



Impact of Rest-Redistribution on Fatigue During Maximal Eccentric Knee Extensions

by

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Redistributing long inter-set rest intervals into shorter but more frequent rest intervals generally maintains concentric performance, possibly due to improved energy store maintenance. However, eccentric actions require less energy than concentric actions, meaning that shorter but more frequent sets may not affect eccentric actions to the same degree as concentric actions. Considering the increased popularity of eccentric exercise, the current study evaluated the effects of redistributing long inter-set rest periods into shorter but more frequent rest periods during eccentric only knee extensions. Eleven resistance-trained men performed 40 isokinetic unilateral knee extensions at 60°·s⁻¹ with 285 s of total rest using traditional sets (TS; 4 sets of 10 with 95 s inter-set rest) and rest-redistribution (RR; 20 sets of 2 with 15 s inter-set rest). Before and during exercise, muscle oxygenation was measured via near-infrared spectroscopy, and rating of perceived exertion (RPE) was recorded after every 10th repetition. There were no differences between protocols for peak torque (RR, 241.58±47.20 N; TS, 231.64±48.87 N; $p=0.396$) or total work (RR, 215.26±41.47 J; TS, 209.71±36.02 J; $p=0.601$), but moderate to large effect sizes existed in later repetitions (6,8,10) with greater peak torque during RR ($d=0.66-1.19$). For the entire session, RR had moderate effects on RPE (RR, 5.73±1.42; TS, 6.09±1.30; $p=0.307$; $d=0.53$) and large effects on oxygen saturation (RR, 5857.4±310.0; TS, 6495.8±273.8; $p=0.002$, $d=2.13$). Therefore, RR may maintain peak torque or total work during eccentric exercise, improve oxygen utilization at the muscle, and reduce the perceived effort.

Key words: muscle oxygenation, velocity, fatigue, resistance training, isokinetic, cluster sets.

Introduction

To maintain acute resistance training performance without needing to decrease training load or volume, it is possible to increase rest time between sets or add short intra-set rest periods, which increases total rest time (Latella et al., 2019; Tufano et al., 2016). Although extending total rest time is effective for acutely maintaining performance or reducing neuromuscular fatigue, it may not always be practical. Therefore, instead of adding additional rest time, redistributing the existing total inter-set rest time to create shorter but more frequent rest periods can serve as a

viable alternative for maintaining performance (Iglesias-Soler et al., 2012; Merrigan, Tufano, Oliver, et al., 2020; Tufano, Conlon, et al., 2017; Zajac et al., 2015). Although researchers have shown that different rest-redistribution strategies can maintain acute performance better than traditional sets of longer but less frequent work and rest periods (Iglesias-Soler et al., 2012; Merrigan, Tufano, Oliver, et al., 2020; Tufano, Brown, et al., 2017; Tufano et al., 2016; Gołaś et al., 2019), the physiological mechanisms behind these findings are less explored (Merrigan, Tufano,

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Fields, et al., 2020; Oliver et al., 2015; Tufano, Conlon, et al., 2019; Tufano, Omcirk, et al., 2019).

Generally, previous literature suggests that more frequent rest periods allow for more frequent replenishment of immediate energy stores, which reduces the extent of muscle fatigue during the exercise bout (Gorostiaga et al., 2012; Tufano, Brown, et al., 2017). The enhanced energy replenishment could then decrease the reliance on anaerobic metabolism, leading to less blood lactate accumulation during rest-redistribution sets compared to traditional sets (Merrigan, Tufano, Fields, et al., 2020; Oliver et al., 2015; Tufano, Conlon, et al., 2019). Furthermore, research has shown that hemodynamic responses and cardiovascular stress are reduced during rest-redistribution (Iglesias-Soler et al., 2015; Río-Rodríguez et al., 2016). Despite the aforementioned studies providing valuable information, the physiological data presented were usually systemic, and only limited data exists on the localized responses of rest-redistribution. By using near-infrared spectroscopy to indirectly provide insight into peripheral oxygenation during exercise (Van Beekvelt et al., 2001), it may be possible to better understand the mechanisms behind rest-redistribution. The limited research that has investigated these responses has indicated increased blood flow and oxygen saturation during concentric actions (Tufano, Omcirk, et al., 2019), which may help explain lower lactate levels during rest-redistribution (Merrigan, Tufano, Fields, et al., 2020; Oliver et al., 2015; Tufano, Conlon, et al., 2019) despite less cardiovascular demand (Iglesias-Soler et al., 2015; Río-Rodríguez et al., 2016). However, since the prior study evaluated concentric knee extensions, and many rest-redistribution studies involve exercises that require both concentric and eccentric actions (Merrigan, Tufano, Fields, et al., 2020; Merrigan, Tufano, Oliver, et al., 2020; Tufano, Conlon, et al., 2017; Tufano et al., 2016), the effect of rest-redistribution during eccentric exercise remains unclear.

Since eccentric muscle actions require less energy than concentric actions (Middleton & Montero, 2004), it is possible that the effects of rest-redistribution may differ between concentric and eccentric actions. Furthermore, eccentric actions deserve more attention in research since

they can induce potent muscular adaptations in those intolerant of concentric actions (Peñailillo et al., 2017) or other young healthy populations (Douglas et al., 2017) due to the greater force producing capabilities and possibly greater degree of muscle remodelling compared to concentric actions (Franchi et al., 2017). Considering these gaps in the research in addition to the unknown effects of rest-redistribution on eccentric muscle actions, several questions should be addressed to assist practitioners and scientists in developing a complete understanding of how rest period manipulation can be utilized in resistance training. Thus, the purpose of this study was to investigate the effect of rest-redistribution on maximal-effort eccentric isokinetic knee extension kinetics, peripheral muscle oxygenation, and perceived exertion. It was hypothesized that rest-redistribution would better maintain torque and work (Tufano, Conlon, et al., 2017) compared to traditional sets, paired with higher muscle oxygen saturation and lower levels of perceived stress (Iglesias-Soler et al., 2015).

Methods

Participants performed unilateral isokinetic eccentric knee extensions using either traditional sets (TS) or rest-redistribution (RR). The protocols were performed separately in a counterbalanced manner at approximately the same time of day on two consecutive Mondays. At the start of each session, baseline measures of peripheral muscle tissue oximetry were taken. Next, participants successively performed a general warm-up of stationary cycling and dynamic stretching before performing that day's protocol (TS, 4 sets of 10 with 95 seconds inter-set rest; RR, 20 sets of 2 with 15 seconds of inter-set rest). For each protocol (TS, RR), participants performed 40 repetitions with 285 seconds of total rest, thereby equating the total rest time and number of repetitions (Tufano, Omcirk, et al., 2019). Tissue oximetry and ratings of perceived exertion (RPE) were assessed periodically throughout each protocol, starting immediately prior to the first repetition and ceasing immediately after the last (Figure 1).

Participants

Eleven resistance-trained men (26.0 ± 1.8 yr, 179.1 ± 9.1 cm, 83.5 ± 9.8 kg) participated in

this study after providing written informed consent. Participants had been resistance-training without any musculoskeletal injuries for at least 6 months and were asked to maintain daily habits including supplementation and diet throughout the study period. All participants were instructed to refrain from strenuous physical activity throughout testing with their last lower-body training session being at least 48 hours prior to the familiarization period. Procedures were approved by the University's ethics committee (identification number 135/2019) and carried out according to the Declaration of Helsinki.

Procedures

Familiarization Sessions

During the four total sessions of the two-week familiarization period, participants performed eccentric actions of the knee extensors at $60^{\circ}\cdot\text{s}^{-1}$ through a range of motion of 10° to 90° knee flexion (0° = fully extended knee joint) using an isokinetic dynamometer. The first session consisted of 25 repetitions at approximately 85% of self-perceived maximal effort and the volume and intensity increased by 5 repetitions and 5% of perceived maximal effort until the fourth session where they performed 40 repetitions at maximal effort. Throughout this time, near infrared spectroscopy techniques and rating of perceived exertion scales were explained to the participants.

Isokinetic Eccentric Exercise Protocols

Participants were secured to an isokinetic dynamometer (HumacNorm, Cybex CSMI, Stoughton, MA, USA) with 90° hip flexion to perform unilateral knee extensions. All isokinetic dynamometer testing occurred on the right leg, which had been previously established as the dominant leg for all participants. For the TS and RR exercise protocols, participants began each repetition at 10° of knee flexion and performed eccentric knee extensions at $60^{\circ}\cdot\text{s}^{-1}$ with continuous maximal effort until they reached 90° knee flexion. At this time, the participants relaxed as the dynamometer actively moved their leg back to the starting position of 10° knee flexion, removing all concentric muscle actions. In attempt to ensure maximal effort, participants were verbally encouraged throughout the entire range of motion for each repetition. Peak torque and total work for each repetition were calculated and exported using the dynamometer's proprietary software. Additionally, to quantify the extent of

mechanical fatigue during the protocols, the overall maintenance of torque and work was calculated as the best of the first four repetitions divided by the average of all repetitions (Merrigan, Tufano, Oliver, et al., 2020).

