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The effects of cluster sets and rest redistribution on acute resistance training sessions

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Habilitation work

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I declare that I have produced the submitted work independently, using only the cited literature or in cooperation with the mentioned colleagues according to each chapter. No data is copied or otherwise misused.

Prague, September 16th, 2020

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Jméno a příjmení:	*Číslo OP:*	*Datum vypůjčení:*	*Poznámka:*

Contents

List of tables

List of figures

List of abbreviations

%MVL	Percent mean velocity loss
%PVL	Percent peak velocity loss
1RM	1 repetition maximum
12RM	12 repetition maximum
ANOVA	Analysis of variance
ATP	Adenosine Triphosphate
C	Cortisol
CRD	Concentric repetition duration
CRDI	Concentric repetition duration increase
CS	Cluster sets
CS2	Cluster set of two repetitions (protocol)
CS4	Cluster set of four repetitions (protocol)
CV	Coefficient of variation
CTUT	Concentric time under tension
DISP	Displacement
DISPD	Displacement decline
ECC	Eccentric
ETUT	Eccentric time under tension
EW:R	Equal work-to-rest ratio
GH	Growth hormone
La	Lactate
LPT	Linear position transducer
MF	Mean force

MP	Mean power
MPD	Mean power decline
MPM	Mean power maintenance
MPmax	Maximum mean power
MV	Mean velocity
MVD	Mean velocity decline
MVL	Mean velocity loss
MVM	Mean velocity maintenance
NER	Number of effective repetitions
NTR	Number of total repetitions
PAP	Post-activation potentiation
PCr	Phosphocreatine
PF	Peak force
PMeanMax	Maximum mean power output
PP	Peak power
PPD	Peak power decline
PPM	Peak power maintenance
PV	Peak velocity
PVD	Peak velocity decline
PVM	Peak velocity maintenance
RM	Repetition maximum
RPE	Rating of perceived exertion
RR	Rest redistribution
RR1	Rest redistribution 1 protocol

RR4	Rest redistribution 4 protocol
RR6	Rest redistribution 6 protocol
RT	Resistance training
SHBG	Sex hormone binding globulin
SSC	Stretch-shortening cycle
TS	Traditional sets
TT	Total testosterone
TUT	Time under tension
TW	Total work
VBT	Velocity-based training

Appendix 1: List of peer-reviewed publications

(Chapter 2) Tufano JJ, Brown LE, and Haff GG. Theoretical and practical aspects of different cluster set structures: a systematic review. *Journal of Strength and Conditioning Research.* 31(3): 848-867, 2017. https://doi.org/10.1519/JSC.0000000000001581

(Chapter 3) Tufano JJ, Conlon JA, Nimphius S, Brown LE, Seitz LB, Williamson BD, and Haff GG. Maintenance of velocity and power with cluster sets during high-volume back squats. *International Journal of Sports Physiology and Performance*, 11(7): 885-892, 2016. https://doi.org/10.1123/ijspp.2015-0602

(Chapter 4) Tufano JJ, Conlon JA, Nimphius S, Brown LE, Banyard HG, Williamson BD, Bishop LG, Hopper AJ, and Haff GG. Cluster sets: permitting greater mechanical stress without decreasing relative velocity. *International Journal of Sports Physiology and Performance*, 12(4):463-469, 2017. https://doi.org/10.1123/ijspp.2015-0738

(Chapter 5) Tufano JJ, Conlon JA, Nimphius S, Brown LE, Petkovic A, Frick J, and Haff GG. Effects of cluster sets and rest redistribution on mechanical responses to back squats in trained men. *Journal of Human Kinetics*, 58(1):35-43, 2017. https://doi.org/10.1515/hukin-2017-0069

(Chapter 6) Tufano JJ, Conlon JA, Nimphius S, Oliver JA, Kreutzer A, and Haff GG. Different cluster sets result in similar metabolic, endocrine, and perceptual responses in trained men. *Journal of Strength and Conditioning Research*, 33(2): 346-354, 2019. https://doi.org/10.1519/JSC.0000000000001898

(Chapter 7) Jukic I & **Tufano JJ**. Shorter but more frequent rest periods: no effect on velocity and power compared to traditional sets not performed to failure. *Journal of Human Kinetics*, 66(1): 257-268, 2019. http://doi.org/10.2478/hukin-2018-0070

(Chapter 8) Tufano JJ, Halaj M, Kampmiller T, Novosad A, Buzgo G. Cluster vs. traditional sets: levelling out the playing field using a power-based threshold. *PlosOne*, 13(11), e0208035, 2018. https://doi.org/10.1371/journal.pone.0208035

(Chapter 9) Jukic I & **Tufano JJ**. Rest redistribution functions as a free and ad-hoc equivalent to commonly used velocity-based training thresholds during clean pulls at different loads. *Journal of Human Kinetics*, 68: 131-140, 2019. http://doi.org/10.2478/hukin-2019-0052

(Chapter 10) Jukic I & **Tufano JJ**. Traditional three-to-five-minute inter-set rest periods may not be necessary when performing fewer repetitions per set, using cleans pulls as an example. *Journal of Strength and Conditioning Research*, 2020. https://doi.org/10.1519/jsc.0000000000003908

(Chapter 11) Jukic I & **Tufano JJ**. Acute effects of shorter but more frequent rest periods on mechanical and perceptual fatigue during a weightlifting derivative at different loads in strength-trained men. *Sports Biomechanics,*2020. https://doi.org/10.1080/14763141.2020.1747530

Appendix 2: Conference Presentations

Tufano JJ, Conlon JA, Seitz LB, Bishop LG, Williamson BD, Haff GG. Acute effects of hypertrophy-oriented cluster sets on work, power, and velocity. *International Conference on Strength Training, Abano Terme, Italy, October 2014. European Journal of Sport Studies, 2(supplement):46, 2014.*

Tufano JJ, Conlon JA, Bishop LG, Williamson BD, Hopper AJ, Seitz LB, Nimphius S, and Haff GG. Effects of cluster sets on acute hypertrophic variables and fatigue during a high-volume squat session. *National Strength and Conditioning Association Annual Conference, Orlando, FL, July 2015. Journal of Strength and Conditioning Research, 30:s5-s6, 2016.*

Tufano JJ, Conlon JA, Nimphius S, Frick J, Williamson BD, Petkovic A, Haff GG. Effect of three different cluster set structures on force, velocity, and power during a high-volume back squat session. *National Strength and Conditioning Association Annual Conference, New Orleans, LA, July 2016.*

Jukić I, Young M, **Tufano JJ**. Effects of different set structures on RPE, velocity, and power decrement during a back-squat exercise. *National Strength and Conditioning Association International Conference*, Madrid, Spain, September 2018.

Halaj M, Gajdoschík A, Mištinová L, Buzgó G, Novosád A, Kampmiller T, **Tufano JJ**. Cluster vs traditional sets: differences in training volume, velocity, and power using a power-loss threshold. *National Strength and Conditioning Association International Conference*, Madrid, Spain, September 2018.

Tufano JJ, Jukic I. Rest redistribution functions as a free and ad-hoc equivalent to commonly used velocity-based training thresholds during clean pulls at different loads.

National Strength and Conditioning Association Annual Conference, Washington DC, July 2019.

Tufano JJ, Jukic I. The effects of rest redistribution on velocity and power during clean pulls at different loads. *National Strength and Conditioning Association Annual Conference*, Washington DC, July 2019.

Abstract

It has been proposed that a muscle’s cross-sectional area plays a large role in a muscle’s maximal shortening velocity and its ability to produce force, making hypertrophy extremely important for all populations. Traditionally, muscle growth has been achieved by performing large volumes of work with short rest periods in between sets, resulting in large amounts of acute neuromuscular fatigue, likely resulting in short-term decreases in strength or power output. More recently, research has shown that hypertrophy can also be stimulated by training with loads that are well below or above the previously mentioned load recommendations. Regardless of the training method used, an underlying theme within many hypertrophy-based studies is that increasing the amount of mechanical work yields a greater hypertrophic response. By utilizing cluster sets, which involve resting between groups of repetitions within a set, or rest-redistribution, which involves redistributing rest periods to create shorter but more frequent sets, partial recovery of adenosine triphosphate and phosphocreatine stores (combined with more frequent waste removal) may allow for greater training loads for a given volume, or a greater volume for a given load. By increasing the load, training volume, or both, a greater amount of external work may be accomplished, possibly increasing muscle growth and mechanical stress that likely increases strength. Additionally, recent research indicates that less-fatiguing resistance exercise is superior to highly fatiguing exercise for the development of strength and power, and is equally beneficial for hypertrophy, as long as the amount of total work is great. Therefore, a period of high-volume training whereby fatigue is minimized may provide the ideal stimuli for the development of muscular strength, hypertrophy, and power. Therefore, the overall purpose of the studies included in this work was to investigate the acute effects of cluster sets and rest redistribution using high volume back squats and other multi-joint movements such as the clean pull exercise. By doing so, it would be possible to determine how acute program

variables can be manipulated to create alternative resistance-training methods that may result in greater hypertrophy, strength, and power output than traditional sets without increasing acute neuromuscular fatigue. The acute effects of set-structure, training load, and rest interval duration and frequency were determined. Then, building on more recent evidence showing that less-fatiguing protocols further enhance strength and power adaptations compared to more fatiguing protocols, set structure design was further investigated. However, in these studies, rest-redistribution was investigated, as it does not require additional training time compared to cluster sets that include extra intra-set rest.

Collectively, the studies included within showed that cluster sets allowed for movement velocity and power output to be maintained compared to traditional sets, during which velocity and power output significantly decreased. Next, more frequent intra-set rest intervals allowed for a greater external load to be lifted for a given number of repetitions, resulting in greater total work and time under tension without decreasing relative movement velocity (i.e. relative fatigue). Then, the research showed that when using the same total rest duration, external load, and number of repetitions, changing the frequency and duration of intra-set rest intervals did not affect mechanical, metabolic, or hormonal responses, but the mechanical responses followed distinct patterns, which led us to further investigate. Following that, another study showed that rest-redistribution and cluster sets are likely only beneficial compared to traditional sets that are highly fatiguing and may not have a large effect compared to less-fatiguing traditional set protocols and that the number of repetitions within each cluster set should not exceed six repetitions. We also showed that rest-redistribution can mimic the desired acute responses to training seen during velocity-based training, what has become a popular and effective training method. However, rest-redistribution does not require any additional physical or monetary investment, meaning that coaches can utilize rest-redistribution during training. Lastly, we also showed that rest-redistribution becomes more important as the load and volume of an exercise increases, making the exercises feel easier while also maintaining performance: a seemingly perfect combination. Therefore, this series of studies concludes that set structures can be manipulated in a variety of ways (cluster sets and rest-redistribution) that may induce different, or even simultaneous, training adaptations ranging from hypertrophy to strength to power.

Chapter 1: General Introduction

Background and significance

Within a resistance training program, exercise selection, load, volume, and rest periods can be manipulated [1]. To induce skeletal muscle hypertrophy, it has been recommended that resistance-training performed two to three days per week, using moderate-to-heavy loads (70–85% of 1 repetition maximum (1RM)) for eight to twelve repetitions per set for one to three sets of single- and multiple-joint free-weight and machine exercises, resting one to two minutes between sets [2]. Interestingly, the optimal load for generating maximal power output for many compound resistance-training movements is similar to the recommended load for stimulating skeletal muscle growth. The main difference in implementation being that power-oriented training utilizes less training volume and longer rest periods [2-4]. Historically, the concept of block periodization concentrates on one primary training goal at a time, of which the residuals of that training phase, or block, will be used and maintained during the next phase to focus on another goal (i.e. hypertrophy, strength, or power) [1, 5]. For example, when aiming to increase skeletal muscle hypertrophy using the recommendations above, one often experiences a great deal of acute and chronic neuromuscular fatigue and must temporarily sacrifice the maximization of strength and power output. Due to this, strength and power may temporarily decrease during a training block that focuses mainly on hypertrophy [6]. Upon completion of a hypertrophic training block in a periodized training program, the focus of training may shift to building maximal strength, followed by maximal power output. In an ideal scenario, the strength- or power-oriented training stimuli would be great enough to maintain the cross-sectional area gained during the previous block of training, but it is possible that the amount of muscle gained may decrease over time, especially if sport-specific training is concurrently being conducted outside of the weight room [7].

To address the inherent drawbacks that are present in the block periodization model, parallel models of periodization may be implemented to allow for the continuous development of multiple training goals simultaneously and possibly over a longer period of time. Additionally, different periodization models may call for alternative methods of balancing fatigue and performance, opening the door for creativity within a set structure. When completing multiple repetitions in a continuous fashion without rest periods within each set (i.e. traditional sets (TS)), fatigue manifests and continues to increase unless a rest period is provided [8]. Therefore, depending on the purpose of a training session, TS structures often include inter-set rest periods ranging from 60 s to encourage metabolic stress to upwards of 300 s to allow for the replenishment of immediate energy sources so that the lifter can continue training at a specified intensity [9]. However, if fatigue is to be controlled or limited, short rest periods can be included within the sets (i.e. cluster sets (CS)) to allow for the maintenance of performance without sacrificing training intensity or volume [10, 11]. For example, if 12 repetitions are performed using TS, all 12 are performed successively. However, if CS are used, it is possible to insert a short rest period in between individual repetitions or groups of repetitions, creating small clusters of repetitions within each set.

In the early stages of my academic career in the beginning of 2013, researchers had mainly investigated the effects of CS on maintaining acute power output during exercises that are normally classified as explosive exercises, such as the power clean, clean pull, jump squat, and bench press throw [12-15]; but the effect of CS on higher-volume protocols indicative of traditional hypertrophic training remained relatively unexplored. Therefore, the central aim of my recent academic work was to examine the effect of various CS loading schemes on the mechanical and hormonal responses to high-volume free-weight back squats in resistance-trained men. Following those early experiments, my work and the work of a few of my students looked at other alternative set designs. Mainly, we investigated the effects of rest-redistribution, as it does not increase total training time, as the increased time necessary for cluster sets became a concern for many coaches. By determining a variety of acute effects (e.g. mechanical, perceptual, and hormonal) to different kinds of cluster set and rest-redistribution structures, coaches can more accurately prescribe exercise for their desired training stressors and subsequent adaptations.

Central Hypothesis

It was hypothesized that different CS protocols would result in different mechanical and hormonal responses when compared to TS and that the frequency and duration of the intra-set rest periods would play a large role in managing acute neuromuscular fatigue.

First aim: To determine how alterations to the number repetitions contained in each cluster of a CS impact the acute mechanical properties of high-volume back squats.

Hypothesis: It was hypothesized that the CS with the most total rest would exhibit greater movement velocity and power output than TS, but that force would be similar between the protocols.

Second aim: To determine if alterations to the load lifted in a CS would alter the mechanical properties associated with hypertrophy (with additional intra-set rest periods).

Hypothesis: It was hypothesized that CS with the greatest load would exhibit greater forces, total work, and time under tension while resulting in slower movements velocities than TS with a lighter load. Additionally, it was hypothesized that the increases in force would counteract the decreases in velocity, resulting in similar power outputs as TS.

Third aim: To determine how alterations to the frequency and duration of rest periods would alter the hormonal, metabolic, perceptual, and mechanical responses to high-volume back squats associated with hypertrophy.

Hypothesis: It was hypothesized that the CS which utilized the shortest and most frequent rest intervals would demonstrate smaller increases in blood lactate, cortisol, growth hormone, and testosterone. Additionally, the CS with the shortest and most frequent rest intervals would display the greatest movement velocities and power outputs as a result of inducing less fatigue.

Fourth aim: To determine whether a greater number of repetitions performed per cluster affects velocity and power maintenance.

Hypothesis: Based on previous research showing that power output decreases after 5 repetitions, it was hypothesized that performing 6 repetitions per CS would not maintain velocity and power output compared to TS.

Fifth aim: To determine whether rest-redistribution is also beneficial to less-fatiguing TS.

Hypothesis: It was hypothesized that rest-redistribution would in fact be less fatiguing than TS, despite the TS not being as fatiguing as previous protocols.

Sixth aim: To determine whether CS are also beneficial compared to less-fatiguing TS when both protocols use a power-based threshold, similar to more current TS structures that use objective measures to truncate each set before excessive fatigue ensues.

Hypothesis: It was hypothesized that CS would still be more beneficial than less-fatiguing TS for maintaining movement velocity and power output.

Seventh aim: Since the previous two aims were to see if rest-redistribution and CS could still be beneficial compared to less-fatiguing TS, this aim was to determine whether rest-redistribution could mimic power and velocity outputs similar to velocity-based training.

Hypothesis: It was hypothesized that rest-redistribution could maintain velocity and power enough to function as an ad-hoc alternative to velocity-based training.

Eighth aim: To determine whether the success of previous rest-redistribution protocols during the back squat would also be beneficial during a more explosive exercise such as the clean pull compared to traditional sets at different loads.

Hypothesis: It was hypothesized that compared to traditional sets, rest-redistribution would maintain acute exercise performance during the clean pull compared to traditional sets at all loads.

Ninth aim: To determine whether rest-redistribution could also maintain performance with variables associated with technique of the clean pull in addition to reducing the perception of effort.

Hypothesis: It was hypothesized that compared to traditional sets, rest-redistribution could maintain performance associated with clean pull technique accompanied by an easier perception.

General Notes about the Following Chapters

Please note that the text within the following chapters does not coincide 100% with the published or submitted form of their respective published versions. As different journals have different reference styles and abbreviation recommendations, the reference styles and abbreviations may have been changed to encourage consistency within this document. However, the body of the text, the information in the tables and figures, the general messages and conclusions, and the references have not been altered in any way.

Chapter 2: Literature Review

In 2008, Haff and colleagues published the first scientific review on CS in the *Strength and Conditioning Journal* [16] which contained a detailed review of all of the CS literature to date: only six studies at the time. In the same year, an article explaining the practical applications of CS appeared in *Professional Strength and Conditioning* [17]. Since then, a surge of CS literature has presented itself within the strength and conditioning literature, requiring an updated critical review on the topic which now includes a larger body of literature and numerous conference presentations. This chapter includes information regarding the brief history of CS, the terminology that will be used throughout this document, the present use of CS within the scientific literature, and directions for future research. In 2017, the following text presented within Chapter 2 was published in the *Journal of Strength and Conditioning Research*, and has since become one of the staple papers of reference for researchers in our field. Please note that the information in this chapter is true, but it is not 100% up-to-date. The information was left to be the same as the original publication so that the reader can understand what the current state of information was in 2016 when the research articles in this document started to be designed. The formatting of this chapter has been adjusted from the original published manuscript to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Theoretical and practical aspects of various cluster set structures: a systematic review

Tufano JJ, Brown LE, and Haff GG

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Abstract: When performing a set of successive repetitions, fatigue ensues and the quality of performance during subsequent repetitions contained in the set decreases. Oftentimes, this response may be beneficial, as fatigue may stimulate the neuromuscular system to adapt, resulting in a super-compensatory response. However, there are instances in which accumulated fatigue may be detrimental to training or performance adaptations (i.e. power development). In these instances, the ability to recover and maintain repetition performance would be considered essential. By providing intermittent rest between individual repetitions or groups of repetitions within a set, an athlete is able to acutely alleviate fatigue, allowing performance to remain relatively constant throughout an exercise session. Within the scientific literature, a set that includes intermittent rest between individual repetitions or groups of repetitions within a set is defined as a CS. Recently, CS have received more attention as researchers have begun to examine the acute and chronic responses to this relatively novel set structure. However, much of the rest-period terminology within the literature lacks uniformity and many authors attempt to compare largely different protocols with the same terminology. Additionally, the present body of scientific literature has mainly focused on the effects of CS on power output, leaving the effects of CS on strength and hypertrophy relatively unexplored. Therefore, the purpose of this review is to further delineate CS terminology, describe the acute and chronic responses of CS, and explain the need for further investigation of the effects of CS.

Introduction

When designing a resistance-training program, several factors such as the choice of exercise, training load, number of repetitions and sets performed, the exercise order, frequency, and length of designated rest periods must be considered in order to optimize the targeted training outcomes. Once all of these program variables have been established, the strength and conditioning professional can effectively define and implement a training program. Ultimately, these decisions are made in order to construct a periodized resistance-training program in accordance with the individual athlete's training goals. However, a largely overlooked and underutilized aspect of developing a resistance-training program is the ability to alter the structure of individual sets [16]. For example, the number of repetitions, training load, and rest periods contained within a set can be manipulated to alter the training stimulus. When conceptualizing a set, two types of general set structures can be used are traditional sets (TS) and cluster sets (CS) [16]. To effectively utilize both types of set structure, the strength and conditioning professional must understand the fundamentals that underpin each type.

Traditional Sets

Traditionally, the completion of a set occurs without any rest being taken between repetitions that are contained within the set. Once the set is completed, a pre-determined rest interval is provided to allow recovery before the initiation of a subsequent set and this basic set configuration is repeated for the targeted number of sets prescribed in the training session. This traditional method of resistance-training set prescription can be described as training using TS.

Regardless of set structure, the manner in which repetitions are performed can largely affect the resultant training adaptations stimulated by a resistance-training program.

For example, strength and conditioning professionals often instruct athletes to perform concentric muscle actions as quickly as possible because explosive concentric muscle actions result in enhanced recruitment of Type II muscle fibers [18] and result in greater training effects compared to intentionally slower concentric muscle actions [18, 19]. Unfortunately, fatigue can quickly manifest itself when repeatedly performing explosive movements under externally loaded conditions using TS training structures [8, 13, 20-24].

One of the most widely accepted causes of muscular fatigue is the reduced availability of phosphocreatine (PCr) and rate of adenosine triphosphate (ATP) re-synthesis within the working muscles [25-27]. Sahlin and Ren [28] showed that after a sustained fatiguing isometric muscle action, maximal force production during a subsequent isometric action can be met, but the subsequent force endurance capacity is decreased, credited to an inability to continually regenerate ATP. Building on this idea, the classic works of Bogdanis and colleagues [25-27] indicate that ATP and PCr stores are significantly reduced after an initial cycle sprint of 10-30 seconds and do not fully recover following 90-240 seconds of recovery (i.e. similar work to rest ratios of many common resistance-training programs), indicated by a decrease in power output during a subsequent cycle sprint. More recently, the work of Gorostiaga et al. [29-31] has confirmed that when performing the leg press exercise at maximal effort, the accumulation of metabolic byproducts and decreased energy availability are accompanied with decreases in power output. The decrease in power output noted in these studies is the basis of the hypothesis that impairments in high velocity movements may occur when TS are chronically employed without sufficient replenishment of ATP and PCr within the active muscles, especially when high volumes of work are completed [6, 16, 17].

Although a fatigue-induced decrease in movement velocity reduces power output [8, 12, 13, 32] especially as the number of repetitions performed in the set increases [29-31, 33], such fatigue may be useful in inducing hypertrophic responses or strength gains because a decrease in concentric velocity results in an increase in the overall time under tension (TUT) [34-36] and increased myoelectrical activity toward the end of a set [37-39], both of which have been suggested to be pre-requisites for the development of strength [40-42]. Additionally, when fatigue ensues and the energy availability from the ATP-PCr energy pathways becomes reduced, an increase in glycolytic dependence results in an accumulation of metabolites within the muscle, decreasing the pH level and subsequently, decreasing performance [26, 27, 29-31, 43]. Although an increase in metabolites such as lactate (La) is associated with a decrease in acute performance [23, 41], some researchers have explained that resistance-training using TS encourages neuromuscular fatigue, which may be warranted for long-term strength development [41, 42, 44].

Considering the relationship between metabolites and hormonal responses to fatigue and resistance-training, TS structures appear to be ideal for promoting skeletal muscle hypertrophy [40, 45, 46]. For these reasons, the recommendations for hypertrophic development set forth by the American College of Sports Medicine [2] and the National Strength and Conditioning Association [4] favor shorter rest periods between TS to promote muscle growth. In line with these recommendations, resistance training using TS has resulted in skeletal muscle hypertrophy, especially in high-volume programs [34, 47, 48]. Based upon this reasoning, some strength and conditioning professionals suggest that the intentional use of slow movement velocities increases the TUT and thus may positively impact hypertrophic responses and strength gains. However, critical analysis of the scientific literature reveals that there is a paucity of conclusive data to support this claim and that the opposite may be true [49-51] as recent research has revealed that faster concentric movement velocities have the potential to stimulate greater gains in strength and hypertrophy compared to slower concentric movements [19, 52].

To support this contention, Hatfield et al. [19] indicated that intentionally slow movement velocities performed with TS result in fewer repetitions being performed, lower peak force (PF) production, reduced peak power (PP) output, and less total training volume when compared to the same exercise performed at quicker movement velocities. Continuing on the cross-sectional work of Hatfield et al. [19], Gonzalez-Badillo et al. [50] found that performing the bench press exercise at maximal intended concentric velocities for six weeks resulted in greater strength gains when compared to performing the bench press with intentionally slower velocities. Similarly, Padulo et al. [18] reported that maximal velocity bench press training (80-100% maximal attainable velocity using 85% 1RM) resulted in greater strength gains and greater peak velocity (PV) at maximal loads when compared to self-selected velocities after three weeks of training. Ultimately, these authors [18, 50] concluded that lifting a load at maximal concentric velocities may be more important than intentionally slow movements that aim to induce maximal strength gains by increasing TUT.

To determine the influence of maximal velocity resistance-training on athletic performance, Pareja-Blanco et al. [51] investigated the effects of six weeks of maximal concentric velocity versus half-maximal concentric velocity back squat training using TS on sprinting and jumping movements. Ultimately, the authors determined that maximal velocity resistance-training may be more beneficial for improving powerful athletic movements such as sprinting and jumping when compared to slower velocity training with equivalent loads [51]. Additionally, the authors specifically stated that a fast concentric movement velocity seemed to be of greater importance than increasing TUT when aiming to develop maximal strength.

Collectively, these studies [18, 19, 50, 51] shed light on the importance of training at maximal concentric velocities in order to maximize strength, power output, and performance gains. Therefore, it may be warranted to implement strategies that limit the typical fatigue-induced reductions in movement velocity seen during TS.

One potential strategy for offsetting the fatigue-induced performance decrements associated with TS could be the use of CS [13]. Based on the work of Gorostiaga et al. [29-31], using CS structures to provide more frequent rest periods should result in enhanced recovery via a greater maintenance of PCr stores and increased metabolite clearance compared to TS training [10, 53, 54]. By using CS structures, there may be an increase in substrate availability (i.e. PCr and ATP) that could result in the maintenance of movement velocity throughout an entire set and ultimately, an entire training session.

Cluster Sets

Set structures inclusive of normal inter-set rest periods accompanied by pre-planned rest intervals within a set are referred to as CS structures [11-13, 22, 55, 56]. Conceptually, the addition of short rest periods within a set while maintaining normal rest periods between sets may offer a methodology for maximizing individual repetition performance whilst reducing accumulated fatigue seen during TS [11-13, 16, 17, 32, 53]. However, due to the wide range of protocols using the CS terminology (further discussed in the "Set Structure Terminology" section of this paper), CS have simply become a set structure in which rest periods are more frequent than TS.

Previous research has indicated that force production remains relatively constant throughout TS and CS [11, 32, 54, 57], but the movement velocity and power output across multiple sets appears to decrease to a greater extent during TS when compared to CS [11-13, 22]. Therefore, it has been hypothesized that a greater training stimulus for power development may be generated in response to the increased movement velocity noted in several studies comparing CS with TS [12, 13, 16, 23, 55, 58]. Fundamentally, training with CS in a "recovered" state may be more beneficial than TS for movements that require large amounts of muscular power output at high velocities [6, 16, 17].

As previously mentioned, fatigue is oftentimes thought to be of paramount importance for the development of muscular strength [2, 47]. However, it has been observed that training to maximal fatigue (i.e. training to failure) is not a prerequisite for the development of maximal strength [59, 60], and resistance-training at maximal velocities may be more effective at developing strength when compared to slower training velocities [19, 50]. Since velocity is better maintained using CS than TS, CS structures may play a role in enhancing maximal strength [61, 62]. Additionally, CS allow for a greater number of repetitions to be performed with a given load [24, 54] resulting in a greater volume load, which may also result in a greater stimulus for the development of maximal strength [2, 63, 64].

Finally, research investigating the hypertrophic effects of CS is scant, but evidence supports the idea of utilizing CS to develop skeletal muscle growth. In particular, it has been shown that after 12 weeks of resistance training, CS resulted in similar gains in lean mass when compared to TS [62]. Moreover, the use of CS appears to allow for a greater number of repetitions to be performed when compared to TS [24, 54] which may ultimately lead to an increase the amount of total work (TW) (i.e. volume load), providing a stimulus for increasing muscle hypertrophy [63, 65, 66]. Alternatively, if the number of repetitions is kept constant, CS may allow for the use of greater training intensities, which may also increase the hypertrophic stimulus [67, 68]. Therefore, the overall volume load may be increased when using CS compared to TS, possibly resulting in a greater stimulus for skeletal muscle hypertrophy [47, 63, 67, 69, 70].

Although TS have been the longstanding set structure for resistance-training programs, the alteration of TS to CS provides a different training stimulus that may benefit certain training goals. Even though there is a growing body of literature that explores the use of CS structures, the current definitions of CS are inconsistent and the applications of CS in a training environment remain inadequate. Therefore, the purposes of this review are to 1) define the CS terminology; 2) describe the acute and chronic responses to CS; and 3) explain the need for further investigation of the effects of CS on strength and hypertrophy.

Defining rest periods

Before discussing the CS literature in detail, it is important to understand the rest period terminology that is used to describe set structures within the scientific literature. Defining rest periods using prefixes such as intra-(within) and inter-(between) describes the location of the rest interval in relation to the remainder of the set.

Inter-set Rest

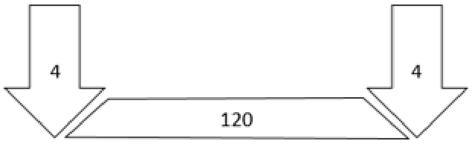
It would be most appropriate to describe the rest interval between sets (i.e. multiple repetitions performed in sequence) as the "inter-set" rest period. Often, inter-set rest periods are established as part of the training program in order to facilitate recovery between sets and target specific training adaptations [71-73]. For instance, when attempting to achieve maximal strength gains, it is recommended that an inter-set rest interval of two to three minutes is employed [74]. To provide an example, an athlete aiming to increase maximal strength could perform two sets of four repetitions with 120 s of inter-set rest allocated between each set (Figure 2.1A).

Intra-set Rest

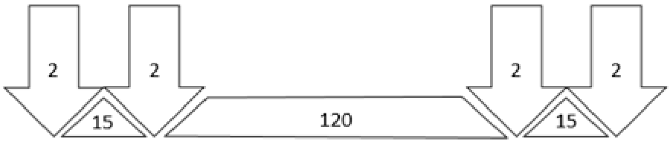
The term "intra-set" would be most appropriate when describing rest periods between groups of repetitions within CS structures. For example, if two sets of four repetitions are prescribed using clusters of two repetitions, each cluster of two could be separated by a short intra-set rest interval of 15 s with 120 s of inter-set rest (Figure 2.1B). Although the number of repetitions within each cluster and the intra-set rest times can largely vary, Figure 2.1B shows that intra-set rest intervals apply to rest periods that occur within a set, but not between sets and not between individual repetitions.

Inter-repetition Rest

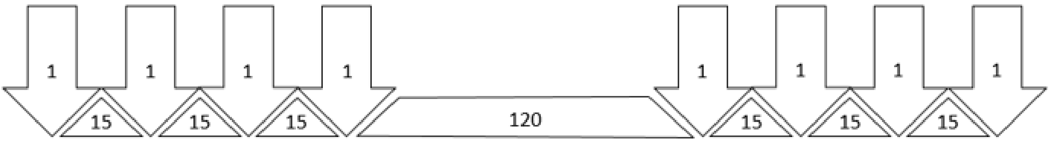
Rest periods that occur between individual repetitions of a set could be best described as "inter-repetition" rest periods (Figure 2.1C). Based upon this line of reasoning, it could be advised that the use of the inter-repetition rest terminology should be limited to rest intervals that are applied only between individual repetitions within a single set, but not groups of repetitions within a set (i.e. clusters) or sets of single repetitions (i.e. TS). For example, if inter-repetition rest is prescribed for two sets of four repetitions, each repetition within each set of four could be separated by a short 15 s inter-repetition rest interval in addition to 120 s of inter-set rest (Figure 2.1C). To conclude, the term intra-repetition should never be used, as it is impossible to rest within a single repetition.



A) Traditional Sets: 2 sets of 4 repetitions with 120-second inter-set rest but neither inter-repetition nor intra-set rest



B) Cluster Sets: 2 sets of 4 repetitions with 15-second intra-set rest and 120-second inter-set rest



C) Cluster Sets: 2 sets of 4 repetitions with 15-second inter-repetition rest and 120-second inter-set rest

Figure 2.1: Two sets of four repetitions with 120 s inter-set rest using three different set configurations. Arrows indicate number of repetitions performed in sequence, triangles indicate intra-set or inter-repetition rest periods, and quadrilateral shapes indicate inter-set rest periods. A) Traditional sets with neither intra-set nor inter-repetition rest. B) Cluster sets doubles with intra-set rest periods. C) Cluster sets singles with inter-repetition rest periods.

Set structure terminology

Since the emergence of sport science, there has been a need for standardized terminology [75]. In a field where scientists and practitioners work side-by-side, it becomes increasingly important for coaches to understand the jargon used in exercise science in addition to the scientists understanding the nomenclature used in practice. In today's world, the internet increases the availability of information, allowing for rapid dissemination of ideas and the inability to regulate the communicative process.

At times, a minor tweak to a simple concept opens the door for various interpretations and other amendments. Consistency of terminology can help eliminate confusion between professionals or between disciplines. For example, even simple barbell exercises such as the squat and bench press leave room for interpretation which can sometimes be misconstrued [76, 77]. Numerous attempts have been made to standardize the nomenclature used in sport science [75-80] and the need still exists as concepts are continuously being compared and contrasted. For this paper, understanding set structure terminology is of great importance.

Specifically, the use of the umbrella term "cluster set" has evolved to include many different types of set structures that simply describe a manner in which repetitions are performed which diverges from the TS structure. Although Byrd et al. [81], Rooney et al. [82], and Keogh et al. [83] used protocols inclusive of various inter-repetition rest periods, the first use of the term "cluster set" in the scientific literature, to our knowledge, was used in 2003 [13]. That paper created a CS by breaking a single TS of five repetitions into a single CS of five repetitions with short inter-repetition rest periods. However, they did not mention any terminology for performing a CS over multiple sets, leaving inter-set rest periods unmentioned and open for interpretation. As a result, the term "cluster set" has evolved to include many different types of protocols that do not necessarily follow a TS structure.

In theory and practice, there are two main things that can happen to the inter-set rest when using CS structures. The inter-set rest periods can remain unchanged, resulting in greater total rest times within the protocol, or the intra-set/inter-repetition rest can be subtracted from the inter-set rest to result in the same total rest time within the protocol. Careful examination of the scientific and non-peer reviewed literature reveals that there is a great deal of disconnect when defining "cluster set" terminology since 2003.

Some authors have created CS structures by equalizing the work to rest ratio [24, 32, 84], dividing inter-set rest periods into shorter but more frequent intra-set rest periods [14, 15, 39, 54, 62, 85-87], or using the rest-pause method [83, 88]. Therefore, it is important to examine the different methods of altering a set structure and how these relate to each other. Ultimately, the purpose of the nomenclature set forth in this paper is to illuminate fundamental differences between protocols that use different forms of CS and to create more appropriate sub-classifications of CS. If adopted, these sub-classes will allow researchers and practitioners to compare and contrast various set structure designs with more accuracy and less confusion.

Basic Cluster Sets

Training using the basic CS in which the inter-set rest periods remain unchanged requires a longer training duration to achieve a desired number of repetitions when compared to a TS structure because the intra-set or inter-repetition rest periods are added to the total rest time (Figure 2.2B) [11-13, 22, 55-57, 82, 89-93]. For example, Verkoshansky and Siff [94] explained that “extensive cluster training” involves four to six repetitions with one's 4-6RM, with 10 s of inter-repetition rest and 1-3 min of inter-set rest. By maintaining the inter-set rest interval, recovery between sets is facilitated as normal, but now with the addition of partial recovery within each set, the quality of repetitions within each set may be elevated across all sets performed. To simplify, a basic CS structure is essentially a TS with additional short rest periods of typically 15 to 45 s inserted within each set [16]. Although it is possible to add short inter-repetition rest periods of one to four seconds [81, 89], the majority of basic CS structures include a minimum of about 10-15 s of inter-repetition or intra-set rest.

An example of basic CS structures is present in the work of Hardee et al. [12, 22, 55] where three sets of six power cleans using TS with three minutes of inter-set rest were compared to two different basic CS structures in which the inter-set rest intervals remained constant at three minutes. The two basic CS structures differed to the TS structure by adding either 20 or 40 s of inter-repetition rest within each set. Additionally, Tufano et al. [11] employed basic CS structures by comparing three sets of 12 with two minutes of inter-set rest with three sets of 12 with 30 s of intra-set rest without adjusting the two-minute inter-set rest periods. In this manner, each basic CS protocol included a greater amount of total rest time when compared to the TS protocol.

Inter-Set Rest Redistribution

One type of CS sub-class is created when the redistribution of inter-set rest intervals occurs [10, 14, 39, 53, 54, 58, 62, 85-87, 95]. In these scenarios, long inter-set rest intervals are often divided into shorter but more frequent inter-set rest intervals, keeping the total rest time equal (Figure 2.2D). For example, Oliver et al. [62] compared four sets of 10 with two minutes of inter-set rest to eight sets of five with one min of inter-set rest. In this manner, each set of 10 was split in to two sets of five and each two-minute inter-set rest period was reduced to one minute. Fundamentally, each set of 10 repetitions was split into smaller but more frequent sets of five, keeping the total rest period between groups the same. Similarly, Moreno et al. [14] used three jump-squat protocols in which each prescribed set and repetition scheme contained equal total rest. Specifically, the set structures were broken into two sets of 10, four sets of five, and 10 sets of two with 90, 30, and 10 s of inter-set rest, respectively. Later, Oliver et el. [58] compared four sets of 10 with two minutes of inter-set rest to four sets of 10 with 90 s inter-set rest and 30 s of intra-set rest. In all of these cases, the investigators increased the frequency but decreased the duration of rest periods while keeping the total rest time equal between sets.

Specific terminology such as “rest redistribution” (RR) could be adapted for CS structures that equate and rearrange rest periods instead of adding additional rest periods as basic CS structures do. Therefore, an RR protocol differs from a basic CS design in that the inter-set rest periods during RR are shortened, the time subtracted from the inter-set rest is redistributed within the protocol, and extra rest is not provided.

Equal Work to Rest Ratio

Some studies have equated work to rest ratios (EW:R) for the entire exercise session and described it as CS training [15, 23, 24, 32, 61, 84, 96]. In these cases, the protocols cannot be randomized because the TS serves as the "standard" from which the work to rest ratio is calculated (Figure 2.2C). For example, the protocols of Iglesias-Soler et al. [24] included the following two protocols: 1) three sets of TS to failure (four, four, and three repetitions per set for example; 11 total repetitions) with three minutes of inter-set rest for a total of 360 s rest, and 2) repetitions to failure with 36 s of inter-repetition rest to ensure an EW:R ratio for the first 11 repetitions in this example (360 s divided by 10 rest periods). It is important to note that these ratios will mostly be subject-dependent and that subjects may be able to complete far more repetitions in the EW:R ratio protocol (i.e. 11 repetitions during TS vs 45 during the EW:R protocol [24]). In this manner, these CS structures may be most accurately described as EW:R protocols in which the total number of repetitions was not controlled and the total number of repetitions performed could vary between subjects. Practically, an EW:R protocol of this nature (i.e. performed to failure) could take up to 20 min if 30 seconds of inter-repetition rest was to be provided for 40 repetitions.

Hansen et al. [32] also utilized EW:R set structures, but kept the number of repetitions in each protocol constant. Unlike Iglesias-Soler et al. [24], subjects in this study [32] always performed the same number of repetitions using the following four protocols with a work to rest ratio of 15 s of work to three minutes of rest: four sets of six with three minutes of inter-set rest; four sets of six with 12 s of inter-repetition rest and two minutes of inter-set rest; four sets of six with 30 s of intra-set rest after every two repetitions and two minutes of inter-set rest; and four sets of six with 60 s of intra-set rest after every three repetitions and two minutes of inter-set rest. In this case, the same number of repetitions was used in each protocol, but no additional rest periods were supplied, and the work to rest ratio remained constant.

At first glance, RR and EW:R protocols appear to be similar because they both take the total rest time and divide it by a certain number of repetitions. However, RR protocols only take the rest time into consideration, whereas EW:R protocols take the time spent lifting the load into consideration as well. By specifically using the EW:R terminology, researchers and practitioners can understand that the total amount of rest is divided by the number of repetitions performed per unit of time, allowing a seemingly countless number of set manipulation variations that can be used to target various training goals.

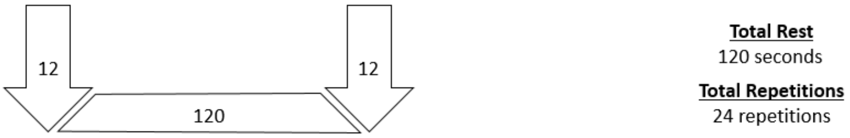
Rest-Pause Method

Another method of varying a set structure is what can be termed as the “rest-pause” method (Figure 2.2E) [40, 81, 83, 88, 89]. Verkoshansky and Siff [94] define “intensive cluster training” as a method of performing single repetitions of an exercise with short rest periods between each repetition for four to six repetitions, allowing a near-maximal load to be lifted multiple times: a method which has alternatively been described as the rest-pause method [40, 97]. Other definitions of the rest-pause method include performing a single set of an exercise with short rest intervals of increasing duration between every couple of repetitions, hoping to increase total volume load [98]; an initial set to failure with subsequent sets to failure performed with 20 s of inter-set rest [88]; and one to four seconds of unloaded rest between repetitions within an otherwise TS [81, 83, 89]. Although the rest-pause method has not been described as CS in the scientific peer-reviewed literature, many text books (as described above) and online training blogs synonymously refer to the rest-pause method as a CS structure, making it important to discuss in this paper.

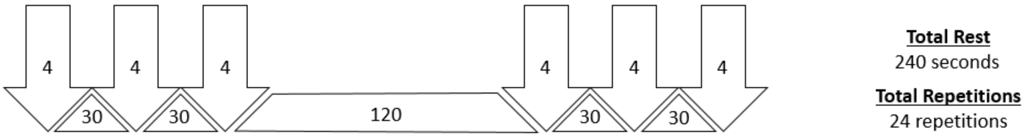
Careful inspection of this method reveals that its application is different from the previously mentioned basic CS, EW:R, and RR sub-classifications. Specifically, the aforementioned definitions of the rest-pause method describe a method in which training to failure often occurs, then a short rest period is applied in order to encourage recovery, allowing for additional repetitions to be completed until volitional failure or a predetermined number of repetitions are completed [40, 88]. When compared to a basic CS, EW:R, or RR protocol, the rest-pause method does not allow for ad-hoc programming of repetitions or rest periods because of the rest-pause method's general reliance on training to failure, creating variable sequences of repetitions which change based upon the athlete's daily fatigue level. In contrast, other sub-classes of CS can allow for a consistent set structure across training days, facilitating the periodization process. Although the rest-pause method is similar to the other sub-classifications of CS training in that short rest intervals are included, its lack of a constantly defined structure highlights its uniqueness among the CS sub-classes.

Summary of different set structures

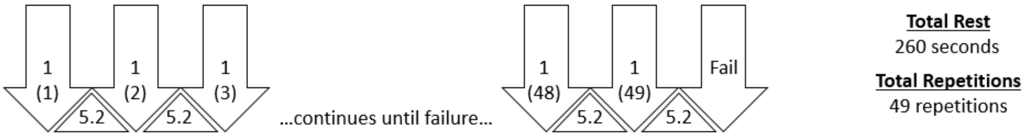
The ability to infinitely manipulate training variables such as the number of repetitions, sets, and rest periods make exercise prescription difficult to describe without providing extremely detailed information. Because of this, specific terminology may help describe subtle differences between types of set structures that otherwise may be difficult to differentiate. After elucidating the differences between the basic CS, RR, EW:R, and the rest-pause method, it may be recommended that they should not all be classified under a single CS description. Nonetheless, the investigation of basic CS, RR, EW:R and the rest-pause method provide valuable insight regarding the effects of rest periods and intra-workout training density on acute and chronic adaptations to resistance-training. A simplified visual representation of TS, basic CS, EW:R, RR, and the rest-pause method is presented in Figure 2.2. Additionally, references are provided for studies that fit into each sub-classification. It is important to note that the referenced studies do not use the exact protocols listed in Figure 2.2, but the main idea of the set structures in each study generally agrees with the designated examples in Figure 2.2.



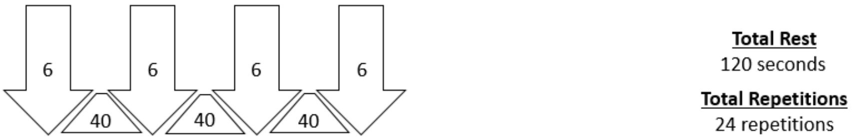
A) Traditional Sets: 2 sets of 12 repetitions with 120-second inter-set rest



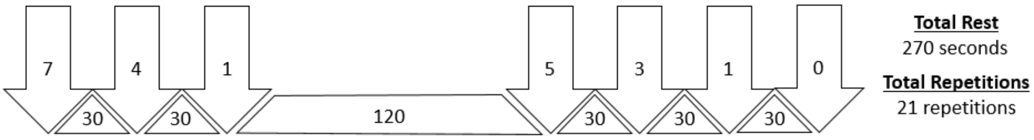
B) Cluster Sets: 2 sets of 12 repetitions with 30-second intra-set rest and 120-second inter-set rest



C) Equal Work to Rest Ratio: using Traditional Set (A) as an example.
(total rest time / (total reps – 1)) = (120 / (24-1)) = (120 / 23) = 5.2
5.2 seconds rest between repetitions until failure



D) Rest Redistribution: 4 sets of 6 repetitions with 80-second inter-set rest



E) Rest Pause Method: 2 sets to failure with 30-second intra-set rest and 120-second inter-set rest

Figure 2.2: Schematic differences between various set structures. Arrows indicate number of repetitions performed in sequence, triangles indicate intra-set or inter-repetition rest periods, and quadrilateral shapes indicate inter-set rest periods. Although not identical, the following studies have employed set structures that can be represented by the conceptual ideas presented in B) [11-13, 22, 55-57, 82, 89-93]; C) [15, 23, 24, 32, 61, 84, 96]; D) [10, 14, 39, 53, 54, 58, 62, 85-87, 95]; and E) [81, 83, 88, 89]; whereas A) represents a traditional set structure which is commonly used as a control, or reference, set structure. Please note, protocols C) and E) do not have to be performed to failure as shown in this diagram, but some studies adopt such designs.

Cluster set literature

To date, the majority of CS research focuses on the acute responses to various intra-set and inter-repetition rest intervals, frequently comparing acute power-related variables between different types of CS and TS [11-13, 22, 39, 57, 58]. The body of literature examining the acute effects of CS is consistently growing, but the number of studies investigating the use of CS training as part of a chronic training program has received significantly less attention. To date, only nine studies have investigated the chronic effects of CS sub-classes, but show inconsistent results most likely due to heterogeneous populations and protocol designs. The following sections will discuss key acute studies that focus on variables related to power, strength, and hypertrophic development. Then, each training study will be discussed in detail.

Acute Power

There is a plethora of evidence supporting the use of CS variations in order to maintain power production during acute bouts of exercise [10-12, 15, 22, 32, 53, 54, 58]. As mentioned previously, concentric movement velocities decrease during TS [8, 20, 21, 23], significantly reducing power output [11-13, 32, 58]. With the addition of intra-set rest intervals, the velocity of repetitions toward the end of various CS protocols are maintained, resulting in the preservation of acute power output [11, 12, 23, 32].

For example, Lawton et al. [15] reported that power output was maintained when an EW:R protocol was compared to TS. Subjects in this study performed six repetitions of the bench press with a 6 repetition maximum (RM) load using TS and three different EW:R strategies. The EW:R protocols consisted of six sets of one with 20 s rest between sets, three sets of two with 50 s rest between sets, and two sets of three with 100 s of rest between sets. By using these set structures, each protocol contained 100 s of rest and the final repetition of all three protocols was completed 118 seconds after the start of the first repetition, assuming 3 s was needed to complete each repetition. The authors concluded that the three EW:R protocols resulted in equally greater total power output than TS. This study [15] showed that various EW:R protocols containing shorter but more frequent rest intervals equally maintained power output during six repetitions of heavy bench press (i.e. about 21-25% greater total power output than TS) when compared to a single TS structure of six repetitions during which power output significantly decreased by approximately 50% in a near-linear fashion.

To compare the effects of RR and TS across multiple sets, Moreno et al. [14] investigated the effect of RR throughout a series of body-weight jump squats. Total rest time was equalized between groups, but it was observed that an RR protocol consisting of 10 sets of two jumps with 10 s of inter-set rest better maintained power output, takeoff velocity, and jump height when compared to two sets of 10 jumps with 90 s of inter-set rest (TS). Building on the study by Lawton et al. [15] who examined EW:R during a single set of the bench press, these authors [14] showed that RR structures alleviate fatigue-induced decreases in movement velocity during multiple sets of body-weight jump squats when compared to TS.

In comparison to Moreno et al. [14] where bodyweight jump squats were used, Hansen et al. [32] investigated the effects of EW:R with more frequent rest periods during loaded jump squats (40kg) in semi-professional rugby players. The players experienced a decline in PV and PP output during four sets of six using TS. However, when EW:R protocols were employed, PV and PP output were better maintained during the latter repetitions of each set. The authors concluded that since individual repetition PF was not different between protocols, the maintenance of PV during loaded jump squats was responsible for the maintenance of power output in the EW:R protocols when compared to TS.

As a whole, the literature shows that it is clear that power output can be maintained when using more frequent rest intervals during exercises that begin with eccentric muscle actions, utilize the stretch-shortening cycle (SSC), and finish with concentric muscle actions (i.e. bench press, jump squats, and back squats) [11, 14, 15, 32, 39, 58]. However, Hardee et al. [12] investigated the effect of CS on power during three sets of six power cleans, which are considered to be predominately concentric in nature. Using 80% 1RM, subjects performed a TS protocol (three sets of six with no intra-set rest) and two CS protocols with inter-repetition rest intervals of either 20 or 40 s. When averaged across all 18 repetitions, PP output, PV, and PF decreased more in TS than the two CS protocols. Contrary to the bench press, jump squats, and back squats [14, 15, 32], power cleans begin with concentric muscle actions. During the power clean, PV is usually obtained during the 2nd pull which is preceded by the double knee bend [99, 100]. Therefore, the velocity of the 2nd pull may be affected by the involvement of the SSC during the double knee bend. Although the authors did not report exactly when PV occurred [12], it is likely that PV occurred during the 2nd pull, partially relying on the SSC during the double knee bend. Therefore, when compared to TS, CS using inter-repetition rest intervals of 20 to 40 seconds maintained PP even when using an exercise that begins with concentric muscle actions, but still utilizes the SSC [12].

To further elaborate on this phenomenon, it appears that CS structures may be beneficial for increasing power output only for exercises that utilize the SSC at some point during the lift [57]. Moir et al. [57] showed that greater reductions in power output were observed when a single set of four deadlifts was performed using CS compared to TS. The authors concluded that when implementing 30 s inter-repetition rest periods, the SSC did not play a major role and the impulse of the deadlifts was greater than that of TS. When performing clusters of two repetitions (using an intra-set rest period of 30 s between the 2nd and 3rd repetition), the second and fourth repetitions were performed quicker and resulted in greater power output than the first and third repetitions. Force remained unchanged during all protocols meaning that, mathematically, a decrease in velocity (i.e. an increase in time) was responsible for the greater impulse observed when using inter-repetition rest periods. Therefore, if maintaining power output is important, CS structures that utilize inter-repetition rest periods may not be warranted when performing exercises that begin with a concentric muscle action and lack SSC involvement, such as the deadlift. However, if multiple repetitions are performed in sequence using the SSC at some point, intra-set rest intervals may be useful.

In summary, EW:R, RR, and basic CS set structures appear to be beneficial for attenuating the acute decline in power output that occurs when using TS in exercises that include some kind of SSC component. Additionally, the maintenance of concentric movement velocity seems to be largely responsible for the maintenance of power output during an acute exercise bout. However, further investigation is necessary to determine the effect of CS on acute power-based variables using different exercises, rest periods, and number of repetitions.

Acute Strength

Previous authors have hypothesized that TS should be chosen over CS when training to develop maximal strength because CS alleviate fatigue, and fatigue is sometimes warranted when aiming to develop muscular strength [16, 17, 39]. However, these claims remain relatively unexplored. While the investigation of various types of CS on power output is more common in the literature, there are some studies that have explored the effects of CS on acute variables that are considered to be indicative of strength development, specifically force production, training volume, and muscle activity. It must be noted that acute studies cannot determine the chronic effect of a protocol on maximal strength, but the results from the following acute studies can be used to extrapolate hypotheses about the effects of CS on strength development.

In a study conducted by Denton et al. [54], subjects completed the bench press using three different protocols. The TS structure included four sets of six with 302 s of inter-set rest. One RR protocol was matched for training volume and total rest time and included eight sets of three with 130 s of inter-set rest whereas a different RR protocol was matched for total rest time and included eight sets with 130 s of inter-set rest, but the odd-numbered sets contained three repetitions and even-numbered sets were performed to failure. The load in all set structures was the same 6RM load. The results of this study showed that the RR protocol that was performed to failure during the odd-numbered sets resulted in a significantly greater number of repetitions performed than the TS or RR protocol that was not performed to failure. In theory, an RR protocol that allows for the performance of more repetitions should increase training volume, and in turn, result in greater maximal strength gains [2]).

Similarly, Iglesias et al. [91] showed that by using a basic CS configuration, training volume can be increased by increasing the load and number of repetitions performed. In this study, subjects completed as many repetitions as possible during a single TS of the bench press and bicep curl using 70% 1RM. Subjects then completed as many repetitions as possible of each exercise with 90% 1RM, but with 30 s of inter-repetition rest. The protocol with inter-repetition rest resulted in a greater number of repetitions performed with a greater load, indicating that CS allowed for a greater load to be used for a greater number of repetitions, increasing training volume.

Although a large majority of the literature shows that compared to TS, CS allow for greater volume load by increasing the number of repetitions, training load, or both, there is one study that does not show this and in fact, shows that CS decrease the number of repetitions performed [89]. In this study, subjects performed four sets of leg press and bench press to failure using 75% 1RM on three separate visits. Each of the three visits included either zero, two, or four seconds of inter-repetition rest. Unique to this study, the subjects continued to support the load in the extended position during the inter-repetition rest periods (i.e. elbows extended during the bench press and knees extended during the leg press). As a result, subjects were able to perform more repetitions during the bench press and leg press when there was no inter-repetition rest (TS) compared to the two protocols in which inter-repetition rest periods were used (CS). Therefore, it can be concluded that when using any type of CS structure to maintain acute exercise performance or increase the number of repetitions performed, it is imperative that the lifter be unloaded and fully relaxed during the intra-set or inter-repetition rest periods.

Hansen et al. [32] determined that rugby players were able to maintain loaded jump squat PF better when using EW:R compared to TS. Four sets of six jump squats were performed with a standard load of 40kg in order to assess the percent change in PF from the first repetition of each set to all subsequent repetitions per set. The absolute PF was not different between protocols when repetitions were collapsed across sets, but the percent change from the first repetition did exhibit differences between protocols. While the EW:R set structures did not fully maintain PF when latter repetitions were compared to the first repetition of each set, there was a greater reduction in force across the set with the TS. Therefore, based upon these data, it appears that EW:R may help attenuate the declines in PF observed during the latter repetitions of TS structures. Although jump squats are generally not assigned to a resistance training program to increase maximal strength, the principle of force maintenance may be applied to other exercises that do focus on strength development

To date, one study has investigated the effect of RR on muscle activity by comparing TS to RR using the back squat exercise at 75% 1RM [39]. The TS protocol consisted of four sets of 10 with two minutes of inter-set rest whereas the RR protocol included eight sets of five with one minute of inter-set rest. To assess muscle activity, the authors reported the root mean squared EMG values for the entire repetition (eccentric, amortization, and concentric phases) in the vastus lateralis and biceps femoris. When collapsed across 10 repetitions (i.e. the first TS set and the first two RR sets), muscle activity increased in a near linear fashion during TS and followed the same pattern for the first five repetitions during RR. However, the muscle activity of the next repetition (6th) of the RR set structure returned to the value of the 1st repetition and followed the same trend as repetitions 1-5. Therefore, TS resulted in greater total muscle activity when compared to RR, because the muscle activity during the final five repetitions of each TS was greater than the muscle activity during the even numbered sets in RR. The authors concluded that TS, rather than RR, should be used when an increase in muscle activity is desired. These conclusions display merit, as various CS set structures are less fatiguing than TS when using the same load [22, 84]. On the other hand, since CS structures are less fatiguing [22, 84], greater loads may have been used during the RR structure to match the effort of TS and muscle activity may have been equivalent or greater in the RR protocol. However, the interaction between muscle activity, load, fatigue, and training volume is complex, resulting in only speculative claims when using EMG data to make inferences about maximal strength development.

In summary, various types of CS may help maintain PF throughout a training session, and the duration of the inter-repetition or intra-set rest interval appears to impact the ability to attenuate force loss, with longer rest intervals resulting in a greater maintenance of PF. Due to the capacity to maintain PF using CS, it is possible that more force can be applied during later portions of a set allowing the athlete to perform the set with overall higher movement velocities, which are also indicative of strength gains [18, 50]. However, current data [39] do not support the use CS to increase muscle activity and research should investigate the effects of greater loads during CS structures to match fatigue observed during TS structures. It has also been shown that greater training volumes result in greater strength adaptations [2], meaning that when designed appropriately, variations of CS structures may be used to increase training volume [54, 91], and possibly maximal strength.

Acute Hypertrophy

As with maximal strength development, acute studies cannot directly determine the effectiveness of a protocol to induce muscle hypertrophy over time. However, it is possible to examine the existing body of CS research that can link specific acute variables with an increased potential for inducing hypertrophy. Specifically, the following acute CS studies incorporate large training volumes that are indicative of classical hypertrophic training as well as other variables that have previously been linked to skeletal muscle growth.

Although not designed as a study to investigate the hypertrophic potential of CS, Hardee et al. [22, 55] noted that the rating of perceived exertion (RPE) was significantly lower during power cleans using CS when compared to TS and that barbell displacement was greater during CS. Since fatigue is a determinant of training volume, set structures that are less fatiguing may enable greater volumes of work to be accomplished [55] by allowing the lifter to perform more sets or more repetitions. The idea of greater training volumes resulting in greater skeletal muscle hypertrophy [63, 65, 101] supports the idea that CS may allow for greater training loads or training volumes and may serve as an alternative method to achieve muscular anabolism.

Building on this, Iglesias-Soler et al. [24] examined the maximal number of repetitions that could be performed using EW:R and TS. Subjects performed three sets of squats to failure using a 4RM load using TS with three minutes of inter-set rest. By using an EW:R protocol, subjects performed single squats with inter-repetition rest periods until muscular failure was achieved. The EW:R protocol allowed subjects to complete about 5-times as many repetitions as the TS protocol (EW:R = 45.5 ; TS = 9.3 repetitions). These data indicate that EW:R training allows for a greater number of repetitions to be performed with the same load when compared to TS, increasing training volume and the amount of external work accomplished: key aspects of hypertrophy training [65, 101, 102]. Therefore, according to the hypothesis that performing more repetitions with the same load results in greater amounts of work, suggesting greater hypertrophy over time [65, 103, 104], the results from this study [24] suggest that CS may have the ability to result in greater hypertrophy than TS.

Other authors have also showed that CS allow for greater training volumes than TS [54] and that RPE is lower during CS than TS when training volume, intensity, and work to rest ratios are equated [84]. However, all of the studies accomplished greater training volumes by increasing the number of repetitions performed, sometimes resulting in inefficient protocols in a practical strength and conditioning realm due to the time needed to complete the protocols [24]. Despite the option for CS to result in greater training volumes, and in turn greater external work, the current body of CS literature has not attempted to address this possibility by increasing the load lifted for an equal number of repetitions.

Rather, studies by Girman et al. [53] and Oliver et al. [10] chose to equalize training volumes (sets x repetitions) between TS and CS protocols and investigate the effect of set structure on physiological markers of hypertrophy [102, 105, 106] such as La and hormonal responses. Together, these studies show that CS protocols result in less La and a blunted hormonal response when compared to TS [10, 53]. Therefore, both groups of researchers concluded that CS should not be used in place of TS when trying to induce skeletal muscle hypertrophy [10, 53]. However, it should be noted that the process of muscle growth is a complex phenomenon which includes both physiological and mechanical factors. Therefore, one area of future research could focus on the ability of CS to increase mechanical factors such as external work, subsequently effecting physiological markers.

In summary, the body of CS literature shows that CS loading can allow for greater training volumes than TS in an acute setting, which may result in greater hypertrophy over time [65, 102, 105]. However, this idea is purely hypothetical, as such study designs do not exist regarding the direct effects of CS on hypertrophy.

Chronic Responses

Although the body of evidence regarding the acute responses of CS structures is vast and continually growing, few studies have chronically implemented CS in a training environment. Therefore, the relatively small number of studies allows the following section to discuss each study, to our knowledge, that has used various CS protocols inclusive of different loads, sets, repetitions, and rest periods. Due to the nature of training studies that target multiple training adaptations simultaneously, each study will be chronologically discussed as a whole rather that dividing the responses into power-, strength- and hypertrophy-subcategories as in the acute sections of this paper.

Lawton et al. [86] compared TS and RR set structures over a 6-week training period in elite junior basketball and soccer players (n = 26) using a 6RM load during the bench press exercise. The subjects performed either four sets of six (TS) or eight sets of three (RR) in the same amount of time in an attempt to equalize the work to rest ratio between groups. However, the TS group actually experienced greater TUT (36.03 s) than the RR group (31.74 s) despite the researchers trying to equate the work to rest ratios. Hence, RR would be considered as the most appropriate sub-class of CS for this study as the total rest time was equal between groups. Following the 6-week training period, subjects in both groups increased bench press throw PP output against 20, 40, and 60kg loads, but no differences were present between groups. However, training with TS resulted in significantly greater bench press strength gains when compared to RR (increases of 9.7% and 4.9% for TS and RR, respectively). Since subjects in this study used the same relative intensity across the various set structures for the duration of the training program, it is possible that implementing RR structures using the same load as TS may have resulted in a decrease in perceived effort during the RR training sessions, as seen in other studies [22, 61, 84]. Decreasing the level of perceived effort may have allowed the athletes to increase the resistance used, resulting in an increased stimulus for the physiological adaptations that underpin the development of muscular strength. However, since no data were reported on the RPE and training loads were kept constant in this study (39), further research is warranted to detemine if RR can allow for an increased training load while producing a similar RPE as in TS. Nonetheless, these data suggest that the strategic use of RR structures may serve as an alternate method for developing strength and power output, but that TS may result in greater increases in strength when all training variables are equal.

Hansen et al. [87] compared RR to TS during the 8-week pre-season period of elite rugby players. The team (n = 18) was split into a TS group and an RR group, with both groups completing the same lower-body resistance-training program consisting of squat and clean variations. The only difference between groups was the redistribution of total rest time for the RR group, which included intra-set rest intervals throughout the training program that were subtracted from the inter-set rest periods (exact times varied per week and are too complex to be summarized here). The total rest time, training load, and training volume were not different between groups at any time during the study. After eight weeks of training, effect sizes showed that RR may have had a greater effect on power output, but neither PV nor PP assessed during loaded jump squats significantly increased for either group. Additionally, the use of TS resulted in significantly greater gains in back squat 1RM strength when compared to RR (an 18.3% increase from 203 to 240kg, and a 14.6% increase from 191 to 216kg for TS and RR, respectively). The greater increase in strength in the TS group shows that RR protocols may not be ideal when both groups use the same training loads, training volumes, and total rest time. Similar to the previously discussed study [86], it is possible that if the RR group experienced less fatigue [22, 61, 84], its subjects may have been able to tolerate greater training loads, leading to greater strength increases when compared to TS. Additionally, the authors also explained that players participated in supplementary concurrent training during the time of the study, which may have interfered with power adaptations. Therefore, the results of this study [87] show that the specific RR protocol used did not result in significant increases in power output during loaded jump squats, but did result in increased back squat 1RM (although a lesser increase than TS) in rugby players participating in concurrent training during the offseason.

Zarezadeh-Mehrizi and colleagues [85] investigated the effect of RR and TS training in 22 male soccer players. After a standardized 4-week block of hypertrophy training, subjects in this study were assigned to an RR or TS group and performed three weeks of strength training (three sets of five with 85% 1RM) followed by three weeks of power training (five sets of five with 30-80% 1RM depending on the exercise) with the total rest time equal between groups. A lack of detail regarding the methods of this training program creates uncertainty of whether rest periods were controlled, evidenced by inter-repetition rest ranging from 10 to 30 s in the RR group. To add to the lack of methodological clarity, 1RM squat strength was not directly assessed and an RM estimation technique was employed, but the paper did not specify how many repetitions were used in the estimation protocol. According to the 1RM estimations, both groups increased maximal strength (from 130 to 165kg and 130 to 147kg for TS and RR, respectively) with the TS group experiencing a significantly greater increase compared to the RR group. To assess power output, the velocity was calculated by dividing vertical displacement by time during six jump squats with 30% 1RM, and force was calculated using mass, gravity, and acceleration. Unfortunately, the authors did not state which mass was included in the calculation (barbell, body, or both) and the acceleration calculation was not provided. Ultimately, the estimated power output was determined by multiplying an estimated force and estimated velocity. With that in mind, the authors reported that the RR group experienced increases in power output (2236 to 2665 W) while the TS group did not (1857 to 1890 W). Although the results from this study indicate preferable power adaptations resulting from RR training, it is important to interpret these results with caution, as the training methodology was not clearly reported, the TS group displayed an average 25kg increase in back squat strength with no concomitant increase in power output, and power measurements were estimated and not directly measured.

Oliver et al. [62] investigated the effect of RR and TS throughout a 12-week total-body hypertrophy-oriented training program in resistance-trained men (n = 22). The TS group trained with four sets of 10 repetitions for all compound lifts with 120 s of inter-set rest, while the RR group performed eight sets of five repetitions with 60 s of inter-set rest, meaning the total rest time was equalized between groups. After 12 weeks, both groups improved bench press, back squat, and vertical jump power output, but the RR group experienced greater increases in bench press and vertical jump power output compared to TS. The authors also observed similar gains in lean mass between groups, but neither group experienced shifts in myosin heavy chain isoform percentage. However, when both groups were collapsed together, the percentage of IIx (13.9 to 8.9%) and slow (51.1 to 47.5%) isoforms decreased while IIa (35.0 to 43.6%) increased, indicating a typical shift in fiber type resulting from resistance-training. It was also noted that RR and TS increased bench press and back squat strength, but contrary to the previously discussed studies (52, 37, 84) the RR group in this study experienced greater increases in strength when compared to the TS group. This anomaly may partly be explained by the inclusion of repeated 1RM tests throughout the study period. Although the relative intensities of the exercises were kept the same for each group (% 1RM), subjects were allowed to adjust their absolute load according to changes in 1RM strength, which was tested every four weeks. In this manner, training residuals from a previous block of training could have been translated into the subsequent training block, indicative of a typical sequential periodized training program that takes advantage of delayed training effects. Although not significantly different, the RR group trained with a greater total training volume compared to TS (effect size range of 0.42 to 0.71; not reported by the authors, but calculated by the authors of the present paper using the effect size calculator found at www.uccs.edu/~lbecker/) for compound exercises. Therefore, it is possible that the continuous increases in strength may have allowed for greater absolute loads to be lifted, but the authors did not focus on this aspect. This study provides compelling evidence that different types of CS structures may allow for greater training loads for the same number of repetitions, resulting in greater training volumes, which may favor strength development when compared to TS.

Iglesias-Soler et al. [61] investigated the effects of a TS and an EW:R protocol over a 5-week period using unilateral knee extensions in sport science students of both genders (n = 13). Subjects were assigned to either the TS group (four sets of eight, 10RM load, 180 s inter-set rest) or RR group (32 repetitions, 10RM load, 17.4 s inter-repetition rest). Data collected during the training sessions showed that TS resulted in slower mean propulsive velocities (0.48 vs 0.54 $m \cdot s^{-1}$) and greater RPE (8.3 vs 6.6) than EW:R, respectively. Following the 5-weeks of training, subjects in the EW:R and TS groups both experienced an equal increase in isometric strength, dynamic 1RM, mean propulsive power, and TW completed with the original 10RM load. The results of this study indicate that an EW:R unilateral knee extension protocol felt easier but resulted in similar increases in strength and power output compared to TS following 5-weeks of training in university students of both genders.

Asadi and Ramirez-Campillo [95] investigated the effects of TS and RR plyometric training in college-aged students (n = 13) who were familiar with plyometric training, but had not participated in such training for at least six months. The TS group consisted of five sets of 20 maximal depth jumps from a 45-cm box with 120 s of inter-set rest. The RR group completed five sets of 20, but with 30 s of intra-set rest after the first 10 repetitions of each set and 90 s of inter-set rest. After training twice per week for six weeks, both groups increased countermovement jump height, standing long jump distance, and decreased t-test, 20 m, and 40 m sprint times. Although there were no significant interactions between groups, the effect sizes were greater in the RR group for countermovement jump height, long jump distance, and t-test time whereas the effect sizes were greater for the TS group for 20 and 40 m sprint times. Therefore, in untrained college students, plyometric training using TS and RR resulted in increased jumping, sprinting, and agility performance.

In summary, four studies show that TS and CS result in similar increases in power output [61, 86, 87, 95] while two studies show that CS protocols may be favorable over TS [62, 85]. Differences in study designs may explain these unequivocal findings. The studies that reported similar increases in power output in TS and CS protocols equated training intensity, volume, and total rest time between protocols, not taking full advantage of the ability of CS structures to increase training volume [24]. On the other hand, the two studies that showed preferable power output adaptations from CS structures also equated total rest time between groups [62, 85], but unique to the study by Oliver et al. [62], the 12-week duration allowed for 1RM measurements every four weeks and possibly greater absolute loads in the RR group. Therefore, CS structures may be more beneficial than TS for the development of muscular power output, but more research must be conducted in this area to make conclusive recommendations.

To date, some studies have reported that strength gains are generally greater in TS set structures than CS [85-87] with only one study reporting that CS structures produce superior strength gains [62] and one study showing similar increases in strength [61]. At first glance, the collective body of RR literature suggests that different CS structures may have a limited application for the development of maximal strength. However, it is important to carefully examine these studies and determine why TS resulted in greater strength development compared to RR training in these instances. Two of the main commonalities within studies that investigate RR are the equalization of the total rest time for RR and TS protocols and the lack of training load variation and systematic progression between the RR and TS set structures [85-87]. Similar to matching total rest time, the equalization of training loads between groups is a sound scientific method. However, if RR and TS set structures are performed using the same training intensities, it is likely that the TS group will experience greater acute fatigue, a greater compensatory response, and possibly greater increases in strength. Therefore, in order to determine the effects of CS on chronic strength adaptations, it is necessary to determine how the RR protocols used in these studies can be reformed to create CS that may elicit strength gains equal to or greater than TS, similar but not limited to the strategy used by Oliver et al. [62].

Only one study has directly measured skeletal muscle hypertrophy following CS and TS training, showing that neither set structure is superior to the other [62]. One of the advantages of CS loading is that greater training intensities can be used for the same training volume, possibly magnifying neuromuscular and morphological training adaptations [2, 16, 65, 67]. Therefore, future research should address the effects of greater total rest times, training loads, training volumes, and total external work in CS training protocols. Lastly, it is important to not neglect the periodization process during training studies in order to elicit progressive adaptations over time in a systematic manner.

Table 2.1: Studies listed by cluster set sub-class, followed by duration (acute or chronic), and author's last name.

Author	Cluster Set Sub-class	Duration	Subjects	Protocols	Response
Boullosa et al., 2013 [56]	Basic CS	Acute	12 resistance-trained men, 5RM half squat 2.33x BM	Countermovement jump height measured before and 1, 3, 6, 9, and 12 minutes after squats with 5RM load TS: 5 reps CS: 5 reps with 30 s IRR	Vertical jump post-activation potentiation occurred after 1 minute using CS compared to 9 minutes using TS.
Garcia-Ramos et al., 2015 [90]	Basic CS	Acute	34 active college-aged men, 1RM bench press 1.02x BM	Bench press throws at 30, 40, and 50% 1RM TS: 15 reps CS1: 15 reps with 6 s IRR CS2: 15 reps with 12 s IRR	Peak velocity was maintained best in CS2, followed by CS1, both of which maintained velocity better than TS.
Haff et al., 2003 [13]	Basic CS	Acute	8 male track & field 5 male weightlifters, 1RM power clean 1.32x BM	Clean pulls at 90 and 120% 1RM TS: 5 reps CS: 5 reps with 30 s IRR	On average, peak velocity was greater during CS compared to TS.
Hardee et al., 2012 [22]	Basic CS	Acute	10 male recreational weightlifters, 1RM power clean 1.39x BM	Power cleans at 80% 1RM TS: 3 x 6 with 180 s inter-set rest CS1: same as TS with 20 s IRR CS2: same as TS with 40 s IRR	CS resulted in greater power output and less exertion than TS. CS with longer rest periods maintained power output and decreased exertion more than when CS rest periods were shorter.
Hardee et al., 2012 [12]	Basic CS	Acute	10 male recreational weightlifters, 1RM power clean 1.39x BM	Power cleans at 80% 1RM TS: 3 x 6 with 180 s inter-set rest CS1: same as TS with 20 s IRR CS2: same as TS with 40 s IRR	Force, velocity, and power were better maintained during CS than TS. CS with longer rest periods maintained these variables better than when CS rest periods were shorter.
Hardee et al., 2013 [55]	Basic CS	Acute	10 male recreational weightlifters, 1RM power clean 1.39x BM	Power cleans at 80% 1RM TS: 3 x 6 with 180 s inter-set rest CS1: same as TS with 20 s IRR CS2: same as TS with 40 s IRR	Vertical displacement was greater during CS, resulting in greater external work than TS.
Iglesias et al., 2010 [91]	Basic CS	Acute	13 males, Bench press 1RM 1.2x BM Bicep curl 1RM 0.25x BM	Bench press and biceps curl with different loads TS: reps to failure using 70% 1RM CS: reps to failure using 90% 1RM with 30 s IRR	CS resulted in a greater number of repetitions performed with a greater load compared to the greatest number of repetitions performed using TS with a lighter load.

Moir et al., 2013 [57]	Basic CS	Acute	11 resistance-trained men, Deadlift 1RM 1.95x BM	Deadlifts using 90% 1RM TS: 4 reps CS1: 4 reps with 30 s IRR CS2: 4 reps with 30 s intra-set rest after 2nd rep	Force was similar between CS1, CS2, and TS, but CS1 resulted in greater time under tension, less power output, and greater impulse than TS.
Tufano et al., 2016 [11]	Basic CS	Acute	12 resistance-trained men, Back squat 1RM 1.9x BM	Squats using 60% 1RM TS: 3x12 with 120s inter-set rest CS1: 3x12 with 120 s inter-set rest and 30 s intra-set rest after every 2 reps CS2: 3x12 with 120 s inter-set rest and 30 s intra-set rest after ever 4 reps	CS1 and CS2 maintained velocity and power output better than TS. More frequent intra-set rest (CS1) resulted in greater maintenance of velocity and power output (CS2).
Valverde-Esteve et al., 2013 [92]	Basic CS	Acute	16 physical education males Bench press 1RM 1.15x BM	Bench press using subject-dependent “optimal load” of about 49% 1RM TS: 1 x 15 CS1: 1 x 15 with 5 s IRR CS2: 1 x 15 with 10 s IRR	Peak power output was maintained best in CS2, followed by CS1, both of which maintained power output better than TS.
Nicholson et al., 2015 [93]	Basic CS	6 Weeks	46 trained college males No baseline data provided	TS Strength: 4x6, 85% 1RM, 900s total rest TS Hypertrophy: 5x10, 70%1RM, 360s total rest CS1: 4x6, 85% 1RM, 1400s total rest CS2: 4x6, 90% 1RM, 1400s total rest	All CS and TS groups resulted in similar increases in isometric force, muscle activity, and jump height. CS2 and TS Strength resulted in greater strength gains compared to TS Hypertrophy and CS1.
Rooney et al., [82]	Basic CS	6 Weeks	18 males and 24 untrained females, Bicep curl 1RM 11-14 kg	TS: 6-10 reps at 6 RM CS: 6-10 reps at 6RM with 30 s IRR	TS resulted in greater gains in strength compared to CS.

Hansen et al., 2011 [32]	EW:R	Acute	20 (semi) and professional male rugby players, Strength level not provided	TS: 4 x 6 with 180 s inter-set rest CS1: 4 x 6 with 120 s inter-set rest and 12 s IRR CS2: 4 x 6 with 120 s inter-set rest and 30 s intra-set rest after every 2 reps CS3: 4 x 6 with 120 s inter-set rest and 60 s intra-set rest after every 3 reps	Power and velocity were greater during CS than TS, with no differences in force between the protocols.
Iglesias-Soler et al., 2012 [23]	EW:R	Acute	10 male judoists, Back squat 1RM 1.58x BM	Back squats with 4RM load TS: 3 sets to failure, 180 s inter-set rest CS: same volume as TS with subject-dependent IRR with same EW:R as TS	CS resulted in greater movement velocity during the protocol and less lactate after compared to TS.
Iglesias-Soler et al., 2013 [24]	EW:R	Acute	9 male judoists, Back squat 1RM 1.57x BM	Back squats with 4RM load TS: 3 sets to failure, 180 s inter-set rest CS: same volume as TS with subject-dependent IRR with same EW:R as TS	CS resulted in a greater number of repetitions while also resulting in greater movement velocity than TS.
Iglesias-Soler et al., 2014 [96]	EW:R	Acute	10 male judoists, Back squat 1RM 1.58x BM	Back squats with 4RM load TS: 3 sets to failure, 180 s inter-set rest CS: same volume as TS with subject-dependent IRR with same EW:R as TS	CS resulted in lower exercise heart rates, systolic blood pressure, and rate pressure product compared to TS.
Lawton et al., 2006 [15]	EW:R	Acute	26 elite junior basketball and soccer males, Bench press 6RM 0.8x BM	Bench press with 6RM load TS: 6 reps CS1: 6 x 1 with 20 s IRR CS2: 3 x 2 with 50 s inter-set rest CS3: 2 x 3 with 100 s inter-set rest	Power output was greater during CS compared to TS

Mayo et al., 2014 [84]	EW:R	Acute	7 male and 1 female sport science students, Bench press 10RM 0.71x BM Back squat 10RM 1.29x BM	Bench press and back squats with 10RM load TS: 5 sets to failure with 180 s inter-set rest CS: same volume as TS with subject-dependent IRR with same EW:R as TS	CS resulted in greater movement velocity and less exertion compared to TS.
Iglesias-Soler et al., 2015 [61]	EW:R	5 Weeks	6 and 7, female and male sport science students, Strength level not provided for each gender	Unilateral knee extensions with 10RM load TS: 4 x 8 with 180 s inter-set rest CS: 32 reps with 17.4 s IRR	CS and TS resulted in similar increases in 1RM, power output, and muscular endurance.
Denton et al., 2006 [54]	RR	Acute	9 healthy men, Bench press 6RM 1.01x BM	TS: 4 x 6, 302 s inter-set rest CS1: 8 x 3, 130 inter-set rest CS2: 8 sets, 130 inter-set rest* (3 reps during odd-sets, reps to failure during even-sets)*	CS1 resulted in similar power output, force, and work compared to TS. CS2 resulted in a greater number of repetitions, work, and lactate than CS1 and TS.
Girman et al., 2013 [53]	RR	Acute	11 resistance-trained men, Strength level not provided	TS: 1 x 6 clean pull 75% and 1 x 10 back squat 70% with 2 min inter-set rest CS: same as TS, but 15 s intra-set rest and 90 s inter-set rest	Blood lactate was lower and jump performance was greater following CS compared to TS. Both protocols resulted in similar growth hormone and cortisol responses.
Joy et al., 2013 [39]	RR	Acute	9 resistance-trained males Back squat 1RM 1.76x BM	Back squats with 75% 1RM TS: 4 x 10 with 120 s inter-set rest CS: 8 x 4 with 60 s inter-set rest	CS resulted in greater power output but less muscle activity compared to TS
Moreno et al., 2014 [14]	RR	Acute	26 recreationally trained college males, Strength levels not reported	Plyometric bodyweight jump squats TS: 2 x 10 with 90 s inter-set rest CS1: 4 x 5 with 30 s inter-set rest CS2: 10 x 2 with 10 s inter-set rest	CS1 and CS2 resulted in similar force but greater jump height, power output, and take off velocity compared to TS.
Oliver et al., 2016 [58]	RR	Acute	12 resistance-trained men, Back squat 1RM 1.7x BM 12 un-trained men, Back squat 1RM 1.1x BM	Back squats with 70% 1RM TS: 4 x 10 with 120 s inter-set rest CS: 4 x 10 with 90 s inter-set rest and 30 s intra-set rest	Velocity and power output were better maintained during CS compared to TS.
Oliver et al., 2015 [10]	RR	Acute	12 resistance-trained men, Back squat 1RM 1.75x BM 11 un-trained men,	Back squats with 70% 1RM TS: 4 x 10 with 120 s inter-set rest	CS resulted in greater volume load and power output than TS, while CS also resulted in less time

			Back squat 1RM 1.07x BM	CS: 4 x 10 with 90 s inter-set rest and 30 s intra-set rest	under tension, less lactate, and similar hormonal responses.
Asadi and Ramirez-Campillo 2016 [95]	RR	6 weeks	13 college males 40 m sprint 6.31 s Countermovement jump 43 cm	Depth jumps from a 45cm box TS: 5 x 20 with 120 s inter-set rest CS: 5 x 20 with 90 s inter-set rest and 30 s intra-set rest	Both groups improved countermovement jump height, standing long jump distance, and t-test agility, 20 m, and 40 m sprint times. Sprinting effect sizes were greater in TS, but jumping effect sizes greater in CS.
Hansen et al., 2011 [87]	RR	8 weeks	18 elite rugby union males 1RM back squat 1.9x BM	Squat and pull variations, 80-95% 1RM TS: 3 to 5 sets of 3 to 8 with 180 s inter-set rest CS: same as TS but with 120 s inter-set rest and 10 to 30 s IRR	CS and TS both resulted in increases in strength, but a greater increase following TS. Neither protocol had a significant change in jump squat force, velocity, or power.
Lawton et al., 2004 [86]	RR	6 weeks	26 elite junior basketball and soccer males, Strength levels not reported	Bench press using 80 to 100% 6RM load TS: 4 x 6 with 260 s inter-set rest CS: 8 x 3 with similar work:rest ratios as TS (but not controlled, making this RR, not EW:R)	Increases in power and strength were present after both CS and TS, but strength increases were greater following TS. TUT during training was greater during TS.
Oliver et al., 2013 [62]	RR	12 weeks	22 men in the military, Bench press 1RM 1.67x BM Back squat 1RM 2.09x BM	Total body workout using 60-75% 1RM TS: 4 x 10 with 120 s inter-set rest CS: 8 x 5 with 60 s inter-set rest	CS and TS resulted in similar increases in lean mass, but CS resulted in greater gains in strength and power.
Zarazadeh-Mehrizi et al., 2013 [85]	RR	6 weeks	22 male soccer players, Back squat 1RM 1.83x BM	Total body workout using 85% 1RM during strength phase and 30-80% 1RM during power phase TS: 3 x 3-5 with 180 s inter-set rest CS: 3 x 3-5 with 120 s inter-set rest and 10-30 s IRR	CS and TS resulted in increased strength, but increases were greater after TS. