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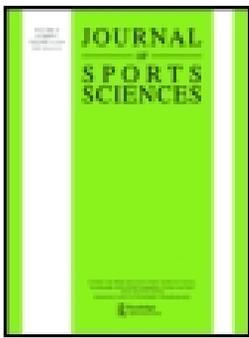


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Inter-repetition rest training and traditional set configuration produce similar strength gains without cortical adaptations

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ABSTRACT

This study compared the functional and neural effects of two strength training programmes differing in set configuration. Thirteen participants performed 10 sessions, over a period of 5 weeks, of unilateral leg extensions with different set configurations but with identical work-to-rest ratios for each limb: a traditional configuration (4 sets of 8 repetitions, 10RM load, 3-min pause between sets) and an inter-repetition rest configuration (32 repetitions, 10RM load, 17.4 s of rest between each repetition). Mean propulsive velocity of the traditional sessions was lower than for inter-repetition rest sessions (0.48 ± 0.06 vs. 0.54 ± 0.06 m · s⁻¹; $P < 0.001$), while perceived exertion was higher (8.3 ± 0.9 and 6.56 ± 1.6 for traditional training and IRT; $P = 0.002$). One repetition maximum (RM), work with 10RM load, maximum mean propulsive power, maximum voluntary contraction and time to failure with 50% of maximum isometric force improved similarly in both legs (time effect, $P < 0.001$; effect size range, 0.451–1.190). Time and set configuration did not show significant main effects or interactions for cortical adaptations (motor-evoked potentials, short-interval intracortical inhibition, intracortical facilitation). There were no significant correlations between changes in cortical and peripheral neural adaptations and strength improvement. In conclusion, inter-repetition rest configuration was as effective as traditional training in improving muscle performance.

ARTICLE HISTORY

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KEYWORDS

Resistance training; cluster training; cortical adaptations; peripheral adaptations; voluntary activation

Introduction

Changes in muscle function after a strength training programme are fundamentally underpinned by neural and morphological adaptations (Folland & Williams, 2007). These adaptations are the result of many different factors such as mechanical, metabolic, endocrine and neural changes which are affected by several training variables (Crewther, Cronin, & Keogh, 2005; Goto, Ishii, Kizuka, & Takamatsu, 2005). Thus, acute and chronic adaptations to resistance training can be modulated by many training components, such as the lifted load, volume (sets × repetition), frequency of training, velocity of contraction, work-to-rest ratio and duration of muscle tension. In addition to these variables, resistance training adaptation may also be modulated by the set configuration, which can be defined as the number of repetitions performed in each set with respect to the maximum possible number of repetitions. Traditional set configuration entails performing repetitions in a continuous manner, near to muscular failure. Alternatively, shorter set configurations manipulate work and rest periods by breaking sets into small clusters of repetitions. This type of training has been termed cluster training, inter-repetition rest training or intra-set rest loading (Haff et al., 2008; Lawton, Cronin, Drinkwater, Lindsell, & Pyne, 2004). Previous studies have shown that a shorter set configuration (i.e. not leading

to failure) reduces the acute metabolic (Sanchez-Medina & Gonzalez-Badillo, 2011) and cardiovascular responses (Iglesias-Soler et al., 2014) and improves the mechanical performance of the resistance exercise (Haff et al., 2003; Iglesias-Soler et al., 2012) in comparison with longer set configurations (i.e. leading or close to failure).

However, some controversy exists regarding the efficacy of resistance training that does not lead to muscular failure, for the improvement of muscle strength. Several studies have suggested that training to failure is more effective since metabolic stimulus is necessary to optimise strength gains (Goto et al., 2005; Rooney, Herbert, & Balnave, 1994), whereas others show that failure is not required in order to improve muscular performance (Folland, Irish, Roberts, Tarr, & Jones, 2002; Izquierdo et al., 2006). In addition, studies of the chronic effects of set configurations have also led to contradictory results, showing either smaller (Hansen, Cronin, Pickering, & Newton, 2011; Lawton et al., 2004) or larger (Oliver et al., 2013) increases in muscular performance for the intra-set compared with the traditional configuration (Hansen et al., 2011; Lawton et al., 2004). Differences between protocols, specifically in those factors that are associated with the work-to-rest ratio, may account for these discrepancies. Another possible explanation for the discrepant findings may be the high inter-participant variability responses (Folland et al., 2002; Lawton et al., 2004)

that may have influenced the comparisons across groups. One methodological strategy for reducing inter-participant variability effect is the unilateral model approach whereby each individual serves as their own comparison since opposite segments use different training conditions (Burd et al., 2010). This approach enables the comparison of different factors with high internal validity (Folland et al., 2002), minimising the variability associated with biological parameters that may affect the training outcomes (Alegre et al., 2015). To our knowledge, no previous studies have used this approach to analyse the effect of set configuration on neuromuscular adaptations.

The main objective of the current study was to compare functional and neural effects of two short strength training programmes differing in set configuration. Since set configuration affects the metabolic response and the mechanical performance (Haff et al., 2003; Iglesias-Soler et al., 2012; Sanchez-Medina & Gonzalez-Badillo, 2011), we hypothesised a higher impact of inter-repetition rest training on strength and power gains while a traditional set configuration should be more effective for muscular endurance performance. Additionally we expected a more favourable change in cortical and peripheral neural changes when training with traditional set configuration since it has been suggested that a protocol with greater metabolic stress could entail an increase in motor unit recruitment (Goto et al., 2005).

Methods

Participants

The sample for this study was made up of 13 sports sciences students (6 females and 7 males; age,

22.5 ± 2.6 years; height, 172.8 ± 7.4 cm; body mass, 66.9 ± 9.1 kg; body mass index (BMI), 22.3 ± 2.0 kg · m⁻²) with at least 6 months of experience in resistance training. Participants were instructed about the experimental design and informed consent was obtained from all individual participants included in the experiment. This study was approved by the institutional ethics committee.

Study design

Participants visited the laboratory on 19 occasions separated by at least 48 h. The first and second sessions were conducted to familiarise the participants with the exercise, the perceived exertion scale (i.e. OMNI-RES) and the neurophysiological evaluation protocol. In the third session, a one-repetition-maximum load (1RM) of a unilateral knee extension exercise was performed by each leg and anthropometric measurements were obtained. In sessions 4 and 5, the load corresponding to 10RM and their reliability within each leg was evaluated. In session 6, a neurophysiological evaluation was conducted. One week later, the participants started the training protocols for a total duration of 5 weeks with a frequency of two sessions per week (i.e. 10 training sessions). Procedures corresponding to sessions 3 and 6 were repeated after training of sessions 17 and 19, respectively. Visit number 18 consisted of performing the maximum number of repetitions with 10RM load as evaluated in session 5, in order to quantify the improvement in muscular endurance for an absolute load. A schematic representation of the experimental design is illustrated in Figure 1.

