Blanco, F. Acute mechanical, neuromuscular, and metabolic responses to different set configurations in resistance training. *J Strength Cond Res* 36(11): 2983–2991, 2022—The aim of this study was to investigate the effect of set configuration on mechanical performance, neuromuscular activity, metabolic response, and muscle contractile properties. Sixteen strength-trained men performed 2 training sessions in the squat exercise consisting of (a) 3 sets of 8 repetitions with 5 minutes rest between sets (3 × 8) and (b) 6 sets of 4 repetitions with 2 minutes rest between sets (6 × 4). Training intensity (75% one repetition maximum), total volume (24 repetitions), total rest (10 minutes), and training density were equalized between protocols. A battery of tests was performed before and after each protocol: (a) tensiomyography (TMG), (b) blood lactate and ammonia concentration, (c) countermovement jump, and (d) maximal voluntary isometric contraction in the squat exercise. Force, velocity, and power output values, along with electromyography data, were recorded for every repetition throughout each protocol. The 6 × 4 protocol resulted in greater mechanical performance (i.e., force, velocity, and power) and lower neuromuscular markers of fatigue (i.e., lower root mean square and higher median frequency) during the exercise compared with 3 × 8, particularly for the last repetitions of each set. The 3 × 8 protocol induced greater lactate and ammonia concentrations, greater reductions in jump height, and greater impairments in TMG-derived velocity of deformation after exercise than 6 × 4. Therefore, implementing lower-repetition sets with shorter and more frequent interset rest intervals attenuates impairments in mechanical performance, especially in the final repetitions of each set. These effects may be mediated by lower neuromuscular alterations, reduced metabolic stress, and better maintained muscle contractile properties.

Key Words: rest-redistribution, lactate, ammonia, rate of force development, electromyography, tensiomyography

Introduction

Fatigue can be defined as an integral process resulting in a temporal decline in force production capacity (3). A better understanding of the mechanical and physiological mechanisms underlying fatigue development during resistance training (RT) sessions is essential to improve our knowledge of strength training methodology. Excessive fatigue development during training sessions may be detrimental for athletes focused on maximizing neuromuscular adaptations (29,30). Shorter set configurations that include rest periods between clusters of repetitions are an effective strategy to attenuate fatigue and maintain mechanical performance (i.e., force production, movement velocity, and, as a consequence, power output) during RT sessions (36). In addition, higher blood lactate (7,8,24) and ammonia (26) concentrations, hormonal response (growth hormone and cortisol) (26,27,37), and muscle damage indicators (i.e., creatine kinase) (26) have been observed after longer set configurations.

Previous literature analyzing set configuration has focused on the effects on exercise performance itself, with limited studies examining the postexercise responses to different set configurations. In this regard, longer set configurations are characterized by inducing greater impairments in back squat (SQ) performance (i.e., velocity attained against a given absolute load) and jump height (24,26). However, the acute effect of set configuration on relevant markers for the evaluation of fatigue in strength training as maximal isometric force (MIF) or maximal rate of force development (RFDmax) remains unexplored. Likewise, recording electromyography (EMG) activity (amplitude, through root mean square "RMS," and frequency, through median frequency "MDF") may provide a better understanding of the mechanisms behind the changes in mechanical performance, such as muscle activation and neuromuscular fatigue accumulated throughout the training session (6). To date, only one previous study has examined neuromuscular activity during different set configurations involving lower-body muscles (25), which compared 6 sets

Address correspondence to Fernando Pareja Blanco, fparbla@upo.es.
Journal of Strength and Conditioning Research 36(11)/2983–2991

of 6 repetitions at 20% of 1 repetition maximum (1RM) in loaded jumps, continuously ($n = 9$) or with a 30-second rest every 2 repetitions ($n = 9$). These authors observed larger increments in RMS throughout longer set configurations; however, both protocols induced similar decrements in MDF (25). However, the fact that different subjects performed each protocol may have obscured potential differences in the EMG spectral parameters between protocols. Finally, EMG recordings have limitations during dynamic muscle contractions (5). Therefore, it would be reasonable to examine the effects of set configuration on neuromuscular fatigue development during both dynamic and isometric contractions.

Tensiomyography (TMG) has been validated for assessing in vivo passive muscle contractile properties through simple measurement of the muscle belly radial deformation and the time it takes to occur in response to a single-twitch stimulus (39). This technique allows the assessment of the changes in muscle contractile properties induced by fatigue after training sessions (4,31,32). Despite evidence indicating TMG as a valid and reproducible tool to screen adjustments in skeletal muscle contractile characteristics (23), to the best of our knowledge, only one study has analyzed the acute effects on TMG outcomes after different set configurations (38). These authors compared 4 isokinetic unilateral knee extension protocols, 2 different set configurations (4 × 10 with 95 seconds of interset rest vs. 20 × 2 with 15 seconds of interset rest) at 2 different velocities (60 vs. 360°·s^{-1}), reporting similar postexercise TMG parameter patterns for all protocols (38). The fact that this study was conducted on an isokinetic device improved the control of confounding variables but sacrificed the ecological validity of real-life resistance exercises. Therefore, information about the acute effects of set configuration in strength training protocols used in practice on muscle contractile properties is lacking in the literature. In this regard, the SQ is one of the most widely used and effective RT exercises for strengthening the lower limbs and improving athletic performance (12). In addition, TMG measurements should be accompanied by postexercise mechanical performance tests to better comprehend how these outcomes interact. In light of these considerations, a more detailed knowledge about the integral response (mechanical, neuromuscular, and metabolic) to different set configurations would provide coaches and scientists with a better understanding of the effects of set configuration manipulation and could lead to further advances in exercise prescription. Therefore, the purpose of this study was to investigate the effect of set configuration on mechanical performance and neuromuscular activity throughout the SQ training session, as well as the acute mechanical, neuromuscular, metabolic, and muscle contractile responses for strength-trained men.

Methods

Experimental Approach to the Problem

A randomized cross-over research design was undertaken to examine the acute mechanical, neuromuscular, metabolic, and muscle contractile properties responses to 2 different set configurations with a load of 75% 1RM during the SQ exercise: (a) 3 sets of 8 repetitions with 5 minutes rest between sets (3 × 8) and (b) 6 sets of 4 repetitions with 2 minutes rest between sets (6 × 4). Training intensity (75% 1RM), total volume (24 repetitions), total rest (10 minutes), and, as a consequence, training density (work-to-rest ratio) were equalized between protocols. Protocols were performed in a random order, separated by a period of 4 days.

To compare the mechanical, neuromuscular, metabolic, and muscle contractile properties response, subjects underwent a battery of tests before and after each protocol: (a) TMG measurements, (b) blood lactate and ammonia concentration, (c) countermovement jump (CMJ), and (d) maximal voluntary isometric contraction (MVIC) in SQ exercise (Figure 1). In addition, to compare the performances attained throughout the session, force, velocity, and power output values along with EMG data were recorded for every repetition.