Muscle Oxygenation

Continuous measurements of total haemoglobin concentrations (tHb) and tissue oxygen saturation (SO_2) were obtained at 1 Hz using near-infrared spectroscopy (OxiPlex TS, ISS Inc, Champaign, IL, USA). The sensor was positioned at the middle of the vastus lateralis muscle belly at 60% of the distance from the lateral epicondyle to the greater trochanter of the femur. This sensor placement was outlined with a marker, which enabled for consistent placement throughout the duration of the study. Baseline values were collected while participants laid supine on a table with their right leg relaxed and supported with 30° of knee flexion. The baseline measure was calculated as the average of a 30-second epoch resting period. Then, the software was paused with the sensor removed and stored in a dark bag during the dynamic warm up and other baseline testing procedures (Tufano, Omcirk, et al., 2019). Once the participant was prepared to begin the exercise protocol, the sensor was again secured to the leg and covered throughout the entirety of the exercise protocol.

To identify key timepoints for subsequent analyses, a digital trigger within the Oxiplex software was used to signal the points immediately before the 1st, 11th, 21st, and 31st repetitions and immediately after the 10th, 20th, 30th, and 40th repetitions. The tHb and SO_2 measures were expressed as percentages of the respective baseline values to account for individual day to day differences. The area under the curve (AUC) was calculated across epochs of interest (repetitions 1-10, 11-20, 21-30, and 31-40) with rest periods included to allow for direct comparisons between TS and RR at specific points (Agbangla et al., 2017).

Rating of Perceived Exertion

During the familiarization period, participants were familiarized with the Borg CR-10 scale, which has been validated for representing resistance training intensity through self-reported ratings of perceived exertion (RPE) (Day et al., 2004). The RPE was assessed immediately after every 10th repetition during TS

and RR, while session RPE was assessed approximately 15 minutes after the final repetition.

Statistical Analyses

Data were screened for normality by the Kolmogorov–Smirnov test of normality, and non-parametric analyses were used for data that were not normally distributed (e.g. RPE data). Means and standard deviations were used to represent centrality and spread of data. Isokinetic peak torque and total work between and within RR and TS were compared using a 2(protocol)*4(set)*10(repetition) mixed model repeated measures analysis of variance (RMANOVA). The within and between differences for tHb and SO₂ of each set (including rest periods) were analyzed using a 2(protocol)*4(time) RMANOVA. Greenhouse-Geisser corrections were used when sphericity was not assumed for all aforementioned analyses. For RPE, non-parametric Friedman tests of differences among repeated measures were used, followed by pairwise comparisons. For session RPE and overall maintenance of peak torque and total work, paired samples t-tests were used to compare TS and RR. All analyses were performed using a statistical software package (SPSS V.26, IBM Corporation; Armonk, NY) with alpha set at $p < 0.05$. Additionally, Cohen's d effect sizes were calculated using a custom excel spreadsheet and defined as small, $d = 0.25-0.49$; moderate, $d = 0.50-0.99$; and large, $d > 1.00$. Effect sizes for non-parametric pairwise comparisons were calculated by dividing the respective Z statistic by the square root of the number of pairs in comparisons.

Results

Isokinetic Performance Measures

For peak torque, there was a protocol*repetition interaction ($p = 0.024$, $\eta^2 = 0.186$, Figure 2a), but there were no other interactions (protocol*set, $p = 0.570$, $\eta^2 = 0.064$; protocol*set*rep, $p = 0.396$, $\eta^2 = 0.073$) or main effect for protocol (RR, 241.58±47.20 N; TS, 231.64±48.87 N; $p = 0.396$, $\eta^2 = 0.073$). The overall maintenance of peak torque was not different between protocols (TS, 89.9±6.0%; RR, 89.9±7.2%; $p = 0.955$; ES [CI95%] = 0.01 [-0.83, 0.85]).

