Increased neuromuscular activity, force output and resistance exercise volume when using 5-minute compared to 2-minute rest intervals between sets

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ABSTRACT:

Longer rest intervals between resistance exercise (RE) sets may promote greater muscle hypertrophy and strength gains over time by facilitating completion of greater training volume and intensity. However, little is known about the acute neuromuscular responses to RE sets incorporating longer vs. shorter rest intervals. Using a within-subjects, cross-over design, 8 healthy, young participants completed two separate acute bouts of 4 sets of 8 × 3-s maximal isometric contractions using either a 2-min (REST-2) or 5-min (REST-5) rest interval between sets. Peak torque (PT) and EMG were measured pre and 5-min post-exercise. PT and mean torque (MT), EMG, mean and median frequencies were measured during each set, while blood lactate (BL), heart rate (HR) and RPE were measured following each set. PT and MT were lower ($p<0.05$) in sets 3 and 4, and sets 2-4 in REST-2 compared to REST-5, respectively. EMG and BL were lower and higher, respectively, in REST-2 vs. REST-5. There was no main effect of condition on HR or RPE. Pre-to-post exercise reductions in PT (-17±9% vs. -4±7%) and EMG (-29±14% vs. -10±7%) were greater ($p<0.001$) in REST-2 vs. REST-5. Total exercise volume was less in REST-2 vs. REST-5 (9,748±2296 N.m vs. 11,212±2513 N.m, $p<0.001$). These results suggest that incorporating 5-min between-set rest intervals into a resistance exercise session facilitates improved neuromuscular function, increased exercise volume and less metabolic stress compared to 2-min rest intervals. Thus, 5-min rest intervals may be more efficacious for promoting muscle hypertrophy and strength gains in a chronic resistance training programme.

Key words: activation, fatigue, quadriceps, recovery, strength.

INTRODUCTION:

It is well recognised that skeletal muscle mass plays a fundamental role in sport and exercise performance, prevention and susceptibility to disease, preparation and recovery from surgery, and healthy ageing (10,36,42). However, the mechanisms of muscle mass regulation and their relationship to various resistance training protocol manipulations are not fully understood. Muscle mass appears to be primarily regulated via mechanical signals (38) and therefore RT strategies to maximise the total mechanical load to muscle may be optimal for promoting hypertrophy. There is a dose-response relationship between resistance training exercise volume and increases in muscle mass (32), with exercise volume potentially the most effective variable to manipulate for skeletal muscle hypertrophy (11).

One method to achieve greater exercise volume is manipulation of the rest interval duration between resistance training sets. As such, recent reviews have suggested that rest intervals ≥ 2-min may be better for increasing muscle hypertrophy (12) and strength (13,30) compared to rest intervals <2-min. The majority of studies in the literature employ rest interval durations of 1-2 mins, with the position stand from the American College of Sports Medicine (ACSM) suggesting 1-2-min rest intervals for novice and intermediate lifters, and 2-3-min rest intervals for advanced lifters, to achieve muscle hypertrophy in young, healthy adults (21). However, several studies have shown that even longer rest intervals durations of 4-5 min are superior to 2-3 min in completing greater exercise volume for a given exercise (15,23,26,27,30,40,41). For example, Hernandez et al.(15) recently compared resistance training volume completed during 4 sets to failure of bench press at 85% single repetition maximum (1RM) using either a 2, 5 or 8-min rest interval duration. The results showed that the total training volume was significantly higher using 5 and 8-min rest intervals compared to 2-min rest intervals, with only an 8-min rest interval duration long enough to match the volume of the first set. Indeed McKendry et al. (19) demonstrated that muscle fractional protein synthetic rates and phosphorylation of key

mechanotransductory proteins were blunted using a 1-min vs. 5-min rest interval duration following four sets of knee extension and leg press exercise to failure at 75% 1RM (19). This was accompanied by a significantly lower total exercise volume completed in both exercises (~ -19% and -13% reduction, respectively) in the 1-min rest interval condition. These results are congruent with other studies demonstrating the relationship between resistance exercise volume and phosphorylation of key anabolic regulatory proteins and myofibrillar protein synthesis (4,37).

The development of muscle tension or force is determined by the number of motor units activated and the rates at which the motor units discharge action potentials (8), which quantitatively represents muscle activation. Muscle activation is globally represented by the electromyographical (EMG) amplitude (9), although they are actually different concepts (2). Greater muscle fibre activation permits the generation of higher peak muscle tension, which may ultimately lead to enhanced mechanotransduction, and greater muscle protein synthesis (29). Although all skeletal muscle fibre types may undergo hypertrophy, the dominant hypertrophic muscle type is type IIa (28), with recent skeletal muscle modelling showing that the magnitude of muscle hypertrophy may be determined by the total mechanical activation of fast twitch fibres (14). Although the potential relationship between rest interval duration, muscle activation and muscle force has been known for some time and used as a rationale for increasing rest interval durations (25), no studies to date have demonstrated this relationship via assessing each of these factors or using moderate (2-min) compared to even longer (5-min) rest interval durations.

The rest interval facilitates many physiological processes that take place in order to try to restore muscle cell homeostasis following resistance exercise. These processes can be primarily neural or metabolic in nature, although these two types of processes are not mutually exclusive. For example, passive rest following intense maximal muscle contractions permits the

resynthesis of ATP via phosphocreatine hydrolysis, oxidation or cellular efflux of lactate, buffering of H^+ ions and the active pumping of Na^+, K^+ and Ca^{2+} ions across various membranes to re-establish membrane potentials and conductivity of action potentials (3,39). Accrual of post-contraction metabolites and ionic disturbances can directly inhibit excitation-contraction coupling via activation of the voltage-dependent chlorine channel protein (ClC-1) and the ATP-sensitive K^+ channel (K_{ATP}), which impair the action potential amplitude and Ca^{2+} release from the sarcoplasmic reticulum (18). Therefore, the availability of ATP for muscle contraction and metabolic status of the muscle are important for the continuation of muscle contractile performance, and the restoration of these for future muscle performance is time-dependant.