Subjects were asked to abstain from any strenuous physical activity for at least 2 days before each trial. Subjects were also instructed to maintain their usual diet, although they were asked to refrain from consuming caffeine 12 hours before attending the study. All sessions took place at a neuromuscular research laboratory under the direct supervision of the researchers, at the same time of the day for each subject and under similar environmental conditions (20° C and 60% humidity, approximately).

Subjects

Sixteen strength-trained men (Age range: 18–35 years; age 23.4 ± 4.4 years; height 1.75 ± 0.05 m; and body mass 73.9 ± 9.1 kg; mean ± *SD*) with at least 2 years of RT experience in the SQ exercise (range 2–6 years; 1RM strength for the SQ exercise: 105.8 ± 12.1 kg; and 1.44 ± 0.11 normalized per kg of body mass) participated in the study. Subjects were injury-free and were fully informed about the procedures, potential risks, and benefits of the study, and they all signed a written informed consent form before the tests. Subjects reported they were not taking drugs, medications, or dietary supplements known to influence physical performance. This study was approved by the Research Ethics Committee of the University of Vigo (Ref: 03-819), in accordance with the Declaration of Helsinki.

Procedures

Progressive Loading Test. One week before the resistance exercise protocols, a progressive loading test was conducted on a Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) with no counterweight mechanism to obtain the 1RM strength and individualized load-velocity relationships. The SQ was performed with subjects starting from the upright position with the knees and hips fully extended and stance approximately shoulder-width apart, and the barbell resting across the back at the level of the acromion. Each subject descended in a continuous motion as low as possible (˜35–40° knee flexion) and then immediately reversed motion and returned to the upright position. Unlike the eccentric phase that was performed at a controlled mean velocity (˜0.50–0.65 m·s^{-1}), subjects were required to always execute the concentric phase at maximal intended velocity. Range of movement and velocity values of all repetitions were recorded at 1,000 Hz with a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain). First, the subjects warmed up by performing 6 repetitions with a 20 kg load. The initial load was set at 30 kg and was progressively increased in 10 kg increments until the mean propulsive velocity (MPV) was ≤0.50 m·s^{-1}. Then, the load was increased with smaller increments (2.5–5.0 kg) for better adjustments. A total of 10.0 ± 1.8 increasing loads were used for each subject. Three repetitions were executed for light loads (≥1.00 m·s^{-1}), 2 for medium loads (1.00–0.80 m·s^{-1}), and one for the heaviest loads (≤0.80 m·s^{-1}). Interset rests

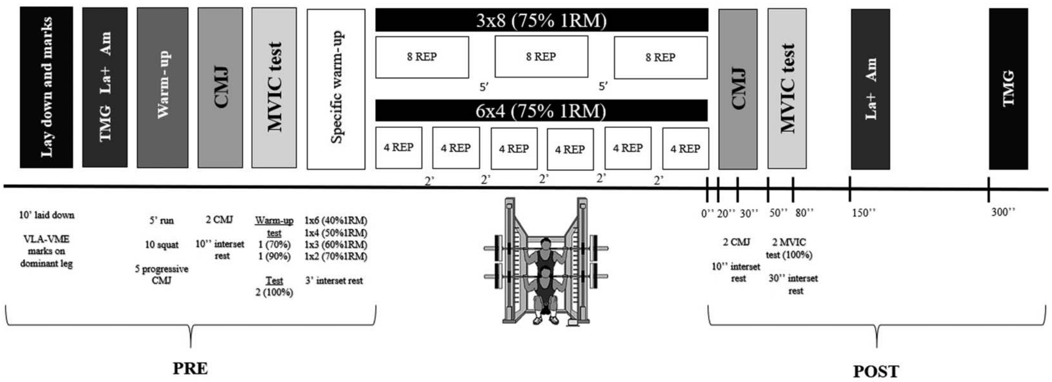

Figure 1. Schematic representation of the study design including the 2 resistance exercise protocols analyzed and the timeline of the battery of tests before and after the protocols.

were 3 minutes for light and medium loads and 5 minutes for heavy loads. Only the best repetition (i.e., highest MPV) with each load was considered for subsequent analysis. The propulsive phase corresponds to the portion of the concentric action during which the measured acceleration is greater than acceleration due to gravity (-9.81 m·s^{-2}) (35).

Resistance Exercise Protocol. Figure 1 provides a detailed timeline description of the experimental protocol. To minimize the effects of fluid changes caused by walking, subjects remained lying down for 10 minutes before starting the TMG measurements and baseline data acquisition. During the time they were lying down, a resting blood sample was collected (lactate and ammonium) and electrode locations (for TMG and EMG) were marked. After baseline TMG and blood lactate measurements were taken, the CMJ and MVIC tests were performed. Then, a standardized SQ warm-up was performed before the resistance exercise protocol, which consisted of: 6-6-4-3-2 SQ repetitions with 20 kg, 40, 50, 60, and 70% of 1RM, respectively, with 3 minutes rest between loads. Relative loads were determined from the individual second-order load-velocity relationship ($R^2 = 0.996 \pm 0.002$) obtained from the progressive loading test. Subsequently, the corresponding protocol was performed (3×8 with 75% 1RM and 5 minutes rest between sets vs. 6×4 with 75% 1RM and 2 minutes rest between sets). The SQ execution technique described in the "progressive loading test" section was carefully reproduced in all repetitions performed in the study. A force plate (FP-500, Ergotech) synchronized with a linear velocity transducer (T-Force System, Ergotech) was installed on the Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) to record mean propulsive values of force (MPF), velocity (MPV), and power (MPP) for every repetition. In addition, EMG data (i.e., RMS and MDF) were also recorded throughout the 24 repetitions. Subjects received immediate velocity feedback while being encouraged to perform each repetition at maximal intended velocity. After completing the final repetition (the 24th), the battery of tests was repeated as follows: CMJ (20 seconds Post), MVIC (50 seconds Post), blood samples (2 minutes and 30 seconds Post), and TMG (5 minutes Post) to obtain the acute postexercise values. This order was chosen to minimize the interference between tests and record valid data; i.e., the acute response to mechanical performance (but not high-fatiguing tests), metabolic response about 2–3 minutes postexercise, and TMG after 4–5 minutes resting. The duration per subject and session was approximately 1 hour.