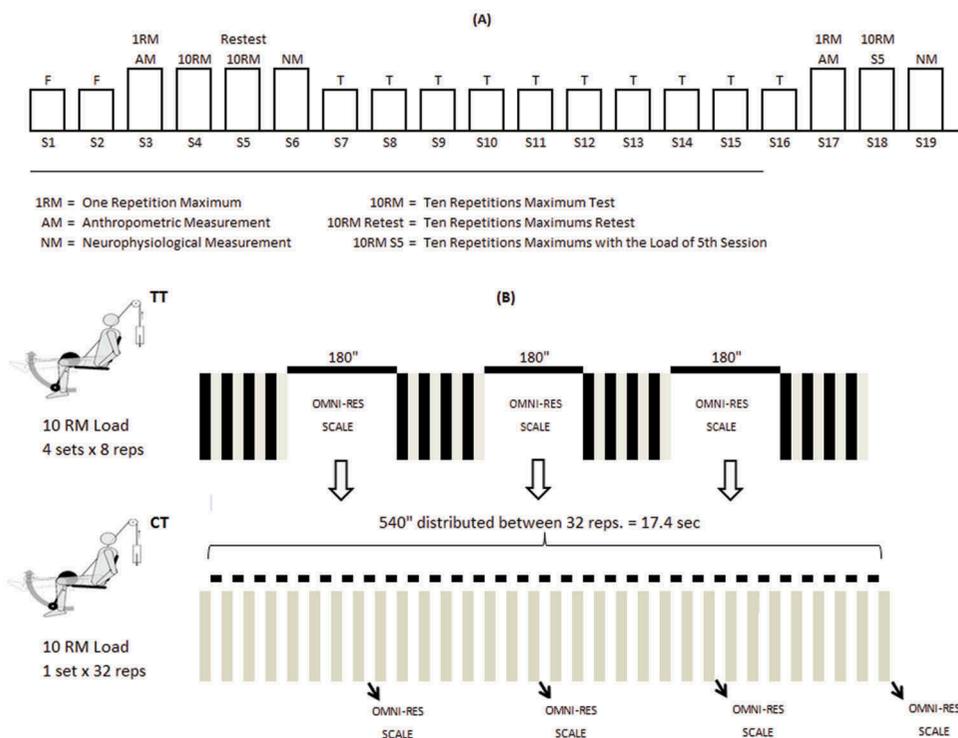


Figure 1. Schematic representation of the experimental design (A) and sessions (B).

Procedures

Familiarisation sessions

Two orientation sessions were performed by each participant in order to familiarise participants with the exercise technique, perform a neurophysiological assessment, anchor the OMNI-RES perceived exertion scale and evaluate the angular positions of the unilateral knee extension exercise. The exercise was performed in a leg extension device (Technogym, Gambettola, Italy), with hip and knee angle set at 90°. The padded lever arm was individually adjusted at a comfortable length, approximately at the level of media malleolus. Knees were placed at the point of the axis of rotation of the machine. These adjustments were recorded and maintained throughout the experiment.

Both sessions started with a standardised warm-up consisting of 5 min of cycling at 80 revolutions per min on a bicycle ergometer (Monark 828E; Monark Exercise AB, Vansbro, Sweden) with resistance fixed at 1.25 W per kilogram of body mass. Thereafter, participants completed 4 sets of 10 repetitions of knee extensions with each leg. Load was adjusted to be near fatigue at the last repetition of the last set. Participants were instructed to maintain their hips in contact with the seat throughout the movement, using the handholds of the leg extension machine.

At the end of every session, participants were familiarised with procedures for the neurophysiological evaluation.

Anthropometric assessment

Height and body mass were measured with a stadiometer and a calibrated digital scale (Omron BF-508, Omron Healthcare Co., Kyoto, Japan) and were recorded to the nearest 0.1 cm and 0.1 kg, respectively. BMI was calculated as body mass in kilogram divided by height in meters squared ($\text{kg} \cdot \text{m}^{-2}$) and rounded to the nearest 0.1 $\text{kg} \cdot \text{m}^{-2}$.

Skinfolds measurements were obtained for each participant by the same trained technician using a calibrated skinfold calliper (Holtain LTD., Crymich, UK). Skinfolds were measured from the seven main sites such as triceps, pectoralis major, subscapularis, mid-axillary line, abdomen, suprailiac and thigh (mid-point). The sum total of all seven sites was calculated.

In addition, thigh girth was measured at mid-point of both legs. The mid-point was defined as the central point between the protuberance of the anterior iliac crest and the upper zone of the patella. The distance from the patella to the measurement point was recorded and used for the evaluation after the training. Thigh circumferences were recorded to the nearest 0.1 cm and corrected for subcutaneous adipose tissue by subtracting pi times the thigh skinfold in centimetre [i.e. Corrected girth = thigh girth - ($\pi \times$ thigh skinfold)].

1RM test

The load for 1RM was obtained using a protocol that combines velocity decrement with increase of load. After the previously described standardised warm-up, each leg was evaluated in a randomised order. The protocol started with the participants performing three knee extension repetitions with 2.5 kg, the repetition with highest velocity was set as reference velocity. After a 1-min rest, a second

trial of three repetitions was performed with a load increment of 10 kg. This procedure was repeated until mean propulsive velocity decreased by 25% compared with the best repetition corresponding to the first load. Mean propulsive velocity was defined as mean velocity during the propulsive phase. The propulsive phase was defined as that portion of the concentric period during which barbell acceleration (a) is greater than acceleration due to gravity (i.e. $a > -9.81 \text{ m} \cdot \text{s}^{-2}$) (Sanchez-Medina & Gonzalez-Badillo, 2011).

Thereafter, successive sets of two repetitions with 2-min rest interval were executed with load increments of 5 kg until mean propulsive velocity decreased by 50% of reference velocity. At this point, load increments were limited to 1–2.5 kg and only one repetition was required in each trial, with a 3-min rest interval. This procedure was repeated until the participant was not able to complete at least 80° of knee extension. 1RM was defined as the maximum load properly lifted. After a 5-min period of rest, the procedure was repeated for the remaining leg. This protocol has been reported to provide a highly reliable evaluation of the 1RM (Iglesias-Soler et al., 2012).

To monitor the mean propulsive velocity during the concentric phase of each repetition, a dynamic measurement device (T-Force System, Ergotech, Murcia, Spain) was employed. This system consists of a linear velocity transducer interfaced to a personal computer by means of a 14-bit resolution analogue-to-digital data acquisition board and custom software. Instantaneous velocity was sampled at a frequency of 1000 Hz and subsequently smoothed with a fourth order low-pass Butterworth filter with a cut-off frequency of 10 Hz. A digital filter with no phase shift was then applied to the data. Validity and reliability of this device have been previously reported (Sanchez-Medina & Gonzalez-Badillo, 2011). Briefly, the mean relative error in the velocity measurements was found to be lower than 0.25%, whereas displacement was accurate to ± 0.5 mm. In addition, an intra-class correlation coefficient for mean propulsive velocity between devices was 1.00 (95% CI = 1.00–1.00) and the coefficient of variation was 0.57%. The linear velocity transducer was attached to the load of the knee extensor machine.

Participants were instructed to perform each repetition *as fast as possible* and were strongly encouraged during the test. For each repetition participants had to start each movement with the load at a downward position to allow for a correct analysis of the concentric phase.

10RM load evaluation

After a general warm-up on a on a bicycle ergometer, each leg was evaluated in a randomised order. The testing protocol started with a specific warm-up consisting of 10 knee extension repetitions with the load equivalent to 50% of 1RM. After a 5-min pause, first attempt to determine 10RM was performed with a load of approximately 70% of 1RM. 10 RM was defined as the load that a participant was able to properly lift 10 times but not 11. If a participant could correctly complete 11 repetitions, a new attempt with an increment of 1–2.5 kg was performed 5 min later. If a participant could not properly complete 10 repetitions, new attempts were

performed with a lower load of 1–2.5 kg. The procedure was repeated for the other leg after a 5-min rest period.