The aims of the current study were to investigate the neuromechanical and metabolic responses to high intensity resistance using a 2-min and 5-min rest interval duration. These rest intervals are chosen based off current health organisation recommendations (e.g. ACSM) and the comparison to literature investigating various longer rest intervals, with the majority of current studies conducted using 5-minute intervals. We hypothesized that the 5-min rest interval would result in higher total exercise volume, a much less pronounced reduction in peak and mean torque, better maintenance of muscle activation and less metabolic stress at the onset of exercise, all compared to the 2-min rest interval condition.

METHODS:

Experimental Approach to the Problem:

This study used a within-subjects, randomised cross-over study design, which included three experimental visits to the laboratory. The first laboratory visit included familiarizing participants with the experimental exercise protocols. Each participant completed one set of

eight maximal, 3-seconds long, isometric voluntary contractions (MVIC) of unilateral knee extensions on an isokinetic dynamometer at 90 degrees knee joint angle (0 degrees = full knee extension) following a brief warm-up (2 sets of 5 repetitions at 50% and 80% perceived MVIC, respectively). Following a minimum of 3 days' rest, participants were randomly allocated to an experimental resistance exercise condition, whereby four sets of eight unilateral knee extension MVICs were completed, separated by either 2-min or 5-min inter-set recovery. The first experimental condition and second experimental condition were separated by 4 days' rest. Neuromuscular characteristics (peak torque [PT], mean torque [MT], EMG amplitude), blood lactate (BLa), heart rate (HR) and rating of perceived exertion (RPE) were assessed during each set of the exercise session, with PT and EMG amplitude also assessed pre-exercise (5-min immediately prior to resistance exercise) and post-exercise (5-min post cessation of exercise).

Subjects:

An a priori power calculation was performed in G*Power software (Version 3.1.9.7) using the exercise volume mean and standard deviations (SD) from the 2-min and 5-min conditions in Hernandez et al. (15). The software was set to estimate a sample size that would show a medium effect size with an alpha level of 0.05 and beta set at 0.8. The results showed a sample size of 8 participants would yield a power of 0.84. A total of 8 participants (7 males, 1 female), aged 22.0 ± 0.5 years (mean ± SD), height 1.75 ± 0.05 m, mass 74.4 ± 7.4 kg, volunteered to take part in the study. Participants were recruited via convenience sampling from the local university campus and gyms, using posters, e-mails and word-of-mouth. Participants are described as recreationally active, taking part in regular physical activity 2-3 times per week (e.g. playing university sports), but not taking part in any formal lower body resistance programs currently, or at least 6 months prior to the beginning of the study. To be eligible for the study, individuals needed to be between 18–39 years of age, not have any musculoskeletal or neurological

disorders, be free from injury and not supplementing with any ergogenic aids either 3 months prior to or during the study. Following a pre-screening physical activity questionnaire to ensure eligibility, participants were provided with an information sheet, outlining the full experimental procedure. Subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the local University's Ethics Committee.

Maximal Voluntary Isometric Contraction (MVIC):

A minimum of two MVICs were performed at baseline (5-min prior to each resistance exercise protocol) and post-exercise (5-mins after cessation of the last repetition of each resistance exercise protocol) on an isokinetic dynamometer (KinCom, Chattanooga, KN, USA). After a series of warm up trials consisting of 10 submaximal isometric contractions, progressed at a self-perceived 50-90% maximal effort, participants were instructed to rapidly exert maximal knee extension isometric torque against the dynamometer lever arm, with a sampling frequency of 250 Hz. Isometric contractions were held for 3 seconds at the plateau with a 60 s rest period between the two contractions. In all participants, the first and second MVICs did not differ by >5%, so there was no need for any further MVIC attempts Instantaneous peak torque was displayed on the dynamometer display screen, providing real-time visual feedback to participants. The highest value of the two contractions was used for peak torque analysis.

Electromypography (EMG ampitude):

Surface EMG signals were acquired at a sampling rate of 2,000 Hz using a Delsys Wireless Trigno system (Delsys Inc., Boston, MA, USA) connected to a digital data acquisition unit

(PowerLab 16/35, AD Instruments, Oxford, UK). One bipolar Trigno sensor was used per muscle site, with each sensor containing Ag/AgCl electrodes with a 10 mm inter-electrode distance, and a dual on-board stabilising reference. The system filtered the EMG data with a 4th order, zero-lag, Butterworth filter (20-450 Hz). Raw EMG amplitudes were then processed as root mean square (RMS, 100 ms epoche) over the entire duration of each muscle contraction using LabChart v8 software (AD Instruments, Oxford, UK). Both peak and mean RMS EMG were obtained from each contraction. To ensure that electrodes were located in the same place for each condition, the location was marked with a 2 cm crosshair using an anatomical pen, which remained clearly visible for the duration of the study. To further reduce variability in EMG activity between conditions as a consequence of electrode placement (5), the mean RMS EMG amplitude from each MVIC was normalised to the peak RMS EMG (200 ms in total, 100 ms either side of the single instantaneous peak data point) elicited during the greatest MVIC recorded on the same experimental day. This was also the method employed to identify peak EMG activity for each contraction during the resistance exercise. This was also the method employed to identify peak EMG activity for each contraction during the resistance exercise. A spectral analysis was also simultaneously performed, with a Fast-Fourier transformation applied to the raw EMG signal to provide the power spectral density, from which the mean (MF) and median (MDF) frequency of each contraction during the resistance exercise sessions were assessed.

Electromyograms were recorded from the *vastus lateralis* muscle at 50% femur length, and 50% *vastus lateralis* width (20). Each electrode's bipolar arrangement was positioned in line with the assumed direction of the muscle fascicles. Before electrodes were attached, all skin locations were prepared by shaving, abrading using a commercially available dermal scrub (St. Ives, UniLever, Wirral, England) and cleansed with an alcohol swab (70% Ethanol) to reduce skin impedance. Each electrode was secured using a combination of the system manufacturer's

own specific electrode double-sided adhesive tape, and further fixation with additional adhesive tape.

Blood Lactate Quantification

To measure blood lactate concentration, an alcohol wipe (Alcotip swab, Universal Hospital Supplies, London, UK) was used to cleanse the participant's finger-tip, and a sterile lancet (Accu Chek, Roche, Mannheim, Germany) was used to pierce the skin to produce blood. A Lactate Pro 2 lactate strip (Arkray, KDK Corp., Shiga, Japan) was used to collect the blood, which was then inserted into a Lactate Pro 2™ lactate analyser (Arkray, KDK Corp., Shiga, Japan), to determine blood lactate concentration. Lactate measures were taken at rest prior to exercise, during the first 20 s immediately following the completion of the set and within the last 20 s, immediately before cessation of the rest interval.

