Traditional sets vs rest-redistribution: a laboratory-controlled study of a specific cluster set configuration at fast and slow velocities

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<th>Journal:</th>
<th>Applied Physiology, Nutrition, and Metabolism</th>
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<td>apnm-2019-0584.R2</td>
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<td>Manuscript Type:</td>
<td>Article</td>
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<td>Date Submitted by the Author:</td>
<td>19-Sep-2019</td>
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</table>
| Complete List of Authors: | Tufano, James; Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic
Omcirk, Dan; Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic
Malecek, Jan; Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic
Pisz, Anna; Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic
Halaj, Matej; Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic; Comenius University in Bratislava, Department of Track and Field, Faculty of Physical Education and Sport
Scott, Brendan; Murdoch University, School of Psychology and Exercise Science |
| Novelty bullets: points that summarize the key findings in the work: | • Although effective at slow velocities, rest-redistribution were likely more effective during high-velocity movements in this study. • Rest-redistribution maintained the ability to produce force throughout an entire range of motion. • Rest-redistribution reduced RPE during both high-velocity and high-force movements |
| Keyword: | tensiomyography, muscle oxygenation, velocity, resistance training < exercise, isokinetic, fatigue |
| Is the invited manuscript for consideration in a Special Issue? | Not applicable (regular submission) |
Title:

Traditional sets vs rest-redistribution: a laboratory-controlled study of a specific cluster set configuration at fast and slow velocities

Authors:

James J. Tufano¹, Dan Omcirk¹, Jan Malecek¹, Anna Pisz¹, Matej Halaj¹,², Brendan R. Scott³,⁴

Affiliations:

1Department of Physiology and Biochemistry, Faculty of Physical Education and Sport, Charles University in Prague

2Department of Track and Field, Faculty of Physical Education and Sport, Comenius University in Bratislava

3College of Science, Health, Engineering and Education, Discipline of Exercise Science, Murdoch University

4Murdoch Applied Sports Science Laboratory, Murdoch University

Corresponding author:

James Tufano, Faculty of Physical Education and Sport, Charles University

31 Jose Martiho, Prague, Czech Republic, 16252

+420 777 144 962 james.j.tufano@gmail.com tufano@ftvs.cuni.cz
Abstract

This study investigated redistributing long inter-set rest intervals into shorter but more frequent intervals at two different concentric velocities. Resistance-trained men performed four randomized isokinetic unilateral knee extension protocols, two at 60°·s⁻¹ and two at 360°·s⁻¹. At each speed, subjects performed 40 repetitions with 285 s of 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 2, 5, and 10 minutes post-exercise, tensiomyography (TMG) and oxygenation (near-infrared spectroscopy; NIRS) were measured. NIRS was also measured during exercise, and rating of perceived exertion (RPE) was recorded after every 10 repetitions. At both speeds, RR displayed greater peak torque, total work, and power output during latter repetitions, but there were no differences between TS or RR when averaging all 40 repetitions. The RPE was less during RR at both speeds (p < 0.05). RR increased select muscle oxygen saturation and blood flow at both speeds. There were no effects of protocol on TMG, but effect sizes favored a quicker recovery after RR. RR was likely beneficial in maintaining performance compared to the latter parts of TS sets and limiting perceived and peripheral fatigue.

- Although effective at slow velocities, rest-redistribution were likely more effective during high-velocity movements in this study
- Rest-redistribution maintained the ability to produce force throughout an entire range of motion
- Rest-redistribution reduced RPE during both, high-velocity and high-force movements

Keywords: tensiomyography, muscle oxygenation, velocity, fatigue, resistance training, isokinetic
INTRODUCTION

Since the 1970’s, the term “cluster set” has evolved to describe set structures whereby short rest periods are frequently implemented within a resistance training session (Iglesias-Soler et al. 2013; Iglesias-Soler et al. 2015; Iglesias et al. 2010; Mayo et al. 2014; Oliver et al. 2016a; Oliver et al. 2015; Oliver et al. 2016b; Tufano et al. 2016a; Tufano et al. 2018; Tufano et al. 2019; Tufano et al. 2016b; Tufano et al. 2017a; Tufano et al. 2017b). More recently, researchers have used the term loosely and turned “cluster set” into an umbrella term that encompasses many different types of set structures that include basic cluster sets by inserting extra intra-set rest periods in addition to the already present inter-set rest periods (Haff et al. 2003; Tufano et al. 2016a; Tufano et al. 2018; Tufano et al. 2016b); rest-redistribution by redistributing the total inter-set rest time to create shorter but more frequent rest periods (Joy et al. 2013; Oliver et al. 2015; Tufano et al. 2019; Tufano et al. 2017a; Tufano et al. 2017b); and inter-repetition rest by exaggerating this rest-redistribution approach to include an extremely high number of single-repetition sets (García-Ramos et al. 2015; Hardee et al. 2012b; Hardee et al. 2013; Iglesias-Soler et al. 2015; Tufano et al. 2019; Tufano et al. 2017b; Valverde-Esteve et al. 2013). As such, the findings of these investigations are not always in agreement, likely because the “cluster sets” compared in these studies include different manipulations of rest time and the traditional sets that they are compared have different levels of difficulty, among a multitude of other possible reasons (Iglesias-Soler et al. 2013; Iglesias-Soler et al. 2012; Jukic and Tufano 2019; Oliver et al. 2016b; Tufano et al. 2018). Unfortunately, most studies only focus on performance outcomes such as movement velocity and power output during commonly used exercises, and very few studies have investigated the mechanisms at play during these different set structures. Although examining performance
outcomes is beneficial, understanding the effects of the study design itself and the mechanisms behind those changes in performance would also be beneficial.