Isometric tests

Maximal voluntary contraction. Participants were seated in a modified leg extension machine (BF100, Biotech Bioiso, Brazil) with the hips and legs flexed 90° and firmly strapped to the lever arm of the machine. The malleolus of the ankle was positioned below the lever arm and participants were allowed to use their hands to grasp the hand-holders in order to avoid the hip and trunk movement. Participants were asked to perform with each leg a maximal voluntary contraction (MVC) “as fast and as forcefully as possible” and maintain it for 4 s. In the case that the attempt was not maximal, another trial was performed 3 min later. Data were recorded using a force cell (sensitivity: 2 mV/V and 0.0028 V/N; NL63-200, Digitimer Ltd, Welwyn Garden City, UK) that was attached to the leg extension machine, at a sample frequency of 5000 Hz and filtered with a bandwidth frequency ranging from 10 Hz to 1 kHz (gain = 1000).

Time to task failure. The participants were asked to exert 50% of their initial MVC with each leg until failure, in order to determine their muscular endurance. The participants were strongly encouraged with visual feedback displayed on a screen. The test was completed when the participants could no longer maintain the target force (50% MVC).

Rate of force development. Contractile rate of force development (RFD) was evaluated using the MVC tests. RFD was calculated as the average slope of the force–time ($\Delta\text{force}/\Delta\text{time}$) curve over time intervals of 0–50, 50–100, 100–150 ms, and relative to the onset of contraction. The onset of contraction was defined as the time point on the force–time curve that exceeded the baseline force by 15 N.

Central, peripheral and cortical assessment

Twitch interpolation. A twitch interpolation technique was applied to the knee muscle extensors. During an MVC, a superimposing supramaximal electrical stimulus was delivered to the femoral nerve, followed by a second electrical stimulus 1.5 s after the end of the MVC.

Electromyographic recordings. Electromyographic signals were recorded using bipolar self-adhesive Ag/AgCl electrodes of 10-mm diameter (F9079P, FIAB, Vicchio, Italy) in bipolar configuration of the rectus femoris, vastus lateralis, vastus medialis and biceps femoris following the SENIAM recommendations (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000), with an inter-electrode distance of 25 mm and the reference electrode on the patella. The skin was shaved, abraded and cleaned with isopropyl alcohol, before placing the electrodes, in order to obtain low impedance (Z , 5 k Ω). The position of the electrodes was marked on the skin to guarantee that the same position was used in the next session. Electromyographic signals were amplified, filtered with a bandwidth frequency ranging from 10 Hz to 1 kHz (gain = 1000) and simultaneously digitised with the torque signal using an acquisition card at a sampling rate of 5 kHz

per channel (Digitimer D360, Welwyn Garden City, UK) and stored for later analysis on a computer with a custom build Signal script. Force and electromyographic signals were synchronised using a Power 1401 A-D converter and Signal software (Cambridge Electronics Design, Cambridge, UK).

M wave. Electrical stimulation was used to activate the femoral nerve. A ball probe cathode was pressed over the femoral triangle 3–5 cm below the inguinal ligament. The anode, a 130 × 80 mm self-adhesive electrode (Cefar-Compex Scandinavia AB, Sweden), was applied to the gluteal fold. Square-wave pulses with a width of 1 ms at a maximal voltage of 400 V of a constant current stimulator (Digitimer DS7A, Welwyn Garden City, UK) were delivered to the resting muscle. The optimal stimulation intensity for a single stimulus was determined by increasing intensity until the amplitude of the evoked twitch showed no further increase (M_{max}). The intensity used for subsequent stimulation (140–240 mA) was 120% of that which evoked a maximal twitch torque with subsequent M_{max} of the rectus femoris.

Transcranial magnetic stimulation of the motor cortex.

Single transcranial magnetic stimulation (TMS) pulses of 1-ms duration (Magstim BiStim 200², The Magstim Company, Dyfed, UK) were delivered via a concave double-cone coil (diameter, 110 mm; maximum output, 1.4 T). The handle of the TMS coil was positioned over the vertex of the head and held tangential to the skull in an anterior–posterior orientation. The coil was positioned over the left motor cortex and the orientation of the coil was determined by localising the largest motor-evoked potential in the corresponding (i.e. left or right) rectus femoris, with the lowest motor response in the biceps femoris. The optimal stimulation site was marked on with an indelible red marker to ensure reproducibility of the stimulus conditions for each participant throughout the sessions. The resting motor threshold was determined as the minimum stimulus intensity required to elicit a motor-evoked potential in the rectus femoris of at least 50 μV in 3 of 5 consecutive trials. The test stimulus was chosen at an intensity whose peak-to-peak motor-evoked potential amplitude was 0.5–1 mV.

Short-interval intracortical inhibition and intra-cortical facilitation was recorded by a test magnetic stimulus preceded by a subthreshold conditioning stimulus (80% of the resting motor threshold). The inter-stimulus intervals were 3 and 15 ms for short-interval intracortical inhibition and intracortical facilitation, respectively. The protocol consisted in a trial of 45 single and paired-pulses randomly delivered with an interval of 6–9 s between stimuli.

Data analysis

The peak-to-peak amplitude of motor-evoked potential and M_{max} were measured offline. The motor-evoked potential measured from the rectus femoris was normalised to the M_{max} elicited in potentiated muscle. Short interval intracortical inhibition and intracortical facilitation values were expressed as a percentage of the unconditioned test motor-evoked potential amplitude. Root mean square of vastus lateralis electromyography, as representative of knee

extensor group (Babault, Desbrosses, Fabre, Michaut, & Pousson, 2006), was calculated during a 0.5 s window during MVC and normalized to M_{\max} .

Resting twitch properties of the potentiated muscle were studied to provide further insights into muscle contractility and action potential propagation. Peak twitch force, maximal rate of force development and time to peak twitch force of the single twitch were measured using femoral nerve stimulation. Maximal rate of force development of the single twitch was calculated as the maximum value of the first derivative over time of the force–time curve during a single twitch.

Voluntary activation was quantified using twitch interpolation. Briefly, the force produced during a superimposed twitch delivered when the participant attained the peak force during the MVC was compared with the force produced by a single twitch delivered during relaxation ~ 2 s after the MVC: voluntary activation (%) = $[1 - (\text{superimposed twitch} / \text{single twitch})] \times 100$.

Training protocols

For every participant, each leg was randomly assigned to inter-repetition rest or to traditional training. Every session started with a warm-up on a bicycle ergometer as previously described, and the right or the left leg was selected randomly for the first exercise. Thereafter, a specific warm-up was performed, and consisted of 10 repetitions at 50% of the 10RM load. After a 3-min rest the training protocol began. Traditional training consisted of 4 sets of 8 repetitions with 10RM load, and a 3-min pause between sets. Inter-repetition rest training entailed performing 32 individual repetitions with 10RM load and 17.4 s of rest between each repetition. Rest periods were selected in order to maintain the work-to-rest ratio equal between conditions. Participants were instructed to start every repetition with the load completely static, performing the movement in a concentric fashion both in traditional and inter-repetition rest training. The protocol was completed with one leg, and only then performed with the other leg. During every training session, participants were instructed to execute each repetition at maximum possible velocity.

Rating of perceived exertion was recorded, using the OMNI-RES scale, at the end of every set in traditional training and after repetitions number 8, 16, 24 and 32 in inter-repetition rest training, in order to obtain values corresponding to similar accumulated work in both limbs. In the current study only final rating of perceived exertion values (i.e. after the fourth set and after the 32th repetition for traditional and inter-repetition rest training, respectively) will be reported, since at these points the work and total resting time were equated between conditions.