Heart Rate and RPE

Heart rate was recorded using a Polar H7 heart rate monitor (Polar, Kempele, Finland) and a Polar RS400 watch, and was taken at rest prior to the first resistance exercise set, immediately post exercise and within the last 5 s immediately before cessation of the rest interval (post recovery). RPE was provided by each participant via the Borg scale and was taken immediately following cessation of each exercise set.

Resistance Exercise Protocol

Participants performed four sets of 8 repetitions of MVICs. Contractions were 3 s in duration (audibly and visually timed and instructed by the dynamometer computer system) with a 2-s passive rest between reps. There was 2-min (REST-2) or 5-min (REST-5) of passive rest between sets. From each 3-s MVIC, peak torque and mean torque were recorded. Summation of the mean torque in all 32 contractions for each rest interval condition was used to estimate total exercise volume for that condition.

Statistical Analysis:

JASP v 0.17.3 was used to run all descriptive and inferential statistical analyses. First, data parametricity was established through the Shapiro wilk test, with all data defined as normally distributed. Paired t-tests were used to determine pre- to post-resistance exercise changes (i.e. peak torque, EMG amplitude) and exercise volume. Cohen's *D* was used to denote effect size in paired samples t-tests, where 0.2 = small, 0.5 = medium and 0.8 = large (7). For contrasts across the four exercise sets (peak torque, mean torque, EMG amplitude, mean and median frequency, lactate, heart rate and RPE), a two-factor within-subjects repeated measures ANOVA was conducted, with the main effects of set (S1, S2, S3 and S4) and rest duration (REST-2, REST-5) analysed. Statistical significance for these key outcomes was accepted at an alpha ≤ 0.05, while the effect size for the ANOVAs was calculated using partial eta squared (η_p^2), 0.01 = small; 0.06 = medium; and 0.14 = a large effect (7), and significant study power was accepted at $\beta \geq 0.8$. For comparisons of interest, mean difference and 95% confidence intervals (C.I. 95%) are also reported.

RESULTS:

Peak Torque, Mean Torque and Exercise Volume

Regarding PT, there was a significant main effect of set ($p<0.001$, $\eta_p^2=0.74$), rest duration ($p=0.014$, $\eta_p^2=0.60$) and a set × rest duration interaction effect ($p=0.007$, $\eta_p^2=0.43$) during the exercise protocol (Figure 1A). Post hoc comparisons for main effect of set showed PT in S3 and S4 were less than both S1 (both $p<0.001$) and S2 ($p=0.037$, $p<0.001$). S4 PT was less than S3 PT ($p=0.037$). Within rest duration, in REST-2, PT was less in S3 and S4 (both $p<0.001$) compared to S1 and less between S2 and S4 ($p<0.001$). Within REST-5, PT did not differ between sets ($p>0.05$). Post hoc comparison of main effect of rest duration showed PT in REST-2 was less than REST-5 ($p=0.014$, mean difference -22.1, 95% C.I. -38.1 to -6.1). Post hoc comparison of set × rest duration interaction showed PT in S3 REST-2 was less than PT REST-5 S1 ($p=0.013$, mean difference -36.9, 95% C.I. -69.5 to -4.1) and REST-5 S2 ($p=0.006$, mean difference -39.7, 95% C.I. -72.4 to -7.0). PT in S4 REST-2 was less than all REST-5 sets, with S1 ($p<0.0001$, mean difference -54.2, 95% C.I. -86.9 to -21.5, S2 ($p<0.001$, mean difference -57.1, 95% C.I. -89.8 to -24.2), S3 ($p=0.001$, mean difference -46.7, 95% C.I. -79.4 to -14.0) and S4 ($p=0.019$, mean difference -37.0, 95% C.I. -70.0 to -3.8). There was a difference in the pre- to post-exercise relative change in MVIC PT, with REST-2 having a greater decrement than REST-5 ($p=0.004$, $d = 1.52$, mean difference -13.2, 95% C.I. -20.5 to -5.9; Figure 1B).

Regarding MT, there was a main effect of set ($p<0.001$, $\eta_p^2=0.87$), rest duration ($p<0.001$, $\eta_p^2=0.83$) and a set × rest duration interaction effect ($p<0.001$, $\eta_p^2=0.68$) during the exercise protocol (Figure 2A). Within rest duration, REST-2 MT was less in each successive set compared with the previous set (all $p<0.05$). Within REST-5, MT was less in S4 compared to S1 ($p=0.022$) and S2 ($p=0.014$). Post hoc comparison of the set × rest duration interaction effect showed MT was less in REST-2 than REST-5 in S2 ($p=0.01$, mean difference -41, 95% C.I. -72 to -10), S3 ($p<0.001$, mean difference -51, 95% C.I. -82 to -20) and S4 ($p<0.001$, mean difference -56, 95% C.I. -87 to -24). For exercise volume, REST-2 (9748 ± 2296 N.m) was less

than REST-5 (11212 ± 2513 $N.m^{-1}$, $p<0.001$, d= -2.0, mean difference -1464, 95% C.I. -2061 to -866, Figure 2B).

INSERT FIGURE 1 HERE

INSERT FIGURE 2 HERE

Electromyography

There was no main effect of set (p=0.13), however there was a main effect of rest duration (p=0.016, η_p^2=0.58) and a set × rest duration interaction effect (p=0.014, η_p^2=0.58; Figure 3A). Within rest duration, in REST-2, EMG was less in S4 (p=0.049) compared to S1. Within REST-5, EMG did not differ between sets (p>0.05). Post hoc comparison of the main effect of rest duration showed EMG in REST-2 was less than REST-5 (p=0.014, mean difference -8.5, 95% C.I. -14.9 to -2.1). Post hoc comparison of the set × rest duration interaction effect showed no differences between EMG in set individual comparisons (p>0.05). There was a difference in the pre- to post-exercise relative change in MVIC EMG with REST-2 having a greater decrement than REST-5 (p=0.003, d = 1.57, mean difference -18.7, 95% C.I. -28.7 to -8.7; Figure 3B).