Tensiomyography. The contractile properties of the vastus lateralis (V_{LA}) and vastus medialis (V_{ME}) muscles of the right leg were assessed using a TMG device (TMG-100 System electrostimulator; TMG-BMC, Ljubljana, Slovenia) to determine their response to an electrically evoked contraction. The electric stimulus was applied through 2 self-adhesive electrodes (5×5 cm, Dura-Stick premium; Cefar-Compex, Hanover, Germany) placed at a 5-cm interelectrode distance. The muscle mechanical response was measured with a digital DC-DC transducer TransTekR (GK 40, Ljubliana, Slovenia) placed perpendicular to the muscle belly and equidistant from the self-adhesive electrodes at a distance of 25–30 mm. Subjects remained lying in a supine position for 10 minutes before starting the TMG data acquisition, and the V_{LA} and V_{ME} were marked according to SENIAM indications and location (16). To ensure the same placement of electrodes between consecutive measurements, the locations were marked on the skin using a permanent marker and subjects were advised to keep the marks in place until the second session. Measurements were taken with the athletes in the supine position and the knee joint fixed at an angle of ˜140° using a wedge cushion. Electrical stimulation was applied with a pulse duration of 1 ms and an initial current amplitude of 40 mA, which was progressively increased in 10 mA steps up to the stimulator's maximal output (100 mA). The use of a stimulus pulse of 1 ms, using a 5×5-cm electrode (the procedure followed in this study) has been recently found to be necessary to reach a reliable and reproducible assessment of muscle contractile properties (33). A 10-second rest period was allowed between each electrical stimulus to avoid fatigue or posttetanic activation. The variables assessed in this study were the maximum radial displacement of the muscle belly (Dm), contraction time (Tc), and delay time (Td). Dm was defined as the peak amplitude in the displacement-time curve of the tensiomyographical twitch response; Tc was obtained by determining the time interval from 10 to 90% of Dm; and Td was defined as the time between the electrical stimulus and 10% of Dm (39). In addition, the velocity of deformation (Vd) was calculated as follows: Dm $(Tc + Td)^{-1}$ (21). Although Vd was originally termed the velocity of contraction, it is now recommended to use the term velocity of deformation, which is mainly dependent on muscle stiffness, to avoid confusion with sarcomere shortening velocity (40). Mean velocities of muscle contraction (mm·s^{-1}) from the onset of electrical stimulation until 10% (V10) and 90% (V90) of Dm were also recorded using equations developed elsewhere (4). All measurements were performed by the same experienced evaluator and only the curve with the highest

Table 1

Mechanical and neuromuscular characteristics of each resistance exercise protocol (average of 24 repetitions).*†

	3 × 8	6 × 4	*p*
MPF (N)	842.9 ± 96.4	869.4 ± 116.9	0.03
MPV (m·s^{-1})	0.59 ± 0.08	0.63 ± 0.08	0.02
MPP (w)	486.4 ± 66.8	524.8 ± 74.5	0.001
RMS (%)	122.4 ± 15.8	108.9 ± 11.1	0.01
MDF (%)	108.4 ± 9.6	110.5 ± 10.4	0.45

*3 × 8 = protocol consisted of performing 3 sets of 8 repetitions with 75% of 1RM; 6 × 4 = protocol consisted of performing 6 sets of 4 repetitions with 75% of 1RM; MPF = mean propulsive force; MPV = mean propulsive velocity; MPP = mean propulsive power; RMS = root mean square averaged from the vastus medialis and vastus lateralis muscles; MDF = median frequency averaged from the vastus medialis and vastus lateralis muscles.
†Data are mean ± *SD*, *n* = 16.

Dm value was considered for further analysis. Test-retest reliabilities for TMG measures, using the intraclass correlation coefficient (ICC) with 95% confidence intervals (CIs) and coefficient of variation (CV) values, were as follows: Dm (ICC [95% CI]: 0.98 [0.96–0.99], CV: 5.3%); Tc (ICC [95% CI]: 0.98 [0.95–0.99], CV: 3.2%); Td (ICC [95% CI]: 0.95 [0.89–0.98], CV: 2.3%); Vd (ICC [95% CI]: 0.98 [0.97–0.99], CV: 4.6%), V10 (ICC [95% CI]: 0.97 [0.95–0.99], CV: 5.3%), and V90 (ICC [95% CI]: 0.98 [0.97–0.99], CV: 4.6%).

Metabolic Variables. After cleaning the skin, 5 and 20 μL of capillary blood from fingertip punctures were used for lactate and ammonia quantification, respectively. Lactate was measured using a portable lactate analyzer (Lactate Pro 2, Arkray, Kyoto, Japan), and ammonia was analyzed using an ammonia checker (Blood Ammonia Meter PocketChem, model BA PA-4140; Arkray, Kyoto, Japan). Both devices were calibrated before each exercise session according to the manufacturer's specifications.

Countermovement Jump. An infrared timing system (OptojumpNext, Microgate, Bolzano, Italy) was used for determining jump height. The CMJ was performed with both hands on the waist while performing a downward movement to about 90° of knee flexion, followed by a maximal vertical jump. All subjects were instructed to land in an upright position and to bend the knees after landing. The subjects were required to do 2 trials separated by 10 seconds, and the mean height was determined. A specific warm-up was performed, consisting of 5 minutes of jogging at a self-selected easy pace, 2 sets of 10 squats without external load, 5 submaximal CMJs, and 3 maximal CMJs. Test-retest reliability values were ICC (95% CI): 0.99 (0.97–0.99) and CV: 1.9%.

Maximal Voluntary Isometric Contraction Test. Kinetic and EMG data were measured during an MVIC in the SQ exercise with the subjects standing with their knees flexed at 90° (180° = full extension) measured with a handheld goniometer. This test was performed on a Smith machine instrumented with 2 telescopic bar holders, with a precision scale placed at the left and right sides of the Smith machine to precisely replicate the individual positions between trials. The subjects were instructed to maintain a constant minimum pretension until the experimenter gave the following verbal instruction: "Push against the ground as hard and as fast as possible" (34). Two 5 seconds trials, separated by 30 seconds rest, were performed. The warm-up protocol consisted of 2 attempts at 70 and 90% of perceived effort with 30 seconds rest between them.

Kinetic Data. External forces were collected at a sampling rate of 1,000 Hz with an 80 × 80-cm dynamometric platform (FP-500; Ergotech) and processed with specific software (T-Force System; Ergotech). Maximal isometric force was defined as the maximal strength value attained during the MVIC. RFDmax was calculated as the maximal slope of the force-time curve measured in 20-ms time intervals. The average value of each variable in the 2 attempts was recorded for further analysis. Test-retest reliability values for MIF and RFDmax were as follows: ICC (95%CI): 0.99 (0.97; 0.99) and 0.94 (0.86; 0.97) and CV: 3.4 and 13.8%, respectively.