For total work, there was a protocol*repetition interaction ($p = 0.025$, $\eta^2 = 0.184$, Figure 2b), but there were no other interactions

(protocol*set, $p = 0.528$, $\eta^2 = 0.059$; protocol*set*rep, $p = 0.174$, $\eta^2 = 0.131$) or main effect for protocol (RR, 215.26±41.47 J; TS, 209.71±36.02 J; $p = 0.601$, $\eta^2 = 0.028$). The overall maintenance of total work was not different between protocols (TS, 90.9±9.3%; RR, 92.7±5.7%; $p = 0.244$; ES, [CI95%] = 0.24 [-0.73, 1.19]).

Near-infrared Spectroscopy

Total hemoglobin and oxygen saturation are displayed for each group of 10 repetitions in Figure 3a and collapsed across the entire protocol in Figure 3b. For the AUC of total hemoglobin during groups of 10 repetitions, there were no main effects for protocol ($p = 0.446$, $\eta^2 = 0.140$) or time ($p = 0.551$, $\eta^2 = 0.067$), in addition to no protocol*time interaction ($p = 0.978$, $\eta^2 = 0.006$). For the AUC of oxygen saturation during groups of 10 repetitions, there were main effects for protocol ($p = 0.002$, $\eta^2 = 0.640$) and time ($p < 0.001$, $\eta^2 = 0.447$), but there was not a protocol*time interaction ($p = 0.078$, $\eta^2 = 0.200$).

Rating of Perceived Exertion

For RPE, a non-parametric Friedman test of differences among repeated measures was significant ($X^2 = 70.23$; $p < 0.001$). Between-condition pairwise comparisons revealed no significant differences ($p > 0.05$). However, effect sizes indicated that RR had a lower RPE at repetitions 10 (ES=0.32), 20 (ES=0.45), 30 (ES=0.64), and 40 (ES=0.56), and a lower session RPE (ES=0.53). Compared to baseline, RPE after repetitions 20, 30, and 40 was elevated during TS ($p \leq 0.001$), while RPE after repetitions 30 and 40 was elevated during RR ($p \leq 0.037$). Session RPE was not different between conditions (RR, 5.73±1.42; TS, 6.09±1.30; $p = 0.307$; Figure 4).

Discussion

The purpose of this study was to investigate the effect of rest-redistribution on maximal eccentric isokinetic knee extension kinetics, peripheral muscle oxygenation, and perceived exertion. It was hypothesized that the total work and peak torque per repetition would be better maintained during RR (Tufano, Omcirik, et al., 2019). Although maintenance calculations were not different between protocols, RR demonstrated greater peak torque in repetitions 1, 6, 8, and 10.

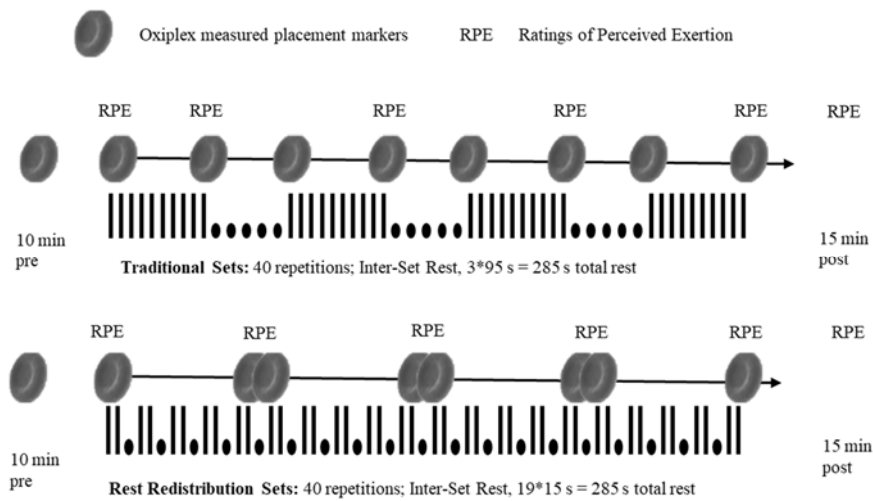


Figure 1

Traditional and rest-redistribution sets during isokinetic eccentric knee extensions at 60°·sec⁻¹, were performed on a separate day with exactly one week of rest between sessions