For MF, there was a main effect of set (p=0.039, η_p^2=0.81), but not rest duration (p=0.319) nor set × rest duration interaction (p=0.355). Post hoc comparisons for main effect of set showed MF in S2 was greater than S4 (p=0.029). For MDF there was no main effect of set (p=0.06), rest duration (p=0.233) or set × rest duration interaction effect (p=0.361).

INSERT FIGURE 3 HERE

Blood Lactate

There was a main effect of set (p<0.001, η_p^2=0.81) and a set × rest duration interaction effect (p=0.012, η_p^2=0.28), with lactate higher in REST-2, but no main effect of rest duration (p=0.23)

during the exercise protocol (Figure 4). Post hoc comparisons for the main effect of set showed lactate PRE was not significantly different to S1 PE ($p=0.22$) but was less than all other time points S2 PE to S4 PR (all $p<0.001$). S1 PE lactate was less compared to all other time points S2 PR to S4 PR (all $p<0.001$). S1 PR lactate was less compared to all other time points from S3 PR to S4 PR (all $p<0.001$). S2 PE lactate was less compared to all other time points S3 PR to S4 PR (all $p<0.001$). S2 PR lactate was less compared to S4 PR ($p<0.001$), and S3 PE lactate was different to S4 PR lactate ($p<0.001$). Post hoc set × rest duration interaction effect comparisons did not show any between rest duration differences in lactate at the concomitant time-point between conditions.

INSERT FIGURE 4 HERE

Heart Rate

There was a main effect of set ($p<0.001$, $\eta_p^2=0.92$) and rest duration ($p=0.029$, $\eta_p^2=0.51$), with higher HR in REST-2, but no set × rest duration interaction effect ($p=0.08$) during the exercise protocol (Figure 5). Post hoc comparisons for the main effect of set showed HR PRE was different to all other time points ($p<0.001$) except for S1 PR ($p=0.065$). PE time points across all four sets were different to all PR time points ($p<0.001$), with no differences between any PE time points across the four sets ($p=1.0$). There were no differences across the four sets between PR time points ($p>0.05$). Post hoc comparison of the main effect of rest duration showed HR in REST-2 was higher than REST-5 ($p=0.029$, mean difference 5.6, 95% C.I. -0.7 to 10.5).

INSERT FIGURE 5 HERE

RPE

There was a significant main effect of set ($p<0.001$, $\eta_p^2=0.74$) but not rest duration ($p=0.62$), and no set × rest duration interaction effect ($p=0.97$) during the exercise protocol. Post hoc

comparisons for the main effect of set showed RPE at S1 (16±1) was significantly less compared to S2 (18±2), S3 (19±2) and S4 (19±2, all $p<0.001$).

DISCUSSION:

The aim of the current study was to evaluate the effect of a 2-min vs. 5-min between-set rest interval duration on exercise volume, and on neuromechanical and metabolic stress responses during maximal isometric resistance exercise. We hypothesized that REST-5 would have a much less detrimental impact on these factors both during, and following, the resistance exercise. The current findings are supportive of our hypothesis in that total exercise volume was greater, and reductions in torque, muscle activation and metabolic stress were less pronounced in REST-5 compared to REST-2.

In REST-5, peak torque was maintained over the course of 4 sets of exercise, whereas mean torque only decreased in set 4 compared to set 1, showing almost complete recovery of muscle performance between sets. Peak torque likely recovered completely across all sets in REST-5, because it is an instantaneous measure, whereas mean torque requires maintenance of torque over 3 s. In REST-2, there was loss of peak torque in sets 3 and 4 compared to set 1, with mean torque decreasing with each successive set after set 1. The inability to maintain torque in REST-2 resulted in REST-5 completing ~15% greater volume than that of REST-2, which is similar to the magnitude of differences in exercise volume completed in McKendry et al. (19) by the 1-min vs. 5-min rest interval duration (~19% and 13% in knee extension and leg press exercises, respectively). Mechanistically, modulation of mechanical overload-induced skeletal muscle hypertrophy occurs through several key mechanotransductory pathways, including FAK/ integrin, stretch-activated calcium ion channels and DAG-kinase mediated pathways, amongst others (29,31). The REST-5 condition from the results of the current study appears to

support an environment where two main factors supporting these mechanotransductory pathways are upheld; maintenance of greater peak torque and muscle activation throughout the workout, and total volume of exercise completed. For example, Burd et al. (4) showed that muscle protein synthesis magnitude and duration, and phosphorylation of key anabolic proteins (e.g. p70S6K, eIF2Be) were related to the total volume of exercise completed. The authors also speculated that the total duration of muscle activation may also be important for sustaining the myofibrillar protein synthetic response (4). Additionally, the study of McKendry et al. (19) demonstrated that muscle protein fractional synthetic rates and phosphorylation of key mechanotransductory proteins were blunted using a 1-min rest interval duration compared to a 5-min rest interval duration following four sets of knee extension and leg press exercise to failure at 75% 1RM. This was despite significant elevations in serum and free testosterone, and plasma lactate, in the 1-min rest interval condition compared to the 5-min condition.

Recently, Hatanaka and Ishii (14) conducted a multiple regression analysis, using the exercise volume and hypertrophic data from 23 resistance training studies, finding that total mechanical activation of type II muscle fibres was the independent variable that had the greatest contribution to the training (hypertrophic) effect. In the current study, peak torque and EMG amplitude were significantly higher with a large effect size post-training in REST-5 vs. REST 2. This shows that there is a subsequent greater inhibition of neuromuscular performance following the 2-min rest interval. It is common for training programs to include more than one exercise per muscle group, therefore, this could have a potentially negative effect on the performance of subsequent exercise within the muscle group and affect the associated adaptive responses. Therefore, the results of the current study suggest that maintenance of peak force through the muscle, due largely to the recovery of muscle activation kinetics, and completion of total overall volume, may provide the conditions for a greater hypertrophic stimulus using 5-min compared to 2-min rest intervals. However, as we did not complete any acute measures

of the molecular/ cellular or muscle protein synthetic responses, this is speculative at this stage and requires further research.