Electromyography Signal Acquisition. Surface EMG electrodes were placed on the same location previously described for TMG measurements. Electromyography signals were recorded continuously during MVIC testing using a parallel-bar, bipolar surface electromyographic sensor Trigno wireless EMG system, with an interelectrode distance of 10 mm, common mode rejection ratio >80 dB, and bandwidth filter between 20 and 450Hz ± 10% (Delsys, Inc., Natick, MA). Baseline noise was <5 μV peak to peak, and sampling rate was 2,000 Hz. The raw data from the EMG were stored in digital format using EMGworks Acquisition software (Delsys, Inc.). From each isometric and dynamic contraction the highest averaged (over sliding windows of 500 ms with an overlap of 499 ms) RMS and MDF values for each muscle were recorded. V_{ME} and V_{LA} muscle excitation values were averaged, and the average of the 2 MVICs was calculated for further analysis. The value of the signal from MVIC at pretraining of each resistance exercise protocol was used to normalize the EMG parameters. The test-retest reliability for RMS measures was ICC (95% CI): 0.95 (0.90–0.98) and CV: 7.4% and for MDF was ICC (95% CI): 0.95 (0.90–0.98) and CV: 5.3%.

Statistical Analyses

Values are reported as mean ± *SD*. Sample size was calculated (using GPower version 3.1.9.4) introducing the following parameters: effect size (ES) 0.85 and 0.70 for mean velocity and mean power between-protocol comparisons based on a recent meta-analysis comparing different RT set configurations (20) and α error probability (0.05) and power (0.95), which resulted in a sample size of 6 and 14 subjects, respectively. Statistical significance was established at $p \leq 0.05$. Thetest-retest absolute reliability was measured by the *SEM*, which was expressed in relative terms through CV. The *SEM* was calculated as the root mean square of the total mean square intrasubject. The relative reliability was assessed using the ICC calculated with the one-way random-effects model and its 95% CI. A paired sample *t*-test was conducted to compare the average values attained during each protocol (averaged 24 repetitions). A 2 (protocol) × 24 (repetitions) repeated measures analysis of variance (ANOVA) with Bonferroni's post hoc adjustments was performed to compare differences between protocols throughout the repetitions completed. In addition, a 2 (protocol) × 2 (Pre vs. Post) repeated measures ANOVA with Bonferroni's post hoc comparisons was performed to analyze the acute response to each protocol. In addition, pre-post ES values were calculated using Hedge's *g* on the pooled *SD* (13) using a purpose-built spreadsheet. The rest of statistical analyses were performed

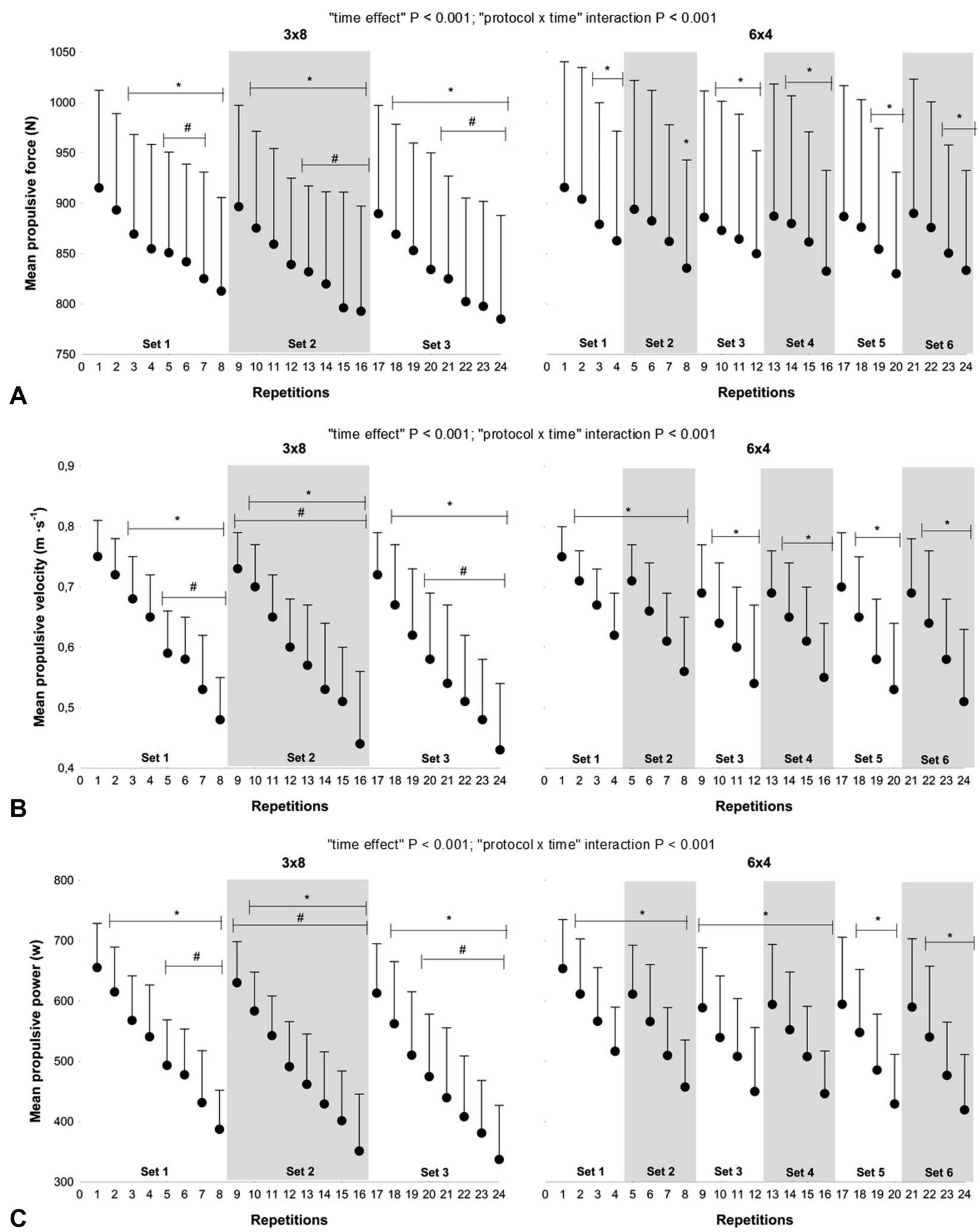

Figure 2. Evolution of mechanical performance throughout the 24 repetitions for both protocols. A) Mean propulsive force; B) mean propulsive velocity; and C) mean propulsive power. Data are mean ± *SD*, *n* = 16.3 × 8: protocol consisted of performing 3 sets of 8 repetitions with 75% of 1RM; 6 × 4: protocol consisted of performing 6 sets of 4 repetitions with 75% of 1RM. Within-protocol significant differences with respect to the first repetition: *$p < 0.05$. Significant differences between protocols at the corresponding repetition: #$p < 0.05$.

using SPSS software version 20.0 (SPSS, Inc., Chicago, IL). Figures were designed using SigmaPlot 12.0 (Systat Software, Inc., San Jose, CA).