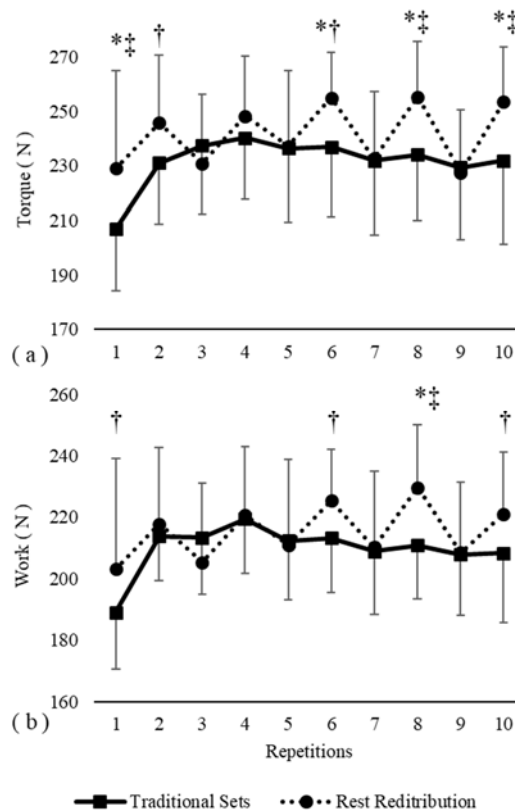


Figure 2

Peak torque (A) and total work (B) during eccentric knee extensions for each repetition when collapsed across traditional sets and rest-redistribution sets (i.e. repetition 1 = mean of repetition 1, 11, 21, 31). Between protocol effects are indicated as: †, moderate effect, $d = 0.50-0.99$; ‡, large effect, $d > 1.00$. *, indicates statistical significance, $p < 0.05$

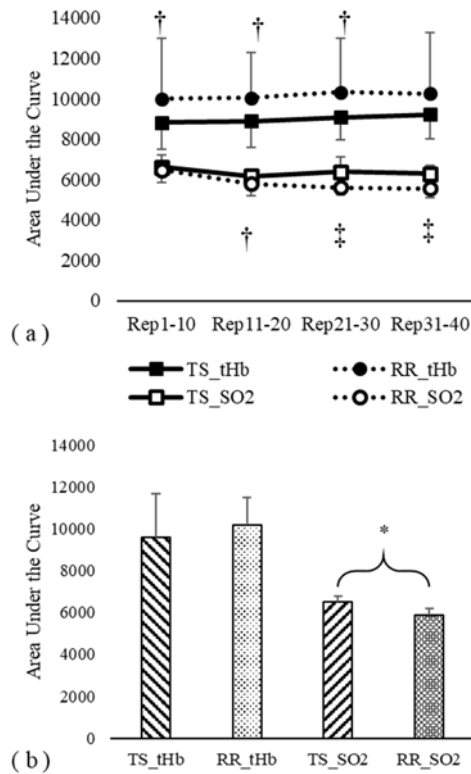


Figure 3

Near-infrared spectroscopy data for vastus lateralis total hemoglobin concentration (tHB) and oxygen saturation (SO2) during traditional sets (TS) and rest-redistribution sets (RR) of eccentric knee extensions. 3A, measures during groups of 10 repetitions; 3B, measures collapsed across the entire protocol; *, statistical significance between protocols ($p < 0.05$). Between protocol effects are indicated as: †, moderate effect, $d = 0.50-0.99$; ‡, large effect, $d > 1.00$

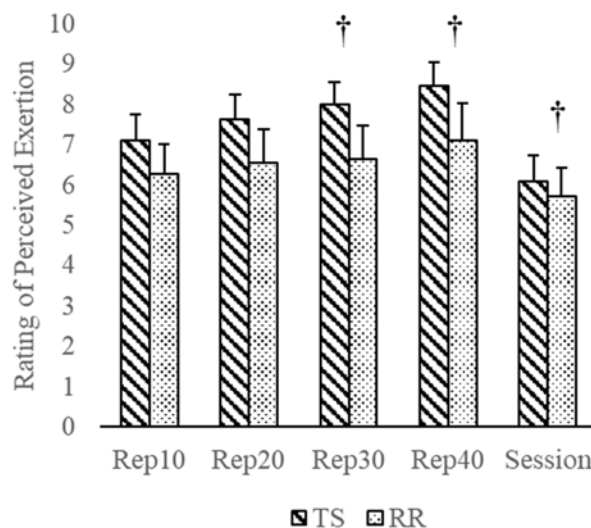


Figure 4

Rating of perceived exertion (RPE) during and after traditional sets (TS) and rest-redistribution sets (RR) at $60^{\circ}\cdot\text{sec}^{-1}$. Between protocol effects are indicated as: †, moderate effect, $d = 0.50-0.99$; ‡, large effect, $d > 1.00$