Although many studies show that movement velocity and power output can be maintained across a variety of exercises using basic cluster sets (García-Ramos et al. 2015; Haff et al. 2003; Hardee et al. 2012a; Tufano et al. 2016a; Tufano et al. 2016b; Valverde-Esteve et al. 2013), mechanistic exploration of these cluster sets is less common (Girman et al. 2014; Morales-Artacho et al. 2018), and the effects of different exercises have not been examined within the same study. On the other hand, when using rest-redistribution, velocity and power output are also often maintained (Merrigan et al. 2019; Tufano et al. 2016a), but knowledge about the mechanisms underlying performance during rest-redistribution is equivocal (Oliver et al. 2015; Tufano et al. 2019). Despite the valuable data presented from these cluster set and rest-redistribution studies, many questions remain to be investigated.

For example, a wide variety of exercises have been used, including ballistic (García-Ramos et al. 2015; Morales-Artacho et al. 2018; Moreno et al. 2014) and heavy (Haff et al. 2003; Iglesias-Soler et al. 2013; Moir et al. 2013; Tufano et al. 2017b) movements, but these have not been investigated within the same study. As such, the influence of the same type of variable set structure (e.g. cluster sets or rest-redistribution) on different exercises is not well-known. Furthermore, many studies involve exercises that include both concentric and eccentric muscle actions (Joy et al. 2013; Oliver et al. 2016a; Tufano et al. 2016a; Tufano et al. 2019), while others implement mainly concentric muscle actions (García-Ramos et al. 2015; Haff et al. 2003; Moir et al. 2013). Although most resistance training includes eccentric and concentric muscle actions, cluster sets and rest-redistribution are most often used to maintain acute concentric exercise performance (Tufano et al. 2016a). Therefore, it would be logical to further investigate the effects of these set
structures on concentric-only exercises in a laboratory-based setting, eliminating any extraneous
effects of eccentric actions or the stretch shortening cycle. Furthermore, it may be that more total
work completed during cluster sets or rest-redistribution (Oliver et al. 2016b) could lead to
accumulated fatigue that may affect subsequent neuromuscular contractile properties (Behm et al.
2002) (e.g. the following exercises within a training session), but this information is lacking within
the literature. Moreover, although researchers often hypothesize that more frequent rest periods
allow for increased replenishment of immediate energy stores (Gorostiaga et al. 2010; Tufano et
al. 2016a), very little work has been done to determine the effect of rest-redistribution on aerobic
The aerobic response may play a significant role during training as PCr replenishment is dependent
on aerobic metabolism, and assessing \( \text{O}_2 \) supply may provide an overall indirect picture of the
potential for PCr resynthesis. Lastly, basic cluster set structures may not always be practical since
they increase total training time (Tufano et al. 2016b). Therefore, rest-redistribution, whereby the
total rest time stays the same, would likely increase practical applications.

Considering these points, a myriad of basic research questions should be investigated so
that coaches and scientists can obtain a deeper understanding of the effects of rest period
manipulation and ultimately prescribe resistance exercises more appropriately. Therefore, the
purpose of this study was to investigate the effect of rest-redistribution during slow (i.e. heavy)
and fast (i.e. explosive) concentric isokinetic knee extensions while also determining the
subsequent effect of these protocols on the muscle contractile properties and active muscle
oxygenation. Based on previous research, we hypothesized that rest-redistribution would maintain
torque output (Hardee et al. 2012a; Tufano et al. 2017a), be less cardiovascularly or aerobically
taxing (Iglesias-Soler et al. 2014; Mayo et al. 2017; Rio-Rodriguez et al. 2016), and result in quicker neuromuscular contractile recovery after exercise (Boullosa et al. 2013) at both speeds.

MATERIALS AND METHODS

General procedures

Subjects performed four isokinetic unilateral knee extension protocols, two at 60°·s$^{-1}$ ($60^\circ$) and two at 360°·s$^{-1}$ ($360^\circ$). At each speed, subjects performed 40 repetitions with 285 s of total rest using either a traditional set (TS) protocol (4 sets of 10 with 95 s inter-set rest) or a rest-redistribution (RR) protocol (20 sets of 2 with 15 s inter-set rest). Similar to other studies that used 4 sets of 10 repetitions as a “traditional set protocol”, we used a similar approach (Merrigan et al. 2019; Oliver et al. 2015). The 15-second rest periods were chosen because 15 seconds is near the lower limit of what is commonly used in practice when using cluster sets (Haff et al. 2008a; Haff et al. 2008b; Tufano et al. 2016a), and 2 consecutive repetitions were performed as previous research has shown that the first repetition is not always the best and performance begins to decrease after only a few repetitions (Jukic and Tufano 2019; Moir et al. 2013; Tufano et al. 2017a). All subjects performed one protocol per session, which occurred in a counter-balanced quasi-randomized fashion with each session occurring approximately 48 to 72 hours apart at roughly the same time of day. Each session began with baseline tensiomyography and tissue oximetry measurements, followed by a general warm-up of stationary cycling and dynamic stretching, the experimental protocols, and post-exercise tensiomyography and tissue oximetry measurements (Figure 1).

To increase the internal validity of the study, a single-limb isokinetic design was used, and post-exercise performance was not tested as to not interfere with the physiological measurements.
that are unique to the present study. The TS protocols were designed in this manner as previous rest-redistribution studies have also used 4 sets of 10 repetitions (Merrigan et al. 2019; Oliver et al. 2015). During RR, each set was divided into two repetitions as previous research has indicated that fatigue begins to ensue after just a few repetitions (Tufano et al. 2016b) and the performance of the first repetition performed after a rest period is not always maximized (Tufano et al. 2016b; Tufano et al. 2017a). As such, we decided not to utilize an RR model with single repetitions, but to implement two repetitions per set in an attempt to maximize performance during the RR protocols.

Subjects

Sixteen resistance-trained men (23.67 ± 2.78 yr, 181.25 ± 7.34 cm, 81.06 ± 8.81 kg) participated in this study. All subjects had been participating in resistance-training for at least 6 months and had not suffered any musculoskeletal injuries during that time. As recent evidence shows that women may not benefit from rest-redistribution (Merrigan et al. 2019) as much as men (Oliver et al. 2015; Oliver et al. 2016b), women were not included in the present study. All procedures were approved by the university’s ethics committee (identification number 205/2018) and carried out according to the Declaration of Helsinki. Subjects were allowed to withdraw from the study at any time without repercussions, and all subjects provided written informed consent to participate.

Specific procedures

Isokinetic Dynamometry

Subjects were secured to the dynamometer (HumacNorm, Cybex CSMI, Stoughton, MA, USA) for seated unilateral knee extension-flexion testing using standard operating procedures. All
testing occurred on the dominant leg and all repetitions were performed with maximal intent during the concentric phase and, upon reaching the end of the extension range of motion (10 degrees short of full extension), subjects immediately relaxed allowing the lower leg to passively fall into knee flexion (90 degrees of knee flexion). During TS\textsubscript{360} and RR\textsubscript{360}, the concentric knee extension and passive knee flexion both occurred at $360^\circ\cdot s^{-1}$, whereas both movements occurred at $60^\circ\cdot s^{-1}$ during TS\textsubscript{60} and RR\textsubscript{60}. Subjects were constantly given verbal encouragement to perform maximally but were not informed of their performance at any point during the testing procedures. After completing the final repetition, subjects were released from the dynamometer and walked approximately 2 meters to lay supine on a table where post-exercise tensiomyography and tissue oxygenation measurements were performed.

For each repetition, peak torque (PT), total work (TW), and power output (POW) were assessed within the device’s software and exported for further analysis. To determine how well subjects were able to maintain performance throughout the entire protocol, the maintenance for each variable was calculated as the average of all repetitions divided by the best repetition (Jukic and Tufano 2019; Tufano et al. 2017b), and to determine the percentage of fatigue while considering that the first repetition of a set is not always the best repetition, the decline for each variable was calculated as the difference between the worst and best repetition of all repetitions divided by the best repetition (Jukic and Tufano 2019; Sanchez-Medina and Gonzalez-Badillo 2011). Then, to simplify analysis procedures and allow for comparisons over time and within each set for PT, TW, and POW, a single collapsed set of ten repetitions was created for each variable by averaging the 1\textsuperscript{st}, 11\textsuperscript{th}, 21\textsuperscript{st}, and 31\textsuperscript{st} repetitions to create the first repetition of the collapsed set, averaging the 2\textsuperscript{nd}, 12\textsuperscript{th}, 22\textsuperscript{nd}, and 32\textsuperscript{nd} repetitions to create the second rep, and so on (Joy et al. 2013; Oliver et al. 2016b).
Tensiomyography

While multi-joint activities such as isometric mid-thigh pulls and countermovement jumps are often used to assess fatigue, these tests are not able to differentiate between localized and systemic fatigue. Since cluster set literature generally hypothesizes that local mechanisms are primarily responsible for the maintenance of performance (Tufano et al. 2016a), non-invasive tensiomyography (TMG) was used to assess the localized neuromuscular properties of the vastus lateralis. TMG measurements were assessed using a 1 ms monophasic electrical impulse that elicited a twitch contraction whereby a digital displacement sensor measured the displacement of the muscle belly (TMG BMC Ltd., Ljubljana, Slovenia). For TMG measurements, subjects laid supine on a table with their right knee relaxed on a support with 30° of knee flexion (0° = full extension) according to the manufacturer’s guidelines. All measurements were recorded in the muscle belly of the vastus lateralis (Wilson et al. 2018) with the stimulating electrodes placed according to the SENIAM guidelines for electromyography, the placement of which were marked with permanent marker for consistent measurements throughout the study period. Stimulations with progressively increasing intensity (i.e. 10 milliamperes) were performed until the time-displacement curve of the evoked muscle twitch did not change or increase. This process was carried out before exercise (BASE) and 2, 5, and 10 minutes post-exercise (P2, P5, P10, respectively).

To account for possible day-to-day differences within each subject and between subjects, all post-exercise TMG variables (amplitude of muscle belly displacement, $D_M$; delay time, $T_D$, from the electrical signal to 10% of the maximal $D_M$; contraction time, $T_C$, the time from 10% to 90% of the maximal $D_M$; and sustain time of the muscle contraction, $T_S$, which is the total time....
that the $D_M$ is greater than 50% of the maximal $D_M$) were expressed as a percentage relative to the
day’s BASE value for each subject.