Complementary experiment

A complementary study was conducted in order to evaluate the impact of different set configurations on cross education. Twelve participants participated in this experiment, and were randomly allocated to one of two groups: a traditional training group (1 female and 5 males; age: 23.0 ± 3.5 years; height: 175.3 ± 5.1 cm; body mass:

70.7 ± 7.5 kg; BMI: 22.98 ± 1.81 kg \cdot m⁻²) and an inter-repetition rest training group (2 females and 4 males; age, 21.3 ± 1.9 years; height, 174.6 ± 10.4 cm; body mass, 69.0 ± 8.5 kg; BMI, 22.6 ± 1.0). The sequence in this study was similar to the main experiment, but each group only trained one leg with one type of set configuration. The duration of the study was identical to the main experiment. Only dynamic (1RM, maximum mean propulsive power and total concentric work) and isometric (MVC and time to failure) performance variables were considered for analysis. In order to quantify the magnitude of cross education, per cent of change (i.e. after with respect to before) was obtained for each group and variable.

Statistical analysis

The results are summarised as means \pm standard deviation. The reliability of the 10RM before training in the main experiment was tested using the test–retest standard deviation of differences and the 95% limits of agreement (Nevill, 1996) calculated by the GraphPad Prism software package for Windows (v5.03 GraphPad Prism Software Inc., San Diego, CA). The remainder of the statistical analysis was performed using the SPSS version 15.0 software (SPSS, Inc., Chicago, IL, USA). Normal distribution of variables recorded for the main experiment was tested using Shapiro–Wilk test. If normality assumption was satisfied, the effect of training was tested by a two-way repeated measures ANOVA (time \times set configuration). Post hoc analyses were conducted using paired *t*-tests when a significant interaction was detected. Differences between values before and after training were also evaluated using paired *t*-tests when a variable had only two levels. When data violated the assumption of normality, logarithmic transformation was applied. If after transformation normality could not be assumed, nonparametric test was used. In this case, a nonparametric ANOVA-type statistics (time \times set configuration) was employed by using the nparLD R software package (Noguchi, Gel, Brunner, & Konietzschke, 2012). If a significant interaction was detected, or if a variable had two levels, paired comparison was performed using the *Wilcoxon* signed-rank test. For the complementary experiment, only nonparametric procedures were applied: nonparametric ANOVA-type statistics (time \times group), paired comparison within groups using the *Wilcoxon* signed-rank test and paired comparison between groups using the *Mann–Whitney U*-test.

Additionally, the adaptation to every training protocol was evaluated using standardised mean differences (SMD: Cohen's *d*) for pre–post scores (Cumming, 2012) and their 95% confidence interval (CI). Furthermore, for variables for which normality could not be assumed, training effect size (ES) was reported by Cliff's Delta and its 95% CI calculated using the orddom (ordinal dominance) R software package. Finally, in order to identify the association between changes (% Δ) of neural variables and strength adaptation (i.e. 1RM and MVC), correlations were performed using Pearson's linear correlation coefficient and Spearman's rho, for variables with a normal and non-normal distribution, respectively. Significance level was set at $P \leq 0.05$.

Results

10RM reliability

The mean 10RM loads obtained in the first tests were 43 ± 15 and 44 ± 15 kg for the leg assigned to the inter-repetition rest and to the traditional training, respectively. The mean 10RM values in the second set of tests were 44 ± 15 and 46 ± 17 kg for the limbs assigned to the inter-repetition rest and to the traditional training respectively. The standard deviation of differences was 1.7 and 2.6 kg for the inter-repetition rest training and traditional training leg respectively. The 95% limits of agreement were from -4.6 to 2.0 kg for inter-repetition rest limb, and from -6.6 to 3.4 kg for the traditional training limb.

The 10RM load of the second evaluation, which was used for the training programme, represented 72 ± 8 and $72 \pm 8\%$ of the 1RM, respectively. No differences between the legs were detected neither for absolute ($P = 0.244$) nor for relative loads ($P = 0.727$).

Anthropometry

Changes after the training period were not significant for body mass ($P = 0.162$), BMI ($P = 0.174$) and sum the skinfolds ($P = 0.339$). ANOVA for corrected thigh girth showed a significant effect of time ($P = 0.002$), indicating larger perimeters after training (49.1 ± 4.2 and 49.3 ± 4.4 cm for inter-repetition rest training and traditional training respectively) compared with the perimeter before training (47.7 ± 4.4 and 47.7 ± 4.7 cm for inter-repetition rest training and traditional training respectively). However, the time \times leg interaction was not significant ($P = 0.387$).

Sessions monitoring

A similar total volume load (i.e. kg \times repetitions) was completed in both training programmes (14191 ± 4865 and 14622 ± 5418 kg for inter-repetition rest training and traditional training respectively; $P = 0.244$; ES = 0.084; 95% CI, $-0.056, 0.220$). The average mean propulsive velocity of each repetition throughout the training session was significantly lower ($P < 0.001$; ES = -1.155 ; 95% CI: $(-1.732, -0.560)$) in traditional training (0.48 ± 0.06 m \cdot s $^{-1}$) than in inter-repetition rest training (0.54 ± 0.06 m \cdot s $^{-1}$). Similarly, the sum of the concentric phase lengths for all the repetitions (i.e. a surrogate estimation of the time under tension) was shorter in inter-repetition rest training with respect to traditional training (242 ± 24 and 255 ± 20 s for inter-repetition rest training and traditional training respectively), but did not reach statistical significance ($P = 0.074$; ES = 0.572; 95% CI, $-0.054, 1.178$). Additionally, Wilcoxon test showed the OMNI scale scores to be significantly different ($P = 0.002$; Cliff's Delta = 0.793) between traditional training (8.3 ± 0.9) and inter-repetition rest training (6.6 ± 1.6).

Dynamic muscular performance

The results of the dynamic muscular tests are summarised in Figure 2. There was a significant main effect of time for the

1RM (Figure 2a), maximum mean propulsive power (Figure 2b) and total concentric work with 10RM load (Figure 2c). However, the time \times set configuration interaction was not significant for any of these variables.

Isometric muscular performance

One participant did not complete the isometric evaluation after training, and thus the sample was reduced to 12 participants. Figure 3 represents values of MVC and time to task failure before and after training. No interaction between factors (time \times set configuration) was detected for any of the variables. However there was a significant main effect of time for both of these variables, showing an increase of performance after training (from 1038 ± 108 to 1275 ± 135 N, and from 49 ± 3 to 61 ± 3 s for MVC and time to task failure, respectively).