Results

Descriptive Characteristics of the Resistance Exercise Protocol

Table 1 shows the mechanical and neuromuscular characteristics of each protocol. Higher MPF, MPV, and MPP values were obtained for the 6 × 4 configuration compared with 3 × 8. In addition, the 3 × 8 protocol exhibited significantly higher RMS during the session than the 6 × 4 protocol, with no significant differences for MDF. Figure 2 shows the evolution of mechanical parameters throughout the 24 repetitions for each resistance exercise protocol. Significant "protocol × repetitions" interactions ($p < 0.001$) were observed for all mechanical variables. Performance in these variables progressively decreased throughout the 24 repetitions for both protocols. However, performance in these parameters (i.e., MPF, MPV, and MPP) was higher for the 6 × 4 protocol compared with the 3 × 8

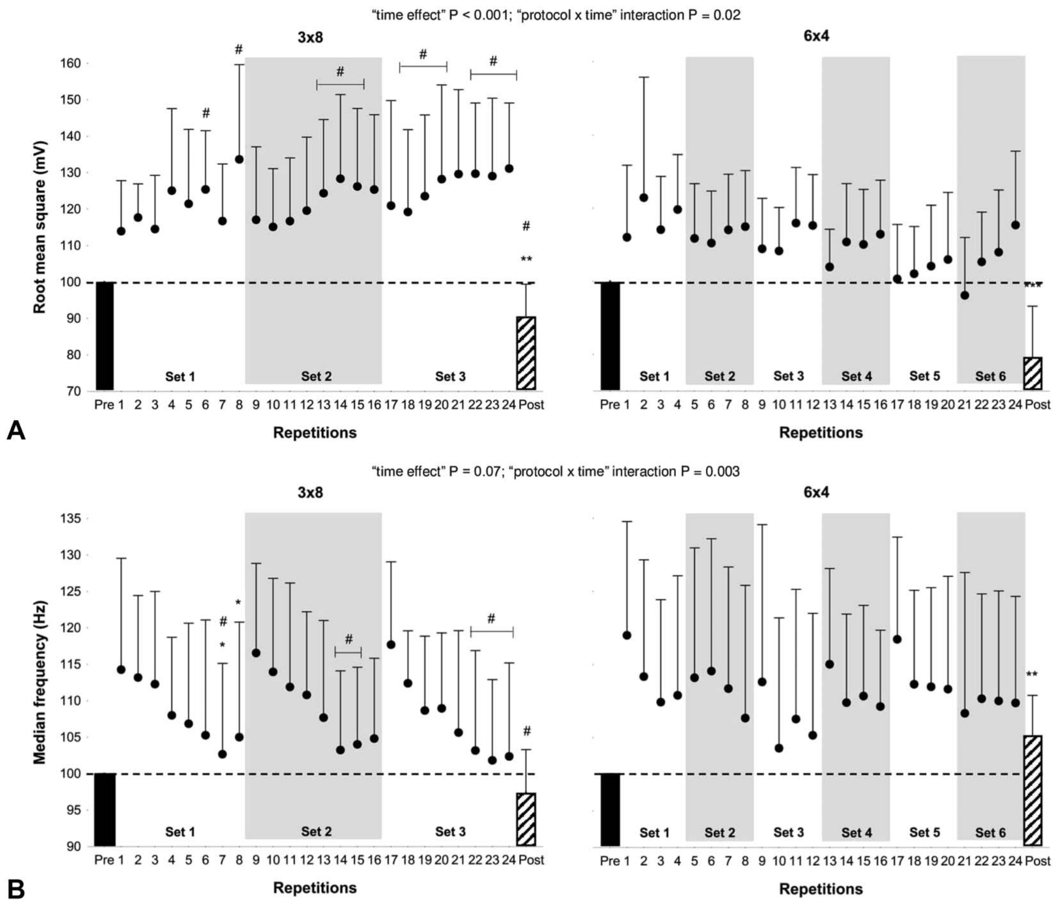

Figure 3. Evolution of neuromuscular parameters throughout the 24 repetitions for both protocols. A) Root mean square averaged from the vastus medialis and vastus lateralis muscles; and B) median frequency averaged from the vastus medialis and vastus lateralis muscles. Data are mean ± *SD*, *n* = 16.3 × 8: protocol consisted of performing 3 sets of 8 repetitions with 75% of 1RM; 6 × 4 = protocol consisted of performing 6 sets of 4 repetitions with 75% of 1RM. Data were normalized with respect to the first repetition of each resistance exercise protocol. Within-protocol significant differences with respect to the first repetition: *$p < 0.05$. Significant differences between protocols at the corresponding repetition: #$p < 0.05$.

protocol. Figure 3 depicts the development of neuromuscular variables throughout the 24 repetitions for each resistance exercise protocol. Significant "protocol × repetitions" interactions were observed for RMS ($p = 0.001$) and for MDF ($p = 0.002$). The 3 × 8 configuration resulted in higher RMS and lower MDF values than the 6 × 4 protocol, particularly for the final repetitions of each set.

Tensiomyography

No significant "protocol × time" interactions were found for TMG-derived parameters (Table 2). A significant "time effect" was observed for all variables, except for V_{LA}-Tc and V_{ME}-Td, with significant decreases in Dm and Vd (in both muscles) and V_{LA}-Td for both protocols at Post. However, the 3 × 8 protocol showed significantly lower values of V_{LA}-Vd, V_{LA}-V10, and V_{LA}-V90 than the 6 × 4 protocol at Post.

Metabolic Response and Jump Performance

Significant "protocol × time" interactions were observed for CMJ height and blood lactate and ammonia values (Table 3). The 3 × 8 protocol induced higher lactate and ammonia concentrations and CMJ height impairments than the 6 × 4 protocol at Post.

Mechanical and Neuromuscular Response during Maximal Voluntary Isometric Contraction

Significant "protocol × time" interactions were noted for neuromuscular parameters (i.e., RMS: $p = 0.02$ and MDF: $p = 0.002$) (Figure 3). However, no "protocol × time" interactions were noted for mechanical outcomes (i.e., MIF and RFDmax) (Table 3). The RMS attained during MVIC decreased for both protocols at Post, although lower values were observed for the 6 × 4 protocol. However, the 6 × 4 protocol induced significant increases in MDF at Post while the 3 × 8 protocol exhibited significantly lower MDF than the 6 × 4 protocol. Moreover, both MIF and RFDmax significantly decreased at Post, with no significant differences between protocols.