A study by Ahtainen et al. (1) investigated both the acute responses and chronic adaptations to 6 months strength training to using 2 vs. 5-min rest intervals in 13 young, strength-trained men. Participants were randomly allocated to complete the first 3 months training using 2 or 5-min rest intervals, then for the following 3 months, the participants completed strength training using the other experimental rest interval condition. The authors employed 5 sets of leg press and 4 sets of squats at 10RM for the 2-min rest interval and 4 sets of leg press and 3 sets of squats at 10RM for the 5-min rest interval, in order to equate volume. The authors found no acute nor chronic differences in neuromuscular function, quadriceps morphology or hormonal responses. However, major study design limitations limit our ability to draw strong conclusions from this study. For example, there was no washout period between the first and second 3-month intervention periods. In a crossover design, an appropriate washout period is critical to allow the participants to return to baseline characteristics as much as possible, so the influence of any previous training intervention is minimised, allowing for greater certainty that any effects observed are solely due to the most recent intervention. A washout period of more than four weeks at least would be necessary to achieve this, as muscle mass and strength levels above baseline can be retained ≥4 weeks after a moderate length strength training intervention (20). The authors designed the training prescription to equate volume between the conditions, which negates the potential value of the longer rest interval to facilitate completion of a greater volume of RT and thus provide a potentially stronger anabolic stimulus for muscle hypertrophy.

Longato et al. (17) studied the effects of 10 weeks' unilateral resistance training employing either 1-min or 3-min rest intervals in recreationally active, non-strength trained male and female participants. The authors found that the pre- to post-training change in quadriceps CSA was significantly greater in the 3-min rest interval and 1-min rest interval volume matched to

3-minute rest interval legs than the 1-min rest interval and 3-min rest interval volume matched to 1-min rest interval legs. This study suggests that, as long as overall training volume is matched, rest interval may be of less importance for hypertrophy. Once again, however, there are several factors that need to be considered within the study, such as incomplete within-participant study design, the training status of the participants (non-trained) and the low-to-moderate volume completed per week. The use of groups of participants to complete two different within-participant designs increases variability in the measurements. In addition, the use of a unilateral training design with assignment of each leg to an experimental condition also introduces a potential confounding influence of the cross-education effect of contralateral strength changes (6). Finally, the 3-min rest interval completed an average of 16±5 reps to concentric failure over 3 sets, suggesting just over 5 reps or so per set on average. However, recent analysis suggests one could expect 10±2 reps for an 80% 1RM loading intensity (24).

Some authors have hypothesised that temporal increases in serum anabolic hormones and metabolites are important contributors to resistance training-induced muscle hypertrophy (1,33). In the current study, there was a significant set × rest duration interaction with regards to blood lactate concentration, with the 2-min rest interval condition exerting higher blood lactate over the course of the four sets. Furthermore, there were concomitant reductions in peak torque, mean torque and muscle activation across the sets. Accrual of post-contraction metabolites and ionic disturbances can directly inhibit excitation-contraction coupling via activation of the voltage-dependent chlorine channel protein (ClC-1) and the ATP-sensitive K^+ channel (K_{ATP}), which impair the action potential amplitude and Ca^{2+} release from the sarcoplasmic reticulum (18). If mechanical stress and volume are primary factors in driving skeletal muscle hypertrophy, employing strategies such as short rest intervals to increase metabolite accrual may only provide at best a smaller additional contribution to the

hypertrophic response, or may even potentially inhibit it. However, as highlighted by Lawson et al.(16), acute and training data in humans regarding the role of lactate and other metabolites in inducing skeletal muscle hypertrophy is scarce and conclusions are unclear. Particularly difficult in this regard is the simultaneous presence of mechanical tension, accumulation of metabolites, muscle activation and accumulation of higher volumes of resistance exercise. Disentangling each of these into independent, distinct factors is difficult to achieve and will require a series of well-controlled studies.

When placing the results into a wider context of the impact of rest interval duration, there are other factors one may wish to consider. For example, as an individual's training status becomes more advanced, they may be able to complete the same volume of training using a shorter than before rest interval duration (35), so volume should be noted and continue to be progressively increased further to try to ensure an effective stimulus is provided. When extrapolating the current findings to different training scenarios one should also consider the nature of the current exercise protocol. This study used a single-joint, isometric exercise configuration, yet most training programs will include dynamic, multi-joint, larger muscle mass/ group exercises. Senna et al. (34) showed in the pectorals and quadriceps, that using either or single- or multi-joint exercises both result in the same pattern of repetition loss no matter if 1, 3 or 5-minute rest intervals were used, however there are no studies outlining if the same is true of isometric training. Also unclear is, how the order of isometric resistance training exercises, or the combination of isometric and dynamic exercises, are affected by rest interval duration, as these have been previously shown to interact with rest interval and affect exercise volume in dynamic exercises, with shorter rest intervals exacerbating reductions in volume (22). Therefore, future studies may wish to consider investigating these factors.

PRACTICAL APPLICATIONS:

The current study has demonstrated that resistance exercise with a 5-min between-set rest interval facilitates higher peak and mean muscle torque, muscle activation and greater exercise volume with a lower blood lactate response and similar heart rate and rating of perceived exertion, compared to the same exercise with a 2-min between-set rest interval. From a coach's perspective, the effect of rest interval duration length permits the attainment of greater overall tension and higher volume through use of heavier loads, for any given equated training prescription (i.e. when sets and reps are identical and load can be manipulated), which may contribute to enhance the gains in muscle size and strength following a period of chronic resistance exercise. Therefore, athletes and strength and conditioning practitioners may wish to incorporate longer (e.g. ≥5 min) rest intervals than are currently recommended (i.e. 2 min) for maximising muscle hypertrophy and strength gains.