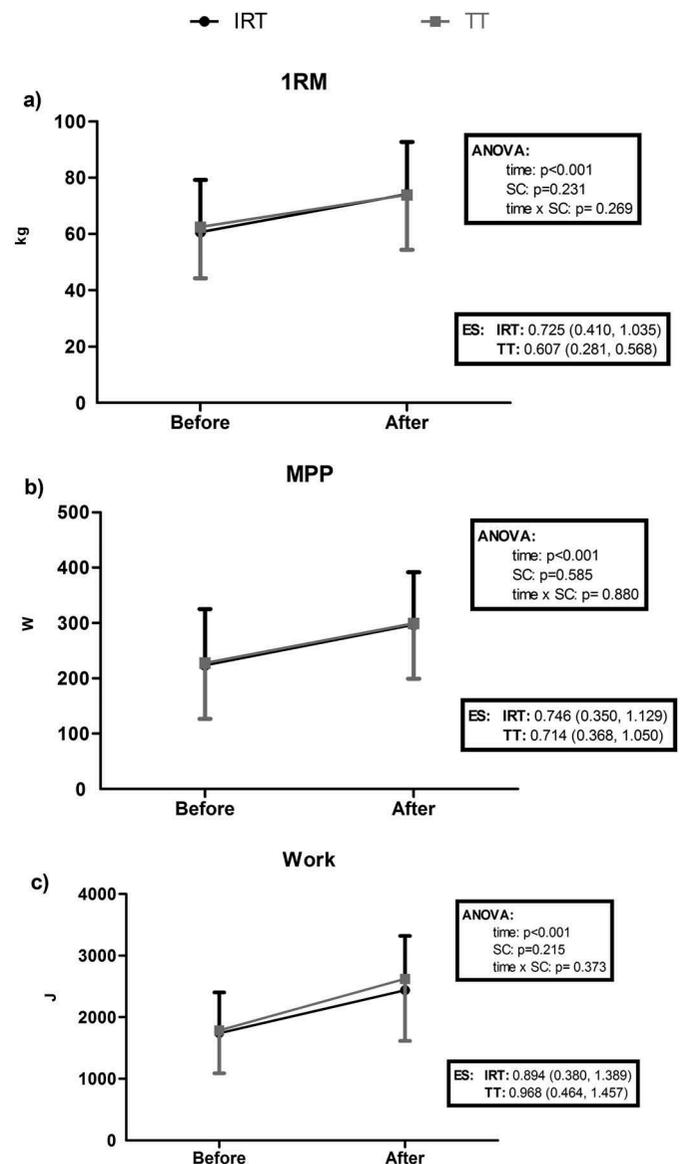


Figure 2. Dynamic muscular performance in study 1: (a) 1 RM; (b) maximum mean propulsive power (MPP); (c) mechanical work performed with 10RM load (pretest). IRT: inter-repetition rest training; TT: traditional training; SC: set configuration; ES: effect size.

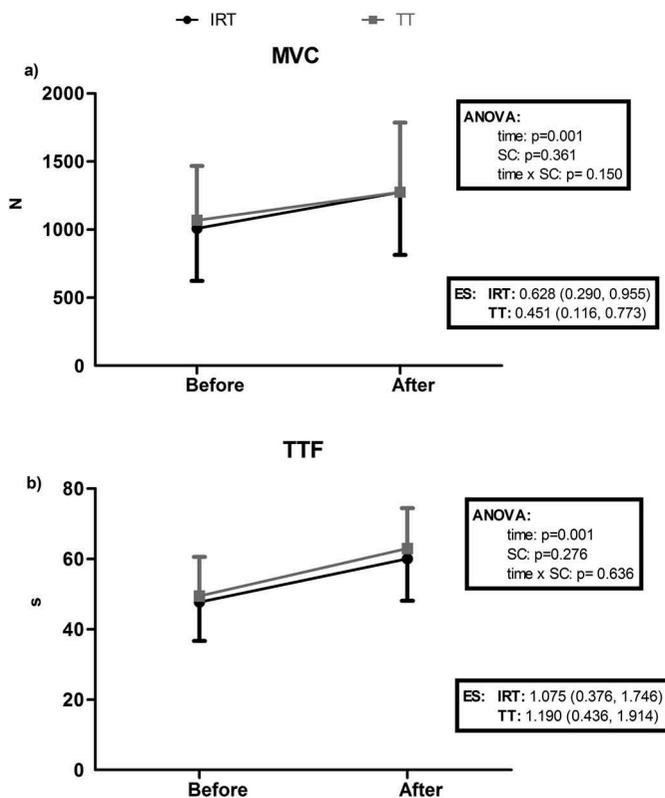


Figure 3. Isometric muscular performance in study 1: (a) Maximum voluntary contraction (MVC); (b) Time to failure maintaining an isometric contraction corresponding to 50% of MVC obtained before training. IRT: inter-repetition rest training; TT: traditional training; SC: set configuration; ES: effect size.

No significant differences or interactions were observed for RFD over time intervals of 0–50, 50–100, 100–150 ms.

Central neural adaptations

Figure 4a summarises the results corresponding to voluntary activation. One of the participants did not complete the neurophysiological protocol and only values higher than 80% were considered for analyses (Folland & Williams, 2007). The voluntary activation sample was reduced to 10 participants accordingly.

ANOVA of voluntary activation showed a significant main effect of time ($95.5 \pm 1.0\%$ and $93.2 \pm 0.7\%$ before and after training, respectively). In addition there was a tendency for an interaction between time and set configuration ($P = 0.077$). The magnitude of the ES for changes after training was notably different across protocols (-1.3 and 0.021 for inter-repetition rest training and traditional training, respectively), not including 0 as a value in the 95% CI of inter-repetition rest training. Post hoc analyses showed a significant voluntary activation decrease in inter-repetition rest training (from $96.5 \pm 3.3\%$ to $91.4 \pm 4.4\%$; $P = 0.002$) (Figure 4a).

Main effect of time for logarithmic scaled values of the normalised root mean square of electromyography was observed ($P = 0.025$) with lower values after training both in inter-repetition rest training (-2.11 ± 0.28 and -2.18 ± 0.21 neperian logarithmic normalised units before and after training, respectively; ES: -0.272 ; ES 95% CI: $-0.989, 0.457$) and in

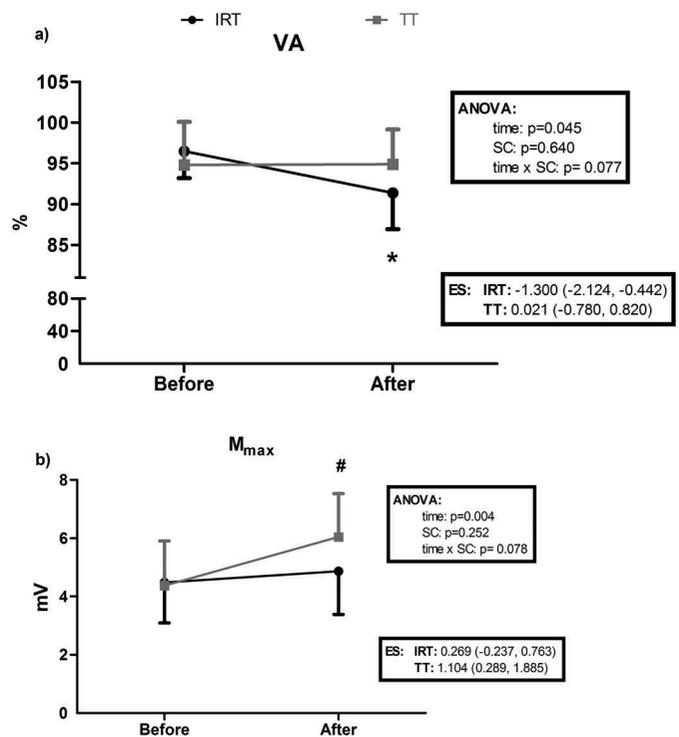


Figure 4. (a) Voluntary activation (VA); (b) Maximum M wave (M_{max}). IRT: inter-repetition rest training; TT: traditional training; SC: set configuration; ES: effect size. *Significant differences from pretest in IRT; # significant differences from pretest in TT.

traditional training (-2.01 ± 0.33 and -2.34 ± 0.29 before and after training, respectively; ES: -1.045 ; ES 95% CI: $-1.984, -0.066$).