Discussion

Integral responses to different set configurations were examined during (mechanical and neuromuscular features) and after exercise (mechanical, neuromuscular, metabolic, and muscle contractile

Table 2

Effects of different resistance exercise protocols on muscles' contractile properties assessed by tensiomyography.*†

	3 × 8			6 × 4				
	Pre	Post	ES	Pre	Post	ES	*p*-value time effect	*p*-value protocol × time
VLA-Tc (ms)	21.80 ± 3.75	22.66 ± 3.57	0.25	21.48 ± 2.84	22.39 ± 3.37	0.26	0.16	0.95
VME-Tc (ms)	21.90 ± 2.83	22.87 ± 3.47	0.32	21.85 ± 2.73	23.04 ± 2.93‡	0.39	0.04	0.63
VLA-Td (ms)	22.82 ± 1.66	21.36 ± 1.84‡	−0.87	22.48 ± 1.64	20.93 ± 1.43§	−0.92	0.004	0.89
VME-Td (ms)	22.00 ± 1.36	22.09 ± 2.17	0.06	21.74 ± 1.14	21.35 ± 1.42	−0.24	0.72	0.41
VLA-Dm (mm)	6.13 ± 1.62	3.77 ± 1.57‖	−1.37	6.05 ± 1.98	4.09 ± 1.58‖	−1.14	<0.001	0.29
VME-Dm (mm)	8.58 ± 1.63	6.61 ± 1.54‖	−1.25	8.35 ± 1.59	6.70 ± 1.45‖	−1.05	<0.001	0.29
VLA-Vd ($mm \cdot ms^{-1}$)	0.138 ± 0.038	0.084 ± 0.029‖,¶	−1.71	0.135 ± 0.040	0.093 ± 0.030‖	−1.42	<0.001	0.10
VME-Vd ($mm \cdot ms^{-1}$)	0.196 ± 0.038	0.149 ± 0.039‖	−1.35	0.193 ± 0.035	0.152 ± 0.034‖	−1.08	<0.001	0.39
VLA-V10 ($mm \cdot ms^{-1}$)	0.027 ± 0.007	0.017 ± 0.006‖,¶	−1.49	0.027 ± 0.008	0.020 ± 0.007‖	−0.91	<0.001	0.12
VME-V10 ($mm \cdot ms^{-1}$)	0.039 ± 0.007	0.030 ± 0.008‖	−1.16	0.038 ± 0.007	0.032 ± 0.007§	−0.83	<0.001	0.38
VLA-V90 ($mm \cdot ms^{-1}$)	0.124 ± 0.033	0.076 ± 0.026‖,¶	−1.57	0.123 ± 0.036	0.084 ± 0.028‖	−1.18	<0.001	0.13
VME-V90 ($mm \cdot ms^{-1}$)	0.177 ± 0.034	0.134 ± 0.035‖	−1.21	0.173 ± 0.031	0.136 ± 0.031‖	−1.16	<0.001	0.38

*3 × 8 = protocol consisted of performing 3 sets of 8 repetitions with 75% of 1RM; 6 × 4 = protocol consisted of performing 6 sets of 4 repetitions with 75% of 1RM; V_{LA} = vastus lateralis muscle; V_{ME} = vastus medialis muscle; Tc = contraction time; Td = delay time; Dm = muscle displacement; Vd = velocity of deformation radial (Dm/(Tc + Td); V90 = velocity of deformation radial to 90% of Dm; V10 = velocity of deformation radial to 10% of Dm; ES = within-protocol effect size from Pre to Post.

†Data are mean ± *SD*, *n* = 16.

‡Intraprotocol significant differences from Pre to Post: $p < 0.05$.

§Intraprotocol significant differences from Pre to Post: $p < 0.01$.

‖Intraprotocol significant differences from Pre to Post: $p < 0.001$.

¶Significant differences between protocols: $p < 0.05$.

properties). The results indicate that redistributing long sets and interset rest periods into shorter but more frequent sets modulates training stimuli. Specifically, shorter set configurations (i.e., 6 × 4) resulted in greater mechanical performance maintenance and concomitant lower neuromuscular markers of fatigue during the exercise compared with longer set configurations (i.e., 3 × 8). Longer set configurations also led to greater metabolic responses, along with greater impairments in jump height and muscle deformation velocity (i.e., Vd, V10, and V90) after exercise. Finally, an overall impairment in isometric force production was observed for both protocols, with no significant differences between them. Therefore, introducing shorter but more frequent interset rests attenuates impairments in mechanical performance, especially in the final repetitions of each set, which may be mediated by lower neuromuscular alterations, reduced metabolic stress, and better maintained muscle contractile properties.

Performance as indicated by mechanical parameters (i.e., force, velocity, and power) progressively decreased throughout the repetitions for both protocols, although shorter but more frequent sets alleviated fatigue-induced impairments in performance during the session. There is compelling evidence that including rest periods between repetitions or clusters of repetitions is an effective strategy to attenuate fatigue and ameliorate loss of mechanical performance during RT sessions (19,20,36). However, the mechanisms underlying this phenomenon have not been clearly established. One of the potential mechanisms associated with the higher acute performance attained using shorter set configurations is that the frequent rest periods may allow for greater maintenance of phosphocreatine (PCr) stores, a partial resynthesis of adenosine triphosphate (ATP), and increased metabolite clearance in the working muscles (9,36). In agreement with previous studies

Table 3

Mechanical, neuromuscular, and metabolic response to the different resistance exercise protocols under study.*†

	3 × 8			6 × 4				
	Pre	Post	ES	Pre	Post	ES	*p* time effect	*p* protocol × time
Metabolic response and jump performance								
Lactate ($mmol \cdot l^{-1}$)	1.7 ± 0.6	12.0 ± 3.8§‖	3.31	1.5 ± 0.7	8.9 ± 4.2§	2.38	<0.001	0.05
Ammonia ($\mu mol \cdot l^{-1}$)	60.5 ± 16.6	103.8 ± 44.9§‖	1.21	65.1 ± 20.4	76.4 ± 44.1	0.31	0.001	0.02
CMJ (cm)	37.3 ± 4.6	27.0 ± 3.8§‖	−2.56	37.5 ± 3.6	29.6 ± 3.4§	−1.96	<0.001	0.02
Maximal voluntary isometric contraction								
MIF (N)	1,267.7 ± 230.9	1,034.5 ± 258.7§	−0.93	1,270.0 ± 279.0	1,017.3 ± 216.8§	−1.01	<0.001	0.62
RFDmax ($N \cdot s^{-1}$)	4,609 ± 1,528	3,998 ± 1431‡	−0.38	5,242 ± 2006	3,924 ± 1224§	−0.82	0.001	0.09

*3 × 8 = protocol consisted of performing 3 sets of 8 repetitions with 75% of 1RM; 6 × 4 = protocol consisted of performing 6 sets of 4 repetitions with 75% of 1RM; Lactate = blood lactate concentration; Ammonia = blood ammonia concentration; CMJ = countermovement jump height; MIF = maximal isometric force; RFDmax = maximal rate of force development; ES = within-protocol effect size from Pre to Post.

†Data are mean ± *SD*, *n* = 16.

‡Intraprotocol significant differences from Pre to Post: $p < 0.01$.