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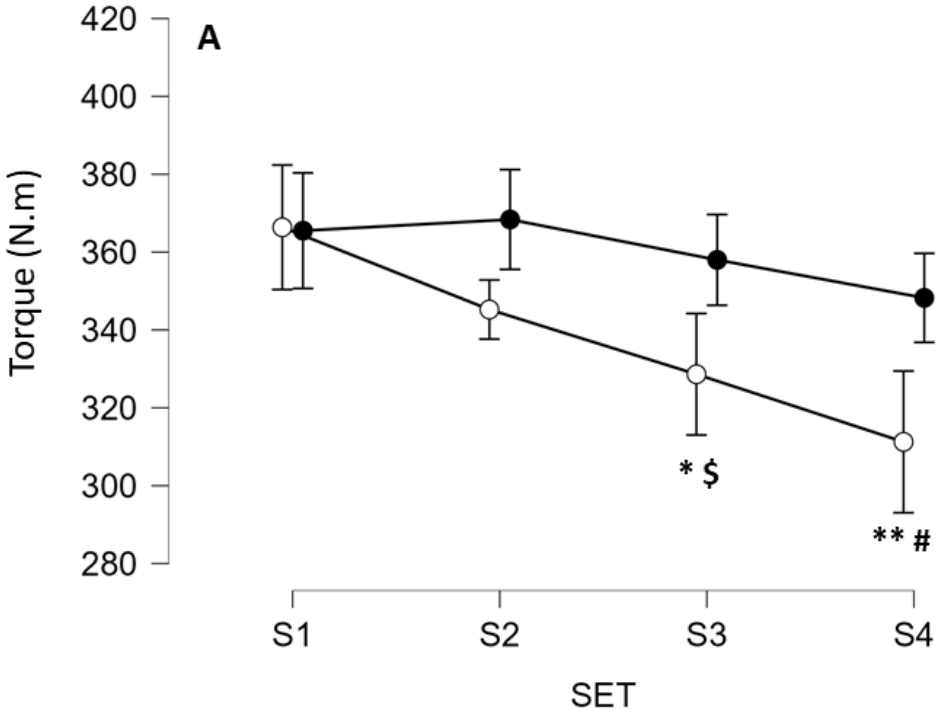

A
420
400
380
360
340
320
300
280
Torque (N.m)
* $
** #
S1
S2
S3
S4
SET

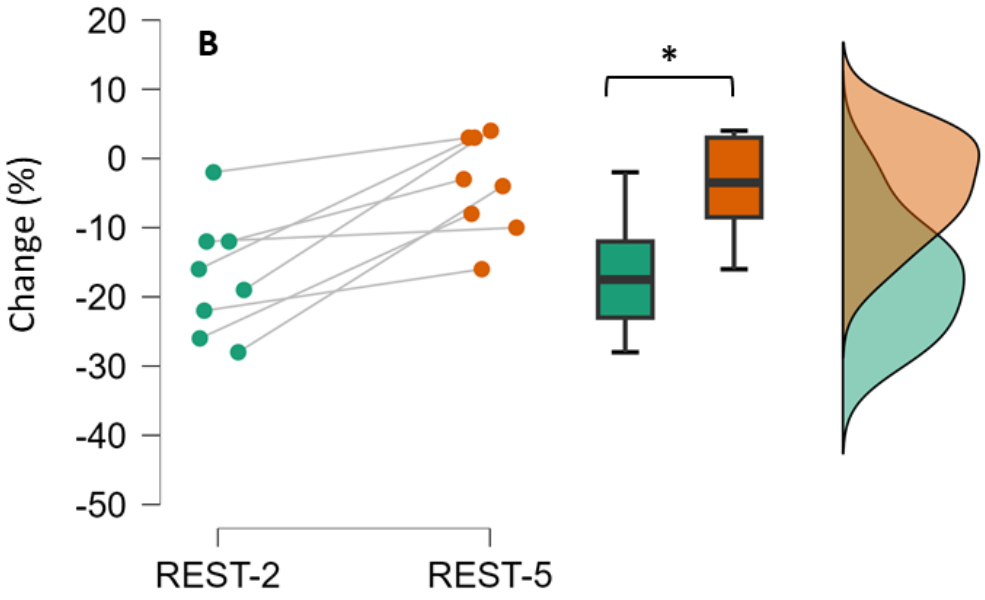
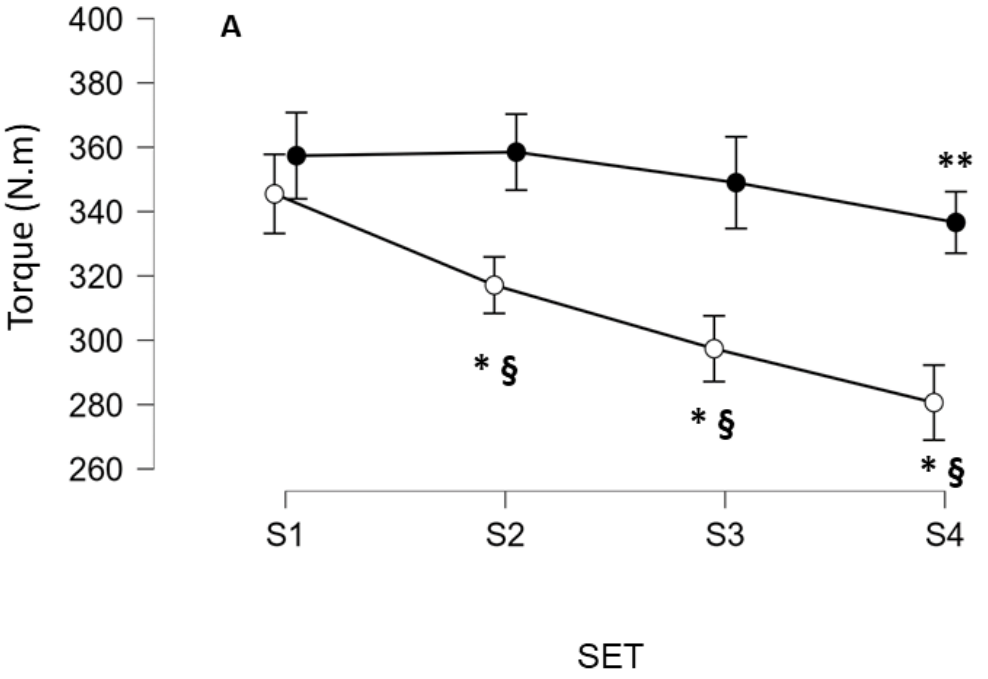

B
20
10
0
-10
-20
-30
-40
-50
Change (%)
*
REST-2
REST-5

Figure 1. Peak torque (A) produced over each set in REST-2 (white circles) and REST-5 (black circles) * Significantly different to S1 ($p<0.05$) in REST-2, ** Significantly different to S1 and 2 ($p<0.05$) in REST-2, # Significantly different to S1-4 ($p<0.05$) in REST-5, $ Significantly different to S1 and S2 ($p<0.05$) REST-5. (B) Pre-post change in Peak torque *Significant difference between rest interval conditions ($p<0.001$).