Peripheral changes

The sample for the peripheral variables was 12 participants, since one participant did not attend the post-test neurophysiological evaluation. M_{max} showed a tendency ($P = 0.078$) for a significant interaction between time and set configuration. Moreover, ES corresponding to changes after training was notably higher in traditional training with respect to inter-repetition rest training (Figure 4b). In this regard, 95% CI included the 0 value for traditional training but not for inter-repetition rest training. Post hoc analysed showed a tendency for higher M_{max} values after training for traditional training compared with inter-repetition rest training (6.0 ± 1.6 vs. 4.9 ± 1.5 mV for traditional training and inter-repetition rest training, respectively; $P = 0.064$). Additionally, values after compared with before training were significantly higher in traditional training (4.4 ± 1.5 and 6.0 ± 1.5 mV before and after training, respectively; $P = 0.005$) but showed no differences in inter-repetition rest training (4.5 ± 1.4 vs 4.9 ± 1.5 mV before and after training, respectively; $P = 0.303$).

Single twitch peak force was higher after training ($P = 0.033$) in comparison with before training both in inter-repetition rest training (188 ± 107 N and 247 ± 85 N before and after training, respectively; ES: 0.614 ; ES 95%CI: $0.138, 1.069$) and in traditional training (185 ± 90 N and 233 ± 99 N

before and after training, respectively; ES: 0.508; ES 95%CI: $-0.084, 1.079$).

Similarly, single twitch maximal rate of force development was significantly higher after training ($P = 0.038$) both in inter-repetition rest training (3828 ± 1737 and $4492 \pm 1673 \text{ N} \cdot \text{s}^{-1}$ before and after training, respectively; ES, 0.390; ES 95% CI, $-0.184, 0.947$) and in traditional training (3084 ± 1546 and $3887 \pm 1984 \text{ N} \cdot \text{s}^{-1}$ before and after training, respectively; ES, 0.452; ES 95% CI, $-0.209, 1.094$).

Nonparametric ANOVA showed a main effect of time ($P < 0.001$) for the single twitch time to peak force, with lower values after training both in inter-repetition rest training (0.078 ± 0.059 and $0.054 \pm 0.021 \text{ s}$ before and after training, respectively; Cliff's Delta = 0.389) and traditional training (0.080 ± 0.060 and $0.046 \pm 0.0071 \text{ s}$ before and after training, respectively; Cliff's Delta = 0.597). There was no significant main effect or interaction for set configuration.

Cortical evaluation

Ten participants from the sample were tested for cortical adaptation to training. Results for resting motor-evoked potentials, short-interval intracortical inhibition and intracortical facilitation are illustrated in Figure 5. These variables did not show significant main effects or interactions.

Correlations

Overall, there were no significant correlations between changes in neuromuscular and strength measurements.

Complementary experiment results

Regarding the non-trained limb, maximum mean propulsive power values showed a significant main effect of time ($P < 0.001$). However, there was no significant time \times group interaction for 1RM, maximum mean propulsive power and total concentric work (Figure 6) showing that the effect of training protocols on non-trained leg was similar between groups (i.e. similar cross education). Per cent changes after training in inter-repetition rest training group were 3.8 ± 9.1 , $8.03 \pm 2.9\%$ and $5.1 \pm 33.3\%$ for 1RM, maximum mean propulsive power and total concentric work respectively. In traditional training group per cent changes were 7.1 ± 11.5 , $15.0 \pm 16.6\%$ and $11.6 \pm 24.4\%$ for 1RM, maximum mean propulsive power and total concentric work respectively. Mann-Whitney U -test did not show significant differences between groups for these increments (P -values: 0.999, 0.200 and 0.873 for 1RM, maximum mean propulsive power and total concentric work respectively). MVC but not time to failure showed a main effect of time (Figure 7). Only a tendency for a time \times group interaction was observed for the time to failure. Paired tests did not reveal significant differences and similar Cliff's Delta values were observed for inter-repetition rest training group (0.278; 95%CI: $-0.446, 0.781$) and traditional training group (0.222; 95%CI: $-0.771, 0.517$). In inter-repetition rest training group per cent of changes after training were

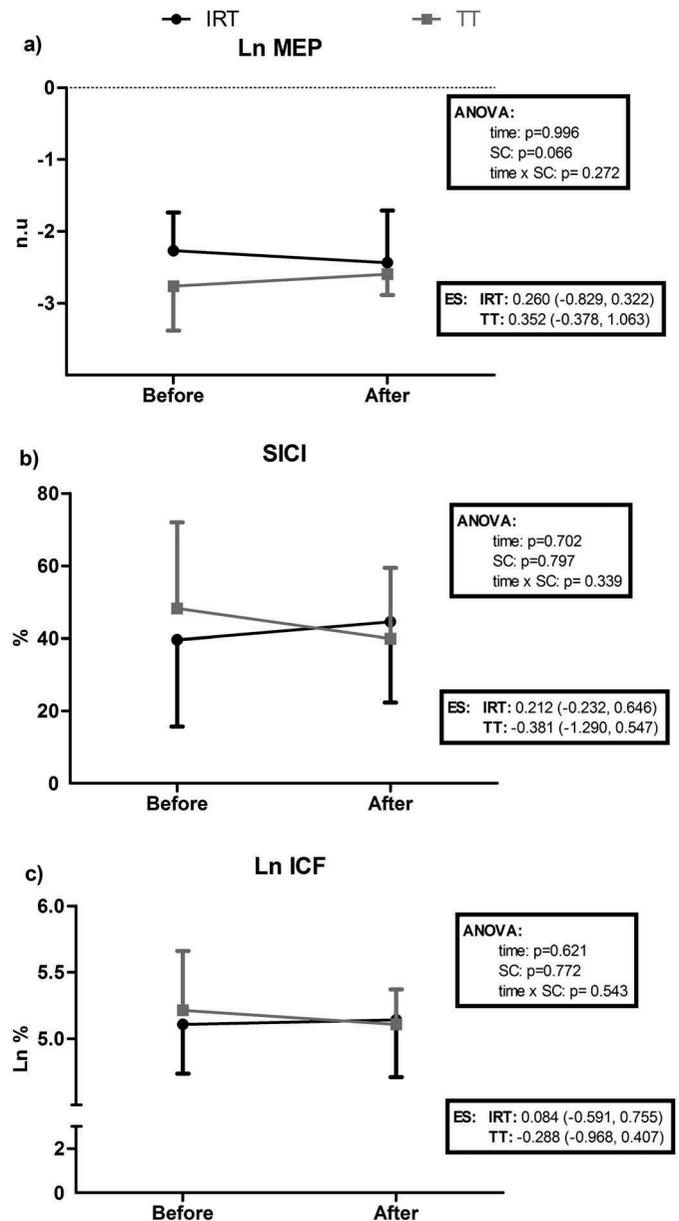


Figure 5. Cortical adaptations: (a) resting motor evoked potentials (MEP); (b) short interval intracortical inhibition (SICI); (c) intracortical facilitation (ICF). IRT: inter-repetition rest training; TT: traditional training; SC: set configuration; ES: effect size; Ln: neperian logarithmic.

$7.7 \pm 13.6\%$ and $11.5 \pm 22.6\%$ for MVC and time to failure respectively. Per cent changes after training in traditional training group were $10.2 \pm 5.4\%$ and $-2.0 \pm 17.5\%$ for MVC and time to failure respectively. Mann-Whitney U -test did not show significant differences between groups for these increments (P -values: 0.631 and 0.262 for MVC and time to failure, respectively).