As outlined in the introduction, previous Additionally, RR did not alter total muscle blood flow (as estimated by total hemoglobin) but did result in lower oxygen saturation. These findings may reflect the higher torque production during RR, which increases intramuscular pressure and subsequent de-oxygenation of the muscle. Although RPE was not significantly different between protocols, RR demonstrated small to moderate effect sizes for lower RPE after every tenth repetition, and lower session RPE values. These collective findings may suggest that the positive effects of rest-redistribution, previously demonstrated during concentric actions, are as prominent during eccentric actions.

Previous rest-redistribution literature has suggested that greater concentric velocity is the main contributor to the greater concentric power output observed during rest-redistribution when concentric forces are similar (Tufano et al., 2016), which is logical when bar displacement and load are consistent. As such, when the external load is kept constant during free weight exercises, the change in velocity is a key variable of interest; but since velocity is often not controlled, the effects of rest-redistribution on force cannot be determined in these instances (Merrigan, Tufano, Oliver, et al., 2020; Tufano et al., 2016). On the other hand, to assess the effects of rest-redistribution on force production, previous studies have controlled movement velocity and evaluated concentric isokinetic single joint movements, finding no differences in kinetics when manipulating rest periods (Chan et al., 2012; Tufano, Omcirk, et al., 2019). The current findings in regard to eccentric actions support the findings of the aforementioned studies as the peak torque and total work, when collapsed across all 40 repetitions, were not different between TS and RR, although trivial effects sizes were in favor of greater peak torque and total work during RR.

Further, to evaluate the extent of fatigue, the ability to maintain performance throughout the protocol relative to the best repetition was calculated, but still, no differences were present between TS and RR. This is in agreement with prior literature that found similar maintenance values between RR and TS during concentric-only knee extensions (Tufano, Omcirk, et al., 2019). However, when evaluating reciprocal eccentric-concentric actions (e.g. back squat repetitions)

rest-redistribution resulted in a better maintenance of velocity and power across an entire session (Merrigan, Tufano, Oliver, et al., 2020). One possible reason for these discrepant findings is the presence of repeated maximal stretch-shortening activities during loaded back squats, which likely reduces the concentric performance of latter repetitions in TS (Gollhofer et al., 1987; Nicol et al., 2006), which was not as pronounced during concentric- (Tufano, Omcirk, et al., 2019) or eccentric-only actions during TS in the present study. However, better velocity maintenance has been shown during rest-redistribution for heavy clean pulls, which do not involve a large eccentric component (Jukic & Tufano, 2019). Interestingly, the positive effects of rest-redistribution were less apparent when the load was less (Jukic & Tufano, 2019) indicating that perhaps exerting maximal effort against heavy loads during multi-joint movements is fatiguing enough for the benefits of rest-redistribution to present themselves. Nevertheless, differences were present for individual repetitions in the current study, despite the lack of differences in peak torque or total work maintenance.

During concentric knee extensions, a previous study noted that rest-redistribution allowed for peak torque to be better maintained in latter repetitions, despite not influencing the overall force production when analyzing all 40 repetitions combined together (Tufano, Omcirk, et al., 2019). However, these results were only seen during fast concentric actions, not during slow actions ($60 \text{ deg}\cdot\text{sec}^{-1}$). Thus, our data agree with the prior findings regarding all 40 eccentric actions of the same speed ($60 \text{ deg}\cdot\text{sec}^{-1}$). However, RR in the present study did result in greater peak torque in later repetitions, as well as repetition 1, when collapsed across sets. Therefore, it is possible that if more repetitions were included in each RR set, the overall peak torque and total work may have favored RR, as the first repetition following a rest period typically had less torque than subsequent repetitions in both protocols. Also, the first repetition to follow the 95 seconds of rest during TS had less peak torque and total work than RR when preceded by a 15 second rest period. Yet, despite the lower effect of shorter rest periods, the first repetition was still lower than the second in each RR set. Although these