A
400
380
360
340
320
300
280
260
Torque (N.m)
**
* §
* §
* §
S1
S2
S3
S4
SET

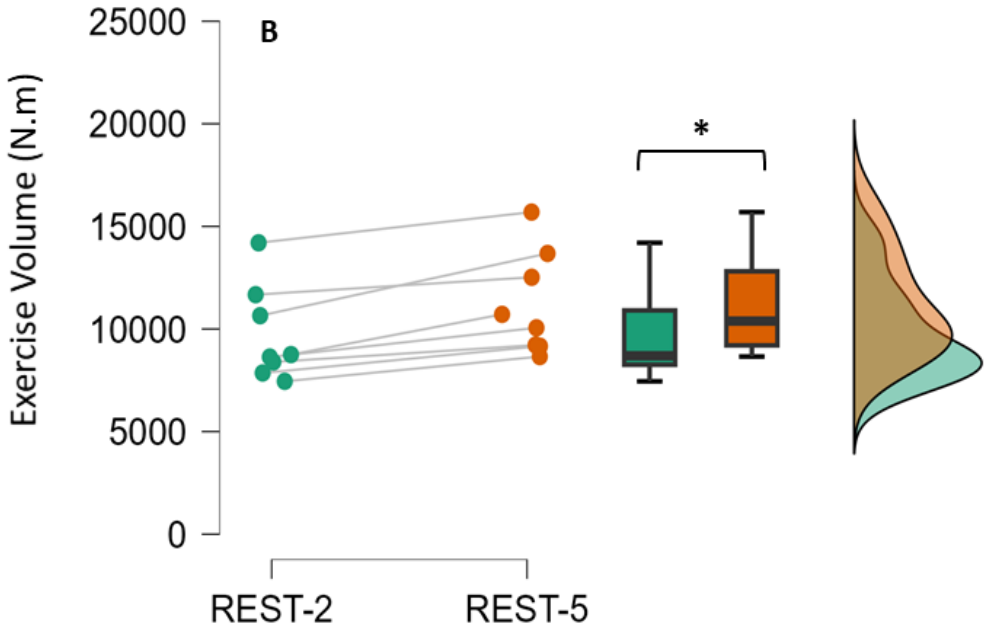
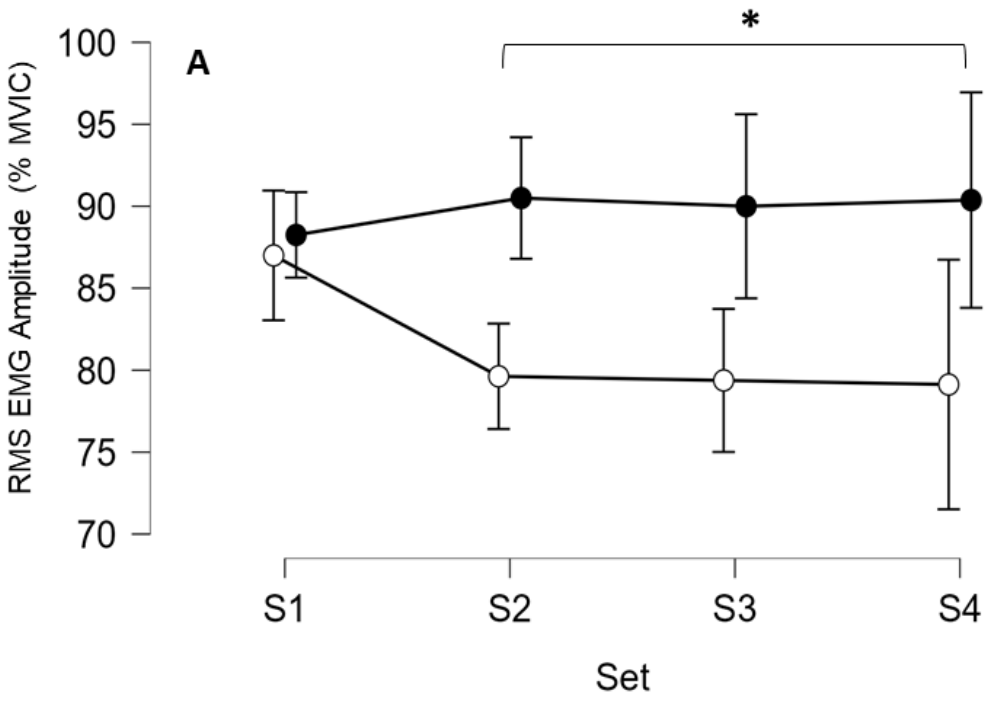

B
25000
20000
15000
10000
5000
0
Exercise Volume (N.m)
*
REST-2
REST-5

Figure 2. Mean torque (A) produced over each set in REST-2 (white circles) and REST-5 (black circles) * Significantly different to S1 ($p<0.05$) in REST-2, ** Significantly different to S1 and 2 ($p<0.05$) in both conditions, § Significantly different to corresponding set ($p<0.05$) in REST-5. (B) Total exercise volume completed *Significant difference between rest interval conditions ($p<0.001$).