**Muscle Oxygenation**

A near-infrared spectroscopy device (OxiPlex TS, ISS Inc, Champaign, IL, USA) was used
to obtain continuous measurements (1 Hz) of total haemoglobin concentration (tHb) and tissue
oxygen saturation ($SO_2$) of the right vastus lateralis. Near-infrared spectroscopy can measure
regional changes in tHb, and these data can be used to provide indirect assessments of blood flow
in the area of examination (Neary 2004). Increased blood flow (i.e. tHb) results in greater oxygen
delivery to working muscles (i.e. $SO_2$), which would likely benefit recovery between high-intensity
efforts by augmenting the aerobic processes associated with phosphocreatine resynthesis
(Dominguez et al. 2018). These variables may therefore provide insight regarding the mechanisms
of why rest-redistribution could benefit exercise performance. To minimize the possibility of
movement beneath the sensor during rapid concentric actions of the large vastus lateralis group,
the rigid sensor was positioned on the lateral aspect of the middle of the vastus lateralis, outlined
with permanent marker for consistent placement throughout the study. This placement also assured
that the OxiPlex sensor would not interfere with TMG measurements. Baseline values were
collected at the same time and in the same supine position as the TMG testing, and the average of
the middle 30-second resting period was used for BASE values. Due to the following dynamic
warm-up procedures and the fragility of the OxiPlex cables, the OxiPlex software was then paused,
the sensor stopped transmitting and receiving signals, and the sensor was removed from the
participant and placed in a dark bag. The sensor was again secured to the leg and remained secured
and covered for the remainder of the visit while the software was running again (i.e. isokinetic
exercise and post-exercise period).
Within the Oxiplex software, an in-built trigger was activated to mark the points immediately before the 1st, 11th, 21st, and 31st repetitions and immediately after the 10th, 20th, 30th, and 40th repetitions for the subsequent analyses of time-sensitive measurements. Like TMG measurements, to account for possible day-to-day differences within each subject and between subjects, tHb and SO_2 were expressed as a percentage relative to the day’s BASE value for each individual. From these relative values, the area under the curve (AUC) was calculated between different triggered timestamps to determine the effect of each protocol across various time epochs of interest (Agbangla et al. 2017), with rest periods included in the analyses to provide comparisons between the TS and RR sessions performed with both fast and slow contraction velocities.

*Rating of Perceived Exertion*

The rating of perceived exertion (RPE) was assessed after every 10th repetition during TS and RR using a 0-10 OMNI scale for resistance exercise (Morishita et al. 2014). Session RPE was assessed approximately 15 minutes after the final repetition, after the post-exercise measures while the subject was preparing to exit the laboratory. Subjects were familiarized with the scale, and an exercise-specific anchoring process was not performed. Considering the different velocities of the protocols and the fact that subjects were not going to reach muscular failure, we simply wanted them to compare their perceived exertion to their general resistance-training experience, as they were resistance-trained.

*Statistical Analyses*

All data were assessed via the Shapiro-Wilk test and were normally distributed. As the purpose of this study was to compare the effect of two different protocols at two different speeds, the two speeds were not compared to each other, but the experiment can be considered to be two
independent experiments: one experiment comparing set structure protocols at a slow speed, and another at a fast speed. Therefore, each statistical test was conducted separately for each speed, meaning that each test occurred twice: once for $60^\circ \cdot \text{s}^{-1}$ and once for $360^\circ \cdot \text{s}^{-1}$.

For PT, TW, and POW, $2(\text{protocol}) \cdot 10(\text{repetition})$ repeated measures ANOVA were used. For RPE, $2(\text{protocol}) \cdot 4(\text{set})$ repeated measures ANOVA were used. For baseline and post-exercise Tc, Dm, Td, Ts, tHb, and SO$_2$, $2(\text{protocol}) \cdot 4(\text{time})$ repeated measures ANOVA were used. The sum of the TW, isokinetic maintenance and decline variables, session RPE, and the mean session values of tHb and SO$_2$ were assessed using paired t-tests. For all ANOVA, an LSD post-hoc follow-up test was used where necessary, and when sphericity was not assumed, a Greenhouse-Geisser correction was used. All tests were performed using SPSS (IBM, version 23). Additionally, Hedge’s g effect sizes were calculated using a custom Excel spreadsheet and can be interpreted as trivial ($g < 0.2$), small ($g$ between 0.20 and 0.49), moderate ($g$ between 0.50 and 0.79), and large ($g \geq 0.80$), but partial eta-squared ($\eta^2_p$) was the reported effect size for each ANOVA.

RESULTS

Isokinetic Performance Measures

For PT$_{60}$, there was a protocol*repetition interaction ($p = 0.038$, $\eta^2_p = 0.189$) (Figure 2a), but no main effect for protocol ($RR_{60} = 226.35 \pm 44.98$ N; $TS_{60} = 219.52 \pm 36.31$ N; $p = 0.298$, $\eta^2_p = 0.072$). For PT$_{360}$, there was a protocol*repetition interaction ($p = 0.020$, $\eta^2_p = 0.202$) (Figure 2a), but no main effect for protocol ($RR_{360} = 113.57 \pm 19.02$ N; $TS_{360} = 107.88 \pm 13.36$ N; $p = 0.119$, $\eta^2_p = 0.154$). There were no differences between protocols for PT maintenance or decline at either speed (Table 1).
For TW$_{60}$, there was a protocol*repetition interaction ($p = 0.007; \eta^2_p = 0.263$) (Figure 2b), but no main effect for protocol (RR$_{60} = 216.59 \pm 42.51$ J; TS$_{60} = 208.92 \pm 35.79$ J; $p = 0.273; \eta^2_p = 0.080$). For TW$_{360}$, there was a protocol*repetition interaction ($p = 0.001; \eta^2_p = 0.254$) (Figure 2b), but no main effect for protocol (RR$_{360} = 70.47 \pm 9.97$ J; TS$_{360} = 65.74 \pm 7.78$ J; $p = 0.102; \eta^2_p = 0.168$). There were no differences between protocols for TW maintenance or decline at either speed (Table 1). There was also no difference in the sum of the TW at either speed (TS$_{60}$ 8.356 ± 1.431 kJ, RR$_{60}$ 8.664 ± 1.700 kJ, $p = 0.271, g = 0.19$ [95% CI -0.50 to 0.89]; TS$_{360}$ 2.629 ± 0.311 kJ, RR$_{360}$ 2.818 ± 0.399 kJ, $p = 0.102; g = 0.52$ [95% CI -0.19 to 1.22]).