§Intraprotocol significant differences from Pre to Post: $p < 0.001$.

‖Significant differences between protocols at the corresponding time point: $p < 0.05$.

(10,26), the longer set configuration (i.e., 3 × 8) induced higher blood ammonia levels. An increase in blood ammonia concentrations during high-intensity exercise is interpreted as indicative of accelerated ammonia production by muscles, resulting from the deamination of adenosine monophosphate to inosine monophosphate (14). In this regard, Gorostiaga et al. (9) observed greater depletion of intramuscular ATP and PCr stores after 5 × 10 vs. 10 × 5 with 85% 1RM with 2 minutes interset rests in the leg press exercise, along with concomitant greater power reductions. Likewise, the higher lactate values observed for the longer set configuration suggest a greater reliance on anaerobic glycolysis for energy for these set structures (19,27). Accordingly, the lower blood ammonia and lactate concentrations observed after the shorter set configurations (i.e., 6 × 4) may indicate better replenishment of ATP and PCr stores, as well as reduced glycolytic requirements within each set, which may result in a greater ability to maintain mechanical performance.

In an attempt to provide a better understanding of the mechanisms behind the different performances achieved with longer and shorter set configurations, we recorded the EMG activity attained in each repetition. Our data suggest that longer set configurations induced higher neuromuscular fatigue (i.e., higher RMS and lower MDF values) during isometric (i.e., MVIC) and dynamic contractions, mainly during the final repetitions in each set (Figure 3). In agreement with our findings, Ortega-Becerra et al. (28) reported higher RMS and higher MDF values during traditional sets (3 sets of 12 repetitions at 60% of 1RM with interset rests of 2 minutes) in the bench press exercise compared with protocols using similar training intensities and volume but including cluster configurations (30-second rest every 4 or 2 repetitions). Fatigue-induced alterations in neuromuscular markers have been attributed to metabolic byproduct accumulation (18). Specifically, increased RMS values may be primarily due to increased muscle activation (i.e., recruitment of higher-threshold motor units, motor unit firing frequency, or changes in intrinsic muscle properties) attempting to compensate for the loss of force in the fatigued state (1,18), whereas decreased MDF values may be evoked by reduced action potential conduction velocity associated with a decline in intramuscular pH (2), changes in action potential shape (15), and decreases in the firing rate of fatigued fast motor units (1). In this regard, it is fair to assume that interpretation of mechanistic information from EMG data is speculative. Nevertheless, our data suggest that from a neuromuscular standpoint, shorter set configurations also contribute to reduced fatigue development, which may be due to lower metabolic byproduct accumulation.

Besides the effects of set configuration on exercise performance itself, it is also important to consider the residual mechanical fatigue induced by these training sessions. In line with the fatigue levels observed during the training session, greater reductions in CMJ height were observed after the longer set configuration. Previous studies have also shown smaller CMJ height losses after training sessions with intraset rest periods compared with traditional structures (8,24). However, the exercise-induced fatigue on isometric strength (i.e., MIF and RFDmax) and several TMG-derived parameters (i.e., Dm, Tc, and Td) was similar for both set configurations. Decreases in Dm after RT have been associated with impaired muscle function (17), muscle swelling, and exercise-induced muscle damage (11), whereas it has been suggested that temporal TMG parameters should be treated with caution (22). On the other hand, the 3 × 8 protocol induced greater impairments in muscle velocity of deformation (i.e., Vd, V10, and V90) than the 6 × 4 protocol (Table 2). The only study that has previously examined the acute effects of different set configurations (4 × 10 with 95 seconds of interset rest vs. 20 × 2 with 15 seconds interset rest) on TMG outcomes did not observe significant differences in TMG parameters during postexercise measurements, although the ES values indicated a lower impaired muscle function for shorter set configurations (38). Therefore, longer set configurations induced greater impairments in neuromuscular ability and muscle function in both voluntary (i.e., squats and jumps) and involuntary (i.e., TMG) actions.

Despite using similar loads (75% 1RM), total volume (24 repetitions), total rest (10 minutes), and, therefore, training density (work-to-rest ratio), implementing shorter but more frequent interset rest intervals allowed for better maintenance of performance, especially in the final repetitions of each set, along with lower alterations of neuromuscular markers of fatigue, a dampened metabolic stress, and a lesser worsening of muscle velocity of deformation. Therefore, rest-redistribution may be a viable strategy for maintaining performance during a training session, which may be mediated by lower neuromuscular alterations, reduced metabolic stress, and better maintenance of muscle contractile properties.

Practical Applications

This study provides a greater insight for sport professionals about the integral responses (mechanical, neuromuscular, and metabolic) to different set configurations, which may allow us to optimize the design of RT programs aimed at enhancing physical performance. Coaches can implement shorter but more frequent rest intervals to spare mechanical performance and alleviate neuromuscular fatigue, whereas longer set configurations could be used to increase metabolic stress. Therefore, a given set configuration could be chosen beforehand, depending on the specific training goal being pursued. Further studies should analyze the long-term effects of different configurations on mechanical, neuromuscular, and hypertrophic adaptations.

References

1. Bigland-Ritchie BR, Dawson NJ, Johansson RS, Lippold OC. Reflex origin for the slowing of motoneurone firing rates in fatigue of human voluntary contractions. *J Physiol* 379: 451–459, 1986.
2. Brody LR, Pollock MT, Roy SH, De Luca CJ, Celli B. pH-induced effects on median frequency and conduction velocity of the myoelectric signal. *J Appl Physiol* 71: 1878–1885, 1991.
3. Cairns SP, Knicker AJ, Thompson MW, Sjogaard G. Evaluation of models used to study neuromuscular fatigue. *Exerc Sport Sci Rev* 33: 9–16, 2005.
4. de Paula Simola RA, Harms N, Raeder C, et al. Assessment of neuromuscular function after different strength training protocols using tensiomyography. *J Strength Cond Res* 29: 1339–1348, 2015.
5. Enoka RM, Duchateau J. Translating fatigue to human performance. *Med Sci Sports Exerc* 48: 2228–2238, 2016.
6. Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG: An update. *J Appl Physiol* 117: 1215–1230, 2014.
7. Garcia-Ramos A, Gonzalez-Hernandez JM, Banos-Pelegrin E, et al. Mechanical and metabolic responses to traditional and cluster set configurations in the bench press exercise. *J Strength Cond Res* 34: 663–670, 2020.
8. Gonzalez-Hernandez JM, Garcia-Ramos A, Castano-Zambudio A, et al. Metabolic, and perceptual acute responses to different set configurations in full squat. *J Strength Cond Res* 34: 1581–1590, 2020.
9. Gorostiaga EM, Navarro-Amezqueta I, Calbet JA, et al. Energy metabolism during repeated sets of leg press exercise leading to failure or not. *PLoS One* 7: e40621, 2012.