findings were in eccentric actions, the same phenomenon has been shown in concentric actions (Moir et al., 2013; Tufano, Omcirk, et al., 2019) and actions that include the stretch shortening cycle (Merrigan, Tufano, Oliver, et al., 2020). Therefore, in all types of muscle actions, it seems as though using rest-redistribution to perform individual repetitions is inappropriate if the goal is to optimize acute performance, as the first repetition following a rest period likely displays decreased performance compared to subsequent repetitions until fatigue ensues. Regardless, this balance of repetitions performed within a set and the length of rest periods is critical for the balance of potentiation and fatigue (Rassier & MacIntosh, 2000).

To further evaluate the fatiguing patterns during these protocols, peripheral oxygenation responses are of interest. In the current study, total hemoglobin levels were not different between protocols. Total hemoglobin reflects microvascular blood volume (Van Beekvelt et al., 2001) and thus local oxygen diffusing capacity, meaning that oxygen availability to the muscle was not affected by redistributing rest compared to TS. In contrast to our hypothesis, a main effect for condition indicated lower levels of muscle oxygen saturation during RR compared with TS. As oxygen saturation indicates the dynamic balance between oxygen supply and consumption within the muscle (Ferrari et al., 2011), this suggests a greater utilization of oxygen at the muscle during RR compared with TS, despite similar oxygen availability. These findings contradict those in concentric knee extensions, where RR resulted in greater total hemoglobin and oxygen saturation in the vastus lateralis (Tufano, Omcirk, et al., 2019).

These differences on muscle oxygenation responses may be due to the type of contractions investigated. Eccentric actions have lower oxygen requirements than concentric actions, due to the lesser muscle activation per torque production in eccentric versus concentric actions (Middleton & Montero, 2004; Peñailillo et al., 2017). Furthermore, maximal eccentric contractions cause lower muscle oxygen saturation during the later stages of exercise compared with concentric contractions, despite no difference in total haemoglobin (Denis et al., 2011). Considering that there is a positive relationship between increased

torque production during contractions and intramuscular pressure (Aratow et al., 1993), exercise which results in higher torque could lead to a greater compression of the microvasculature and subsequent decreases in muscle oxygenation (Denis et al., 2011). As the RR protocol in the current study resulted in greater torque than the TS exercise at several points, this may explain the more severe de-oxygenation which was also observed in RR.

In concentric actions where rest-redistribution resulted in similar peak torque and total work, the ratings of perceived exertion were lower during rest-redistribution (Tufano, Omcirk, et al., 2019). However, in the current study where RR resulted in greater torque in later repetitions, RPE was only slightly lower and not statistically different. Other literature evaluating actions including concentric (and eccentric) actions found lower ratings of perceived exertion via rest-redistribution (Merrigan, Tufano, Fields, et al., 2020; Oliver et al., 2015). However, in the current study, the ratings of perceived exertion were not different between TS and RR during repetitions 1-20. Interestingly, RPE was moderately lower for repetitions 21-40 during RR, accompanied by a lower session RPE (according to effect size). During eccentric actions perceived exertion levels are lower than concentric actions (Hollander et al., 2003), which may explain why RR did not decrease the perceived exertion to the same extent as prior literature in concentric actions.

In conclusion, kinetics, particularly peak torque, during eccentric actions were improved for later repetitions (6, 8, 10) when inter-set rest periods were redistributed into shorter more frequent rest periods. Further, returning from the shorter rest periods resulted in greater peak torque during repetition 1, compared to performances following long inter-set rest periods. Thus, RR protocols for eccentric only exercise may be as beneficial as they are for concentric exercise (as shown in previous research). Since most exercises are performed with reciprocal concentric-eccentric actions, RR is likely beneficial for maintaining overall performance, as both concentric and eccentric performances may be better maintained. Additionally, the higher torque production of later repetitions may have resulted in lower oxygen saturation, via increased intramuscular

pressure, and allowed greater utilization of oxygen at the muscle. Lastly, RPE was no different between protocols, suggesting no perceived differences in effort despite greater force production in later repetitions. Thus, for

those intolerant to concentric actions, RR may allow further benefit for the already useful eccentric contractions by allowing greater force production to be achieved during select repetitions, greater oxygen utilization, and slightly lower perceived exertion.

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