For POW$_{60}$, there was neither a protocol*repetition interaction ($p = 0.058; \eta^2_p = 0.169$) nor a main effect for protocol (Figure 2c) (RR$_{60}$ = 236.69 ± 46.93 J; TS$_{60}$ = 228.35 ± 38.51 J; $p = 0.200, \eta^2_p = 0.107$). For POW$_{360}$, there was a protocol*repetition interaction ($p = 0.004, \eta^2_p = 0.257$) (Figure 2c), but there was not a main effect for protocol (RR$_{360}$ = 680.81 ± 115.23 J; TS$_{360}$ = 647.86 ± 79.41 J; $p = 0.132, \eta^2_p = 0.144$). There were no differences between protocols for POW maintenance or decline at either speed (Table 1).

**Rating of Perceived Exertion**

For RPE$_{60}$, there was not a protocol*set interaction ($p = 0.283, \eta^2_p = 0.080$), but there was a main effect for protocol ($p = 0.003, \eta^2_p = 0.445$) and set ($p \leq 0.001, \eta^2_p = 0.679$). RPE was significantly less during RR$_{60}$ compared to TS$_{60}$ ($p = 0.003$), and RPE progressively increased throughout the protocols (Set1 < Set 2 < Set 3 < Set 4; all $p \leq 0.002$) (Figure 3). Session RPE$_{60}$ was less ($p = 0.006; g = 0.64$ [95% CI -0.07 to 1.35]) during RR (5.75 ± 1.64) than TS (6.75 ± 1.39).
For RPE\textsubscript{360}, there was neither a protocol*set interaction (\(p = 0.360, \eta^2_p = 0.062\)) nor a main effect for protocol (\(p = 0.093, \eta^2_p = 0.177\)), but there was a main effect for set (\(p \leq 0.001, \eta^2_p = 0.493\)) with RPE progressively increasing throughout the protocols until final set (Set 1 < Set 2, Set 3, and Set 4, \(p \leq 0.003, 0.001\), and 0.001, respectively; Set 2 < Set 3 and Set 4, \(p = 0.029\) and 0.027, respectively) (Figure 3). Session RPE\textsubscript{360} was less (\(p = 0.036; g = 0.56 [95\% \text{ CI } -0.14 \text{ to } 1.27]\)) during RR (2.31 ± 1.31) than TS (3.00 ± 1.06).

\textit{Tensiomyography Measures}

For T\textsubscript{C60}, there was neither a protocol*time interaction (\(p = 0.118, \eta^2_p = 0.135\)) nor a main effect for protocol (\(p = 0.115, \eta^2_p = 0.157\)), but there was a main effect for time (\(p \leq 0.001, \eta^2_p = 0.667\)). When collapsed across protocol, P2, P5, and P10 were all less than BASE (\(p \leq 0.004\)), and P10 was greater than P2 and P5 (\(p < 0.001\)) (Figure 4a). For T\textsubscript{C360}, there was neither a protocol*time interaction (\(p = 0.054, \eta^2_p = 0.183\)) nor a main effect for protocol (\(p = 0.055, \eta^2_p = 0.244\)), but there was a main effect for time (\(p \leq 0.001, \eta^2_p = 0.443\)). When collapsed across protocol, P2 and P5 were less than BASE (\(p \leq 0.001\)), but P10 was not different than BASE (\(p = 0.269\)) (Figure 4a).

For D\textsubscript{M60}, there was neither a protocol*time interaction (\(p = 0.433, \eta^2_p = 0.049\)) nor a main effect for protocol (\(p = 0.350, \eta^2_p = 0.058\) or time (\(p = 0.928, \eta^2_p = 0.002\)) (Figure 4b). For D\textsubscript{M360}, there was neither a protocol*time interaction (\(p = 0.262, \eta^2_p = 0.085\)) nor a main effect for protocol (\(p = 0.210, \eta^2_p = 0.102\)) or time (\(p = 0.412, \eta^2_p = 0.052\)) (Figure 4b).

For T\textsubscript{D60}, there was neither a protocol*time interaction (\(p = 0.629, \eta^2_p = 0.018\)) nor a main effect for protocol (\(p = 0.552, \eta^2_p = 0.024\)), but there was a main effect for time (\(p = 0.007, \eta^2_p = 0.362\)). When collapsed across protocol, P2 and P5 were less than BASE (\(p \leq 0.001\)), but P10 was
not different than BASE (p = 0.985) (Figure 4c). For T_{D360}, there was neither a protocol*time interaction (p = 0.320, \eta_p^2 = 0.021) not a main effect for protocol (p = 0.955, \eta_p^2 = 0.000), but there was a main effect for time (p < 0.001, \eta_p^2 = 0.397). When collapsed across protocol, P2 and P5 were less than BASE (p < 0.001), but P10 was not different than BASE (p = 0.534) (Figure 4c).