As far as the dynamic performance of the trained leg, a main effect of time for 1RM, maximum mean propulsive power and total concentric work with 10RM load ($P < 0.001$) was observed. There was no significant group effect ($P > 0.529$ across variables) nor a significant interaction ($P > 0.102$ across parameters). Isometric performance of the trained leg was similar between groups and only a significant main effect of

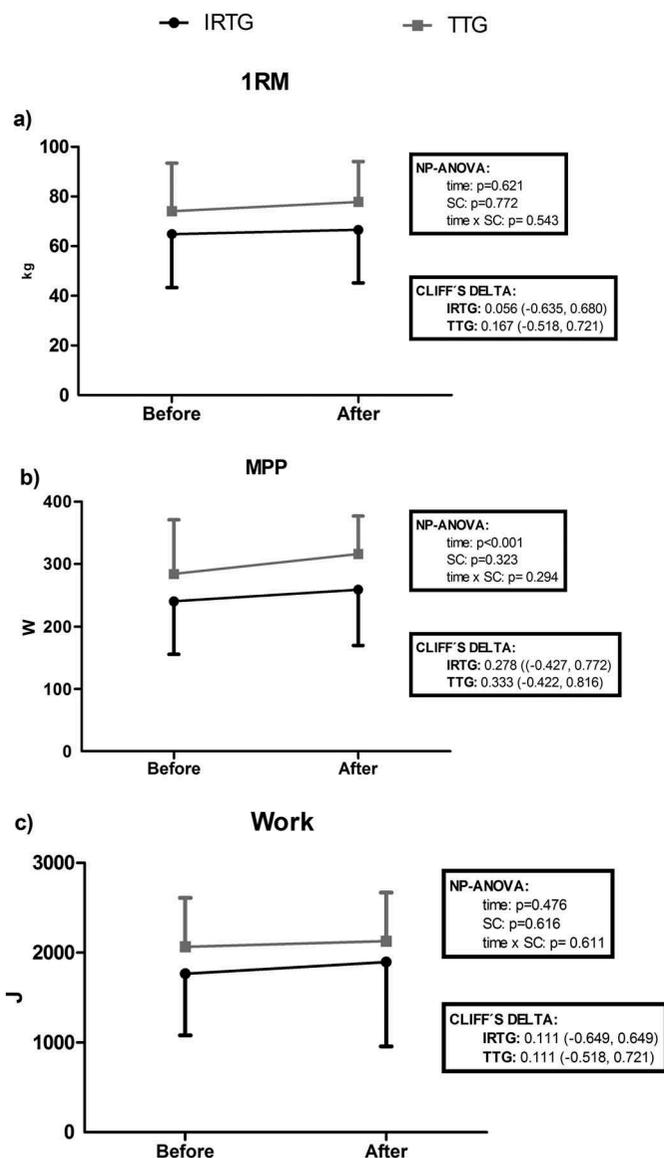


Figure 6. Non-trained leg dynamic muscular performance obtained in the complementary study. The training protocols were the same as that employed in the main experiment, with the exception that each participant only exercised one leg. (a) 1 RM; (b) maximum mean propulsive power (MPP); (c) mechanical work performed with 10RM load (pretest). NP-ANOVA: nonparametric ANOVA-type statistics; IRTG: inter-repetition rest training group; TTG: traditional training group; SC: set configuration.

time was detected for both MVC ($P < 0.001$) and the time to failure ($P = 0.003$) while time \times group interactions were not significant ($P = 0.608$ and $P = 0.524$ for MVC and time to failure, respectively).

Discussion

The main findings of our study were (1) functional improvements were similar across protocols although some differences were observed for central (voluntary activation) and peripheral (M_{max}) neuromuscular adaptations; (2) inter-repetition rest training induced similar improvements in muscular performance as traditional training, but with a higher mechanical performance and lower perception of effort

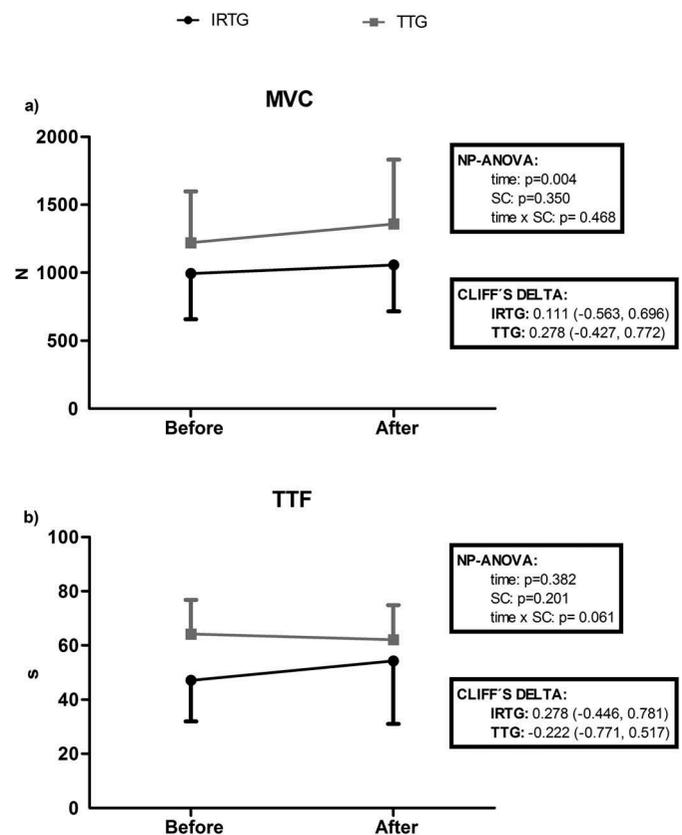


Figure 7. Non-trained leg isometric muscular performance obtained in the complementary study. (a) Maximum voluntary contraction (MVC); (b) Time to failure maintaining an isometric contraction corresponding to 50% of MVC obtained before training. NP-ANOVA: nonparametric ANOVA-type statistics; IRTG: inter-repetition rest training group; TTG: traditional training group; SC: set configuration.

during training sessions; (iii) neural changes did not correlate with strength increase.

Dynamic and isometric performance improved similarly after both training conditions suggesting that when volume and work-to-rest ratios are equated, strength and muscular endurance gains are nearly the same. These results are in line with a previous study that reported similar improvements between different protocols with identical volume (i.e. repetitions \times load) (Alegre et al., 2015). However, longer set configuration leading to failure has been reported to be more effective in short-term strength training (Folland et al., 2002), although in this study the work-to-rest ratio between configurations was not equated. In addition, the muscular group that we focused on (leg extensors) may also explain the lack of differences observed between the configurations. This is supported by findings showing that training to failure is more effective in improving muscular endurance for a bench press but not a half squat (Izquierdo et al., 2006), suggesting that lower limbs might be less sensitive to different set configurations.

Although, our findings show that both set configurations lead to the same functional improvements it is plausible that the underlying mechanisms for these improvements are different for each set configuration. Higher mean propulsive velocities of inter-repetition rest training during the training

sessions might be related to lower metabolic stress compared with traditional training (Sanchez-Medina & Gonzalez-Badillo, 2011). This is supported by the lower RPE observed in inter-repetition rest training than that in traditional training. Therefore, the mechanical factors may have more relevance in the adaptations to inter-repetition rest training while metabolic stimuli may be more predominant in traditional training (Crewther et al., 2005).

The average increase in thigh circumference with both training protocols was similar to that reported by Alegre, Jimenez, Gonzalo-Orden, Martin-Acero, and Aguado (2006) after 13 weeks of explosive squat training. However, comparison with the current study is limited since the training period, the exercise and the point at which perimeter was measured were not the same. Our findings suggest that both set configurations were able to induce structural adaptation in a short training programme, which is in line with previous studies that have showed muscle size and architectural adaptations after a 5-week training period (Blazevich, Gill, Bronks, & Newton, 2003; Seynnes, de Boer, & Narici, 2007). However, our findings should be interpreted with caution since we did not use precise techniques to evaluate structural adaptations. In this regard, it has been previously suggested that metabolic stress plays a dominant role in adding sarcomeres in parallel (i.e. pennation angle increase) while for the addition of sarcomeres in series (i.e. fascicle length increase) mechanical stress may be predominant (Reeves, Maganaris, Longo, & Narici, 2009), suggesting different muscle architectural adaptations between set configurations. Further research is required to determine the effect of set configuration on architectural adaptations.

Voluntary activation and normalised root mean square of electromyography did not increase after training, suggesting that the voluntary neural drive was not affected in both configurations. Voluntary activation evaluates the level of motoneuronal drive at MVC, and values lower than 100% could represent incomplete recruitment and/or suboptimal firing of motor units (Shima et al., 2002). The lack of voluntary activation improvements observed after both training protocols is in agreement with findings of previous studies (Cannon, Kay, Tarpenning, & Marino, 2007; Herbert, Dean, & Gandevia, 1998; Lee, Gandevia, & Carroll, 2009). Some authors (Del Balso & Cafarelli, 2007) reported increments in voluntary activation after resistance training for muscles with low voluntary activation baseline levels (~80%), however no changes have been found for muscles with higher baseline levels (Cannon et al., 2007; Duchateau, Semmler, & Enoka, 2006; Lee et al., 2009). This is consistent with our current findings where the mean voluntary activation before training was over 95%. Another plausible explanation for the lack of improvement is the young age of the participants in our study. Walker & Häkkinen (2014) observed that voluntary activation of leg extensors after a resistance training programme only increased in older people but not in a young sample. Even though we did not find a significant interaction (time \times set configuration) for voluntary activation, we observed larger reductions (i.e. ES) after inter-repetition rest training, while values after traditional training remained unaffected. Although, a decrease in individual

voluntary activation levels has been previously reported after strength training (Herbert et al., 1998), in our study the decrease in voluntary activation was consistent for 8 out of 10 participants after inter-repetition rest training. Additionally the twitch amplitude at rest increased after both training programmes, so it seems that the strength improvements produced by both the inter-repetition rest training and traditional training configurations are due to mechanisms other than an increase in voluntary drive to the tested muscles.

In line with the aforementioned, we found a decrease of the normalised root mean square of the electromyographic signals in both legs after the training. Normalised root mean square of electromyography is considered to reflect central drive since local changes (e.g. muscle membrane properties) are removed by the normalisation procedure with respect to M_{\max} (Noorkoiv, Nosaka, & Blazevich, 2014). Previous studies reported increases in normalised root mean square of the electromyographic signals after strength training (Cannon et al., 2007; Tillin, Pain, & Folland, 2011) and thus, it is plausible that in our study, both the inter-repetition rest training and traditional training entailed low agonist activation. This is supported by a previous study, using a unilateral leg extension exercise (Burd et al., 2010), which showed the highest electromyography amplitude when 50% of the repetitions were completed until volitional fatigue. Furthermore this peak electromyographic amplitude only occurred for the two first sets. Therefore, it is possible that in our study the inter-repetition rest training and traditional training configurations accumulated most of the work at lower EMG amplitudes.

Peripheral adaptations were evaluated by M_{\max} and evoked contractile properties. M_{\max} represents the synchronous activation of the entire pool of motor units and its increase has been associated with changes in membrane ionic activity (Pensini, Martin, & Maffiuletti, 2002). Our results showed higher M_{\max} amplitudes after training, especially for traditional training. These findings suggest an enhancement in membrane excitability after traditional training, but this did not affect the voluntary muscular performance, which was similar for the two set configurations. One hypothesis for this is that the improvement in the response to a short electrical stimulation pulse (i.e. M_{\max}) has little transference for longer muscle activation.

Evoked contractile properties improved after training both in traditional training and inter-repetition rest training. Changes in twitch contractile properties are attributed to muscular mechanisms such as excitation–contraction coupling process or modifications in passive stiffness of the series-elastic component (Pensini et al., 2002; Scaglioni et al., 2002). Reductions in contraction time have been related to an enhancement in ATPase activity and calcium kinetics (Scaglioni et al., 2002). Similarly, increase in peak twitch has been explained in terms of changes in Ca^{2+} release by the sarcoplasmic reticulum and/or variations in the Ca^{2+} sensitivity of contractile proteins (Pensini et al., 2002). It is possible that in the case of traditional training the twitch contractile properties could be partially enhanced by the increment in muscle membrane excitability while

inter-repetition rest training could lead to a higher involvement of intramuscular mechanisms beyond the membrane ionic process.

To our knowledge this is the first study that analyses the impact of set configuration on cortical adaptations. Our results showed no significant effect of training on motor responses evoked by TMS (i.e. motor-evoked potentials, short-interval intracortical inhibition and intracortical facilitation). The lack of changes in MEP at rest is in agreement with that reported previously in the literature (Carroll, Selvanayagam, Riek, & Semmler, 2011; Jensen, Marstrand, & Nielsen, 2005; Latella, Kidgell, & Pearce, 2012; Lee et al., 2009). The degree of novelty of the task used for training has been suggested to have a modulating effect on the motor-evoked potentials (Latella et al., 2012). For this reason, we used familiarisation sessions in an attempt to avoid confounding factors such as changes in the descending corticospinal volley that are associated with learning. Additionally, the lack of changes in short interval intracortical inhibition and intracortical facilitation are consistent with similar results using a ballistic ankle training exercise (Beck et al., 2007). Therefore, it can be concluded that both inter-repetition rest training and traditional training did not induce changes in the corticospinal volley, nor were there changes in the intracortical facilitation and inhibition. These findings support the notion that strength training may affect the properties of spinal cord circuitry rather than the output from motor cortex (Duchateau et al., 2006). Additionally it could be speculated that if resistance training induces cortical adaptations, they would be achieved with longer training programmes than that used in the current study. Finally, it is possible that resting motor-evoked potentials may lack the precision to detect subtle cortical changes produced by strength training, as previously suggested (Carroll et al., 2011).

The results from the complementary experiment showed an improvement of the dynamic and isometric performance of the trained limb for both groups, replicating the results from the main experiment. In addition, we found a significant effect of time factor for MVC and maximum mean propulsive power in the non-trained leg, supporting the existence of the cross education phenomenon. However, our data showed that the magnitude of this phenomenon was similar across groups since neither group main effect nor significant time \times group interactions were detected, 95% CI of ES were quite similar between groups and no significant differences between groups were detected for the per cent changes after training. These results suggest that set configuration did not modulate the cross education effect and that the results of the main experiment were not influenced by the contralateral strength training effect. However, the sample used in the complementary experiment was relative small and thus, further studies should be conducted in order to evaluate the influence of the set configuration on the cross education phenomenon.

Conclusion

In summary, similar improvements in muscular performance were observed after both protocols; however inter-repetition

rest training produced higher mechanical performance and lower rating of perceived exertion than traditional training during the sessions. In addition, neural changes did not correlate with performance improvement, showing that differences observed between the configurations with regards to central (i.e. voluntary activation) and peripheral (i.e. M_{\max}) changes were not translated into differences in the voluntary contraction capacity. The present work demonstrates that inter-repetition rest training is as effective in improving muscle performance as traditional training, at least after a short period of training (i.e. 5-week training period).

Disclosure statement

No potential conflict of interest was reported by the authors.

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