10. Gorostiaga EM, Navarro-Amezqueta I, Calbet JA, et al. Blood ammonia and lactate as markers of muscle metabolites during leg press exercise. *J Strength Cond Res* 28: 2775–2785, 2014.
11. Harmsen JF, Franz A, Mayer C, et al. Tensiomyography parameters and serum biomarkers after eccentric exercise of the elbow flexors. *Eur J Appl Physiol* 119: 455–464, 2019.
12. Hartmann H, Wirth K, Klusemann M. Analysis of the load on the knee joint and vertebral column with changes in squatting depth and weight load. *Sports Med* 43: 993–1008, 2013.
13. Hedges LV, Olkin I. Estimation of a single effect size: Parametric and nonparametric method. In: *Statistical Methods for Meta-Analysis*. San Diego, CA: Academic Press, 1985. pp. 76–108.
14. Hellsten-Westing Y, Norman B, Balsom PD, Sjodin B. Decreased resting levels of adenine nucleotides in human skeletal muscle after high-intensity training. *J Appl Physiol* 74: 2523–2528, 1993.
15. Hermens HJ, Bruggen TA, Baten CT, Rutten WL, Boom HB. The median frequency of the surface EMG power spectrum in relation to motor unit firing and action potential properties. *J Electromyogr Kinesiol* 2: 15–25, 1992.
16. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* 10: 361–374, 2000.
17. Hunter AM, Galloway SD, Smith IJ, et al. Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography. *J Electromyogr Kinesiol* 22: 334–341, 2012.
18. Hunter SK, Duchateau J, Enoka RM. Muscle fatigue and the mechanisms of task failure. *Exerc Sport Sci Rev* 32: 44–49, 2004.
19. Jukic I, Ramos AG, Helms ER, McGuigan MR, Tufano JJ. Acute effects of cluster and rest redistribution set structures on mechanical, metabolic, and perceptual fatigue during and after resistance training: A systematic review and meta-analysis. *Sports Med* 50: 2209–2236, 2020.
20. Latella C, Teo WP, Drinkwater EJ, Kendall K, Haff GG. The acute neuromuscular responses to cluster set resistance training: A systematic review and meta-analysis. *Sports Med* 49: 1861–1877, 2019.
21. Loturco I, Pereira LA, Kobal R, et al. Muscle contraction velocity: A suitable Approach to analyze the functional adaptations in elite soccer players. *J Sports Sci Med* 15: 483–491, 2016.
22. Macgregor LJ, Hunter AM, Orizio C, Fairweather MM, Ditroilo M. Assessment of skeletal muscle contractile properties by radial displacement: The case for tensiomyography. *Sports Med* 48: 1607–1620, 2018.
23. Martin-Rodriguez S, Loturco I, Hunter AM, Rodriguez-Ruiz D, Munguia-Izquierdo D. Reliability and measurement error of tensiomyography to assess mechanical muscle function: A systematic review. *J Strength Cond Res* 31: 3524–3536, 2017.
24. Mora-Custodio R, Rodriguez-Rosell D, Yanez-Garcia JM, et al. Effect of different inter-repetition rest intervals across four load intensities on velocity loss and blood lactate concentration during full squat exercise. *J Sports Sci* 36: 2856–2864, 2018.
25. Morales-Artacho AJ, Garcia-Ramos A, Perez-Castilla A, et al. Muscle activation during power-oriented resistance training: Continuous vs. Cluster set configurations. *J Strength Cond Res* 33(Suppl 1): S95–S102, 2019.
26. Moran-Navarro R, Perez CE, Mora-Rodriguez R, et al. Time course of recovery following resistance training leading or not to failure. *Eur J Appl Physiol* 117: 2387–2399, 2017.
27. Oliver JM, Kreutzer A, Jenke S, et al. Acute response to cluster sets in trained and untrained men. *Eur J Appl Physiol* 115: 2383–2393, 2015.
28. Ortega-Becerra M, Sanchez-Moreno M, Pareja-Blanco F. Effects of cluster set configuration on mechanical performance and neuromuscular activity. *J Strength Cond Res* 35: 310–317, 2021.
29. Pareja-Blanco F, Alcazar J, Sanchez-Valdepenas J, et al. Velocity loss as a critical variable determining the adaptations to strength training. *Med Sci Sports Exerc* 52: 1752–1762, 2020.
30. Pareja-Blanco F, Rodriguez-Rosell D, Sanchez-Medina L, et al. Effects of velocity loss during resistance training on athletic performance, strength gains and muscle adaptations. *Scand J Med Sci Sports* 27: 724–735, 2017.
31. Pereira LA, Ramirez-Campillo R, Martin-Rodriguez S, et al. Is tensiomyography-derived velocity of contraction a sensitive marker to detect acute performance changes in elite team-sport athletes? *Int J Sports Physiol Perform* 1–7, 2019. Epub ahead of print.
32. Piqueras-Sanchiz F, Martin-Rodriguez S, Martinez-Aranda LM, et al. Effects of moderate vs. high iso-inertial loads on power, velocity, work and hamstring contractile function after flywheel resistance exercise. *PLoS One* 14: e0211700, 2019.
33. Piqueras-Sanchiz F, Martín-Rodríguez S, Pareja-Blanco F, et al. Mechanomyographic measures of muscle contractile properties are influenced by electrode size and stimulation pulse duration. *Sci Rep* 10: 8192, 2020.
34. Rodriguez-Rosell D, Pareja-Blanco F, Aagaard P, Gonzalez-Badillo JJ. Physiological and methodological aspects of rate of force development assessment in human skeletal muscle. *Clin Physiol Funct Imaging* 38: 743–762, 2018.
35. Sanchez-Medina L, Perez CE, Gonzalez-Badillo JJ. Importance of the propulsive phase in strength assessment. *Int J Sports Med* 31: 123–129, 2010.
36. Tufano JJ, Brown LE, Haff GG. Theoretical and practical aspects of different cluster set structures: A systematic review. *J Strength Cond Res* 31: 848–867, 2017.
37. Tufano JJ, Conlon JA, Nimphius S, et al. Different cluster sets result in similar metabolic, endocrine, and perceptual responses in trained men. *J Strength Cond Res* 33: 346–354, 2019.
38. Tufano JJ, Omcirk D, Malecek J, et al. Traditional sets versus rest-redistribution: A laboratory-controlled study of a specific cluster set configuration at fast and slow velocities. *Appl Physiol Nutr Metab* 45: 421–430, 2020.
39. Valencic V, Knez N. Measuring of skeletal muscles' dynamic properties. *Artif Organs* 21: 240–242, 1997.
40. Valenzuela PL, Montalvo Z, Sánchez-Martínez G, et al. Relationship between skeletal muscle contractile properties and power production capacity in female Olympic rugby players. *Eur J Sport Sci* 18: 677–684, 2018.