For T_{S60}, there was neither a protocol*time interaction (p = 0.256, \eta_p^2 = 0.085) nor a main effect for protocol (p = 0.569, \eta_p^2 = 0.022), but there was a main effect for time (p < 0.001, \eta_p^2 = 0.666). When collapsed across protocol, P2, P5, and P10 were less than BASE (p < 0.001), P2 was less than P5 and P10 (p < 0.05), but P5 and P10 were not different (p = 0.197) (Figure 4d). For T_{S360}, there was neither a protocol*time interaction (p = 0.542, \eta_p^2 = 0.046) nor a main effect for protocol (p = 0.423, \eta_p^2 = 0.043), but there was a main effect for time (p < 0.001, \eta_p^2 = 0.714). When collapsed across protocol, P2, P5, and P10 were less than BASE (p < 0.001), P2 was less than P5 and P10 (p \leq 0.004), but P5 and P10 were different (p = 0.229) (Figure 4d).

**Near-infrared Spectroscopy**

The muscle blood flow and oxygenation characteristics as estimated via NIRS are shown in Figure 5. For the AUC of tHb for groups of 10 repetitions, a significant main effect was observed for protocol (p < 0.001, \eta_p^2 = 0.979), but not for time (p = 0.888, \eta_p^2 = 0.015) or the protocol*time interaction (p = 0.645, \eta_p^2 = 0.043). *Post hoc* analyses demonstrated differences existed between all protocols (all p < 0.001), with the highest values observed during the RR_{60} protocol, and the lowest for the TS_{360}. For the AUC of tHb across the entire exercise bout (inclusive of all rest periods), there was a significant main effect for protocol (p < 0.001, \eta_p^2 = 0.610), with all protocols differing from one other (all p \leq 0.033). In the 10 minutes of rest following each trial, there was no main effect of protocol on tHb AUC (p = 0.743, \eta_p^2 = 0.027).
For the AUC of SO\textsubscript{2} for groups of 10 repetitions, there were significant main effects for protocol ($p < 0.001$, $\eta_p^2 = 0.986$) and time ($p < 0.001$, $\eta_p^2 = 0.557$), but not for the protocol*time interaction ($p = 0.493$, $\eta_p^2 = 0.056$). Post hoc analyses indicated that SO\textsubscript{2} AUC values were different between all protocols (all $p < 0.001$), with the highest values during the RR\textsubscript{60} protocol, and the lowest for TS\textsubscript{360}. The first 10 repetitions demonstrated higher SO\textsubscript{2} AUC values compare to the 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} groups of 10 repetitions (all $p < 0.001$). The AUC of SO\textsubscript{2} for the entire exercise bout demonstrated a significant main effect for protocol ($p < 0.001$, $\eta_p^2 = 0.651$), with post hoc analyses indicating all protocols differed from each other (all $p < 0.001$) with the exception of RR\textsubscript{60} and TS\textsubscript{60} ($p = 0.057$). In the 10 minutes of rest following each trial, there was no main effect of protocol on SO\textsubscript{2} AUC ($p = 0.438$, $\eta_p^2 = 0.058$).

**DISCUSSION**

This study is the first to investigate the effects of rest-redistribution on a variety of performance and physiological responses to isokinetic concentric knee extensions, and several novel findings were observed. First, redistributing long inter-set rest periods into shorter but more frequent sets seemed to have no effect on the overall PT, TW, or POW during exercise at either speed, despite the TS protocols mimicking the progressive decline in velocity and power present in previous studies (Jukic and Tufano 2019; Oliver et al. 2016b; Tufano et al. 2016b; Tufano et al. 2017b) and decreased performance for select latter repetitions during TS (Figure 2), especially for TS\textsubscript{360}. Secondly, session RPE was significantly less during RR than TS at both slow and fast speeds, and effect sizes generally indicated lower RPE during exercise, especially during RR\textsubscript{60}. Thirdly, there were no significant effects for protocol on TMG variables, but effect sizes favored a quicker recovery after RR compared to TS. Lastly, RR resulted in increased total muscle blood
flow and oxygen saturation during exercise compared to TS, indicating a greater oxygen supply to the muscle during the course of the entire RR protocol.

*During exercise*

Within the cluster set realm, this is the first rest-redistribution study conducted on an isokinetic dynamometer. Although free weights and Smith machine exercises have more ecological validity, velocity of concentric muscle actions is not controlled and is usually a dependent variable using these exercises. As such, it has been difficult to determine whether rest redistribution directly affects force output since peak force relates to both the external load and movement velocity (Bentley et al. 2010) and mean force largely depends on the external load (Tufano et al. 2017b) during free-weight movements. Thus, velocity has not been controlled during any previous cluster set or rest-redistribution studies (García-Ramos et al. 2015; Tufano et al. 2019; Tufano et al. 2017a; Tufano et al. 2017b) and force output could not be assessed in isolation. By using a fixed angular velocity, the present study is the first to show that when averaging all 40 repetitions together, RR did not have an overall effect on force output (i.e. torque), but it maintained PT compared to the latter repetitions of TS (Figure 2). This effect was significant during RR⁸₀, indicating that rest-redistribution may be more effective during explosive activities compared to maximal strength activities, but future research should determine this notion in multi-joint exercises within the same study.

Much of the cluster set literature suggests changes in velocity are primarily responsible for changes in power output, with force remaining unchanged (Oliver et al. 2016b; Tufano et al. 2018; Tufano et al. 2016b). Although this phenomenon may be true, such statements are likely oversimplified because velocity likely occurs relative to the amount of force produced, and rate at which it is generated. Therefore, “velocity maintenance” is likely the result of the ability to
continuously produce rapid force. By using an isokinetic dynamometer, we were able to determine not only if subjects could maintain PT, but whether they were able to produce greater torque throughout the entire range of motion by measuring TW throughout a standard distance.