A
*
100
95
90
85
80
75
70
RMS EMG Amplitude (% MVIC)
S1
S2
S3
S4
Set

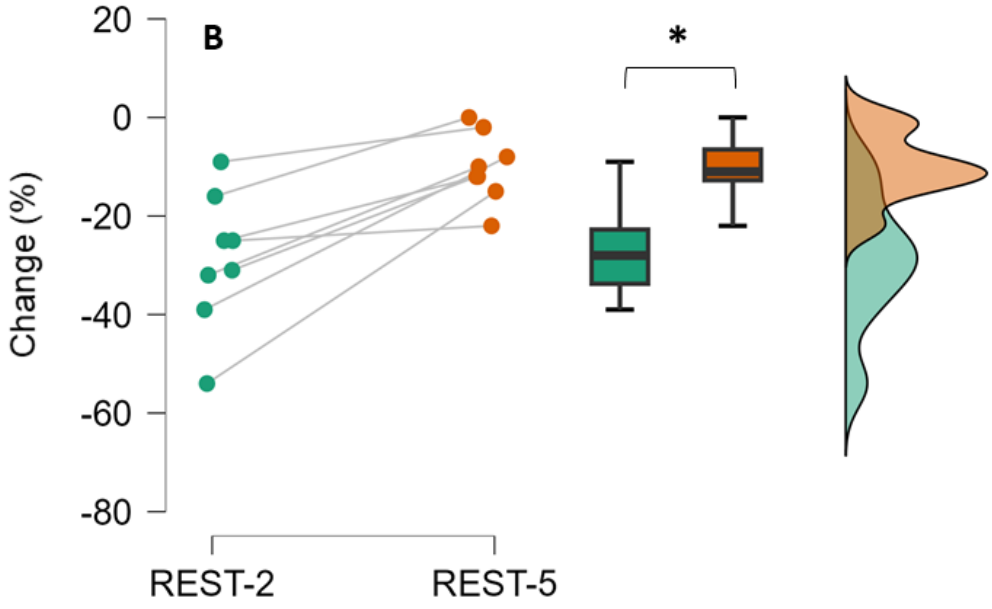

B
*
20
0
-20
-40
-60
-80
Change (%)
REST-2
REST-5

Figure 3. EMG amplitude (A) produced over each set in REST-2 (white circles) and REST-5 (black circles) * Significant main effect of rest duration and rest duration × set interaction ($p<0.05$). (B) Pre-post change in MVIC EMG amplitude *Significant difference between rest interval conditions ($p<0.001$).

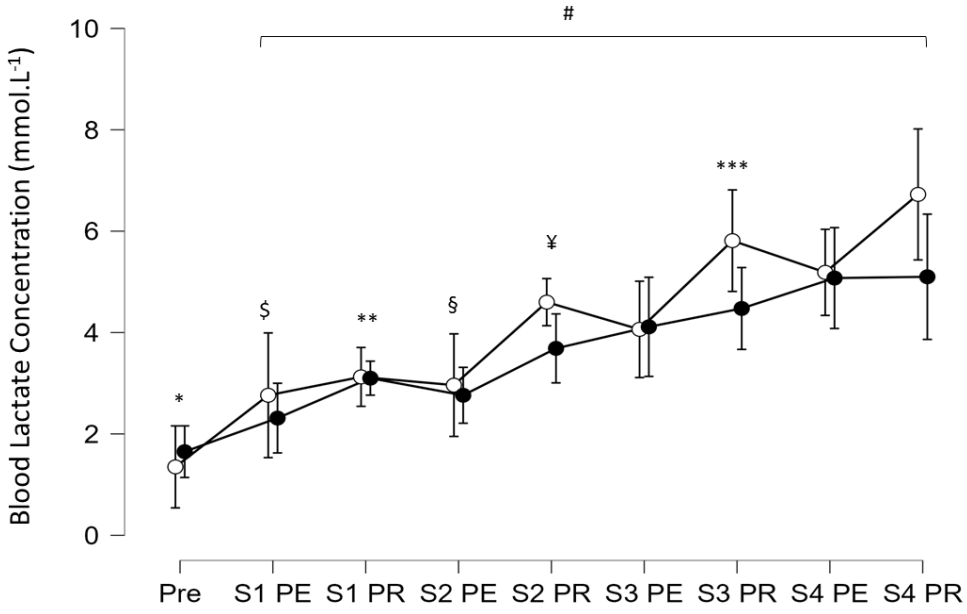


Figure 4. Blood lactate over each set in REST-2 (white circles) and REST-5 (black circles). # Significant main effect of rest duration × set interaction, with lactate higher in REST-2 ($p<0.05$).* Significantly different to all other time points except S1 PE ($p<0.05$), $ Significantly different to all time points from S2 PR to S4 ($p<0.05$) ** Significantly different to all time points from S3 PR to S4 ($p<0.05$), § Significantly different to all time points S2 PR to S4 ($p<0.05$). ¥ Significantly different to S4 PR ($p<0.05$). *** Significantly different to S4 PR ($p<0.05$). PE = post exercise, PR = post recovery.

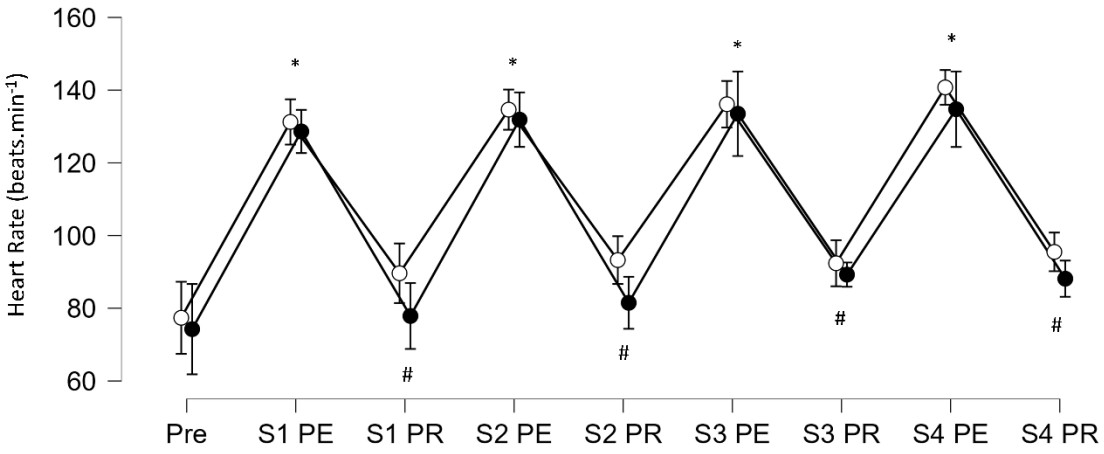


Figure 5. Heart rate over each set. * Significantly different to pre-exercise and post-recovery in each set ($p<0.001$). # Significantly different to pre-exercise ($p<0.001$). PE = post exercise, PR = post recovery.