Interestingly, our data show that RR may have had a greater effect on TW than on PT, evidenced by greater pro-RR effect sizes for TW than PT compared to TS, especially during RR360 (Figures 3a and 3b). In previous cluster set and rest-redistribution studies that utilized free-weight exercises, total work is usually the same between the set structures as it goes hand-in-hand with mean force (i.e. external load) and displacement of the barbell (Denton and Cronin 2006). However, by accounting for torque that is applied throughout an entire fixed range of motion, the present study indicates that not only can rest-redistribution help in maintaining maximal concentric force (i.e. greater PT) compared to latter repetitions of traditional sets, but it may also help athletes generate greater force over a larger range of motion (i.e. greater TW), which could have significant real-world implications.

Furthermore, Figure 2 shows that performance decreased during the first repetition performed after the 95-second rest periods during TS, and a similar pattern can be seen after the 15-second rest periods during RR but to a much lesser extent. This finding is important to consider, as many researchers and coaches utilize inter-repetition rest, which may work well if the inter-repetition rest periods are short, for example 15 seconds like in the present study or perhaps even up to 30 or 40 seconds as was previously observed (García-Ramos et al. 2015; Moir et al. 2013; Tufano et al. 2017a). However, if a rest period extends towards 45 or 60 seconds, the performance of the next repetition may be decreased (Tufano et al. 2017a). Although numerous studies have indicated that inter-repetition rest is beneficial for maintaining acute performance compared to traditional sets (Iglesias-Soler et al. 2013; Iglesias-Soler et al. 2012; Iglesias et al. 2010), many of
those studies did not compare multiple inter-repetition rest durations (Tufano et al. 2016a), or if they did, the durations remained within the previously described “potentiation period” under 15 seconds with a few extending to 30 seconds. Therefore, it is still unknown how long inter-repetition or intra-set rest periods can be before the performance of the subsequent repetition is decreased, but the present data indicate that at both speeds, 15-seconds likely functions within this potentiation period whereas 95-seconds does not.

Despite PT, TW, and POW being similar between RR and TS at both speeds, RPE was less during RR than TS, with larger effects being present at the slower speed. This finding corresponds with previous research showing lower RPE scores during rest-redistribution protocols (Jukic and Tufano 2019; Mayo et al. 2014; Mayo et al. 2019). Such findings are often explained by the hypothesized quicker replenishment of immediate energy stores when rest periods are more frequent (Gorostiaga et al. 2010), but the present study adds another dimension to that hypothesis via tissue oximetry.

The muscle oxygenation data indicates that for each group of 10 repetitions, the RR protocols resulted in significantly greater tHb and SO$_2$ values (Figure 5a-b). This is likely because of the longer total time needed for 10 repetitions to be completed during RR compared with TS. Each group of 10 repetitions in the RR protocols were split into clusters of 2 with 15 s rest between; therefore, each group of 10 repetitions in the RR sessions took an additional 60s to complete (i.e. 15 s rest between reps 2 to 3, 4 to 5, 6 to 7, and 8 to 9). We also observed that the TS$_{60}$ and RR$_{60}$ protocols facilitated greater tHb and SO$_2$ values compared with TS$_{360}$ and RR$_{360}$. These results are also likely influenced by the time taken to complete groups of 10 repetitions, which is obviously greater when contractions are performed at slower speeds. Nevertheless, previous research has also shown that oxygen saturation is more affected by slower muscle actions, possibly due to a greater
muscle deoxygenation (Formenti et al. 2018). A more severe deoxygenation of the muscle would increase reliance on anaerobic metabolism, which would likely impact physical performance and potentially acute hypertrophic responses during exercise (Schoenfeld 2013).

Additionally, tHb and SO$_2$ was also greater during RR when examining the total area under the curve inclusive of all rest periods and muscle contractions (Figure 5c-d), which likely represents a greater oxygen supply at the muscle during the course of the entire RR protocols, which were time-, range of motion- and repetition-matched to TS. Considering this, these data are likely even more important when considering the entirety of the protocols. One explanation could be the frequent concentric muscle actions that occur during RR, increasing the frequency of mechanical pumping to facilitate venous return, possibly reducing metabolite accumulation, increasing circulation, and replenishing PCr stores to a greater extent compared to TS. Unfortunately, heart rate was not measured in this study, and future research should pair these localized responses with global cardiovascular responses. Nevertheless, as our primary objective was to determine the localized demands associated with TS and RR protocols, the observation that RR facilitated increased blood flow and oxygen saturation compared to TS, irrespective of the contraction velocity, is a novel finding and could partially explain the lower lactate values of cluster set protocols reported by many (Denton and Cronin 2006; Oliver et al. 2015; Tufano et al. 2019), despite a lesser cardiovascular demand (Iglesias-Soler et al. 2014; Mayo et al. 2017; Rio-Rodriguez et al. 2016).

After Exercise

The majority of cluster set and rest-redistribution literature has focused on the effects of rest period duration and frequency on exercise performance itself, with few studies investigating the post-exercise effects of different set structures. Our TMG data show that fatigue was present
following TS and RR at both speeds, with decreases in Tc that only recovered by P10 after RR\textsubscript{360} and TS\textsubscript{360} but did not fully recover after RR\textsubscript{60} and TS\textsubscript{60}. These data are supported by previous research that shows more post-exercise fatigue during maximal strength exercise compared to explosive exercise (Linnamo et al. 1997). Although there was no significant difference between the TS and RR protocols at either speed, effect sizes favored a quicker and more complete recovery for RR at all post-exercise time points, indicating that TS likely resulted in greater residual fatigue than RR. Similar post-exercise patterns were observed for Dm, Td, and Ts, but the effect sizes between RR and TS were lower and the standard deviations were quite large, meaning that Dm, Td, and Ts may not have been sensitive enough to reflect any possible changes in peripheral fatigue. Furthermore, the percentage decline for PT, TW, and POW were less in this study (approximately 30% decline) compared to other studies using free-weights performed closer to, or reaching, failure (about 50-70% decline) (Izquierdo et al. 2006; Sanchez-Medina and Gonzalez-Badillo 2011), indicating that in some real-life resistance-training scenarios, TS may affect muscle contractile ability to an even greater extent than in the present study. Therefore, as Tc recovered quicker following RR compared to TS, and considering that the present study implemented unilateral concentric knee extensions, coaches should be aware that TS may result in accumulated fatigue during training, especially during compound multi-joint movements performed to or near failure, but this hypothesis should be tested in future research.

In addition to subjects exhibiting a lower RPE for RR than TS during exercise, the session RPE, which was measured at 15 minutes after the protocol, retained this relationship, with subjects still perceiving that RR was easier than TS at both speeds. This finding was expected, and previous researchers have also noted that session RPE is less during cluster set or rest-redistribution protocols (Jukic and Tufano 2019; Mayo et al. 2014; Rio-Rodriguez et al. 2016). However, despite
greater tHb and SO$_2$ during RR, the post-exercise area under the curve was not different between RR and TS. Mean SO$_2$ increased for up to 5 minutes post-exercise in all conditions, after which time it remained stable (data not shown), which may indicate that the single joint exercise implemented was not metabolically challenging enough to observe differences between RR and TS protocols on post-exercise tissue oxygenation characteristics, despite the during-exercise differences.

**General summary and limitations**

Although this study sheds light on how rest-redistribution affects concentric performance at different speeds, future research should investigate the effects of rest-redistribution using eccentric muscle actions, the stretch-shortening cycle, or both, but still in a controlled laboratory setting where extraneous variables can be limited. Along these lines, the present study sacrificed the ecological validity of traditional resistance training for internal validity via a more controlled experimental design. While this could be considered as a practical limitation of our design (i.e. no eccentric component and isokinetic velocities that do not occur in real-life), we have provided novel findings that highlight the importance of rest-redistribution for maintaining concentric force output during the entire range of motion (i.e. total work) at fast and slow velocities. Unfortunately, we were unable to implement post-exercise strength testing, as it may have interfered with the TMG and oxygenation measurements, and therefore post-exercise fatigue could not be comprehensively explored. Nevertheless, we did identify a quicker peripheral recovery after exercise with rest-redistribution. Additionally, the isokinetic knee extensions in the present study were unilateral, and it is possible that the single-joint nature of the knee extensions was not as demanding as a multi-joint exercise (Thomas et al. 2018) despite RPE$_{60}$ reaching 6 to 7 out of 10 and RPE$_{360}$ reaching only 2 or 3 out of 10.
CONCLUSION

Splitting long inter-set rests into shorter but more frequent rest periods was beneficial for maintaining performance and encouraging quicker recovery after exercise, especially when exercising at a faster velocity. It is important to note that these findings hold true in the present study, but may not be applicable with lower training volumes, as the pattern of fatigue only become noticeable during latter repetitions. Therefore, rest-redistribution may be a more viable strategy to use when aiming to maintain performance during explosive, ballistic exercises, but still may play a smaller role during maximal strength exercises.

Acknowledgements: none

Conflict of Interest: None. All results are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

References


Table 1: Maintenance and decline of peak torque, total work, and power output during traditional sets (TS) and rest-redistribution sets (RR). Maintenance was calculated by comparing all repetitions of each protocol of the best repetition of that protocol, and decline was calculated as the percentage difference between the worst and best repetition of all repetitions divided by the best repetition. There were no differences (p > 0.05) or moderate-to-large effect sizes between protocols for any variable.

<table>
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<tr>
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**Figure 1:** Traditional and rest redistribution sets were both performed at 60°·sec⁻¹ and 360°·sec⁻¹, each on a separate day, resulting in four protocols, each separated by approximately 48 to 72 hours.

**Figure 2:** Isokinetic dynamometry data during traditional sets (TS) and rest redistribution sets (RR) for a) peak torque (PT); b) total work (TW); and c) power (POW). Significant differences between TS and RR (p < 0.05)* are shown in addition to moderate and large effect sizes where appropriate.

**Figure 3:** Rating of perceived exertion (RPE) during and after traditional sets (TS) and rest redistribution sets (RR) at 60°·sec⁻¹ and 360°·sec⁻¹. Significant differences between TS and RR (p < 0.05)* are shown in addition to moderate and large effect sizes where appropriate.

**Figure 4:** Tensiomyography measures before and after traditional sets (TS) and rest redistribution sets (RR) for a) contraction time (Tc); b) muscle belly displacement (Dm); c) delay time (Td); and d) sustain time (Ts). No significant differences were present (p > 0.05), but moderate and large effect sizes (Hedge’s g) are displayed where appropriate.

**Figure 5:** Near-infrared spectroscopy data for total hemoglobin concentration and oxygen saturation during traditional sets (TS) and rest-redistribution sets (RR) at slow (60) and fast (360) speeds. * different than 60RR, # different than 360RR, † different than 60TS, ‡ different than 360TS (all p < 0.05).
Traditional Sets

Inter-Set Rest: 3 x 95 s = 285 s

Rest Redistribution Sets

Inter-Set Rest: 19 x 15 s = 285 s

RPE: Rating of perceived exertion

Tensiomyography measures

Oxiplex continuous measurement with triggered placement markers

409x161mm (96 x 96 DPI)
Figure 2

252x190mm (96 x 96 DPI)
Figure 3

240x176mm (96 x 96 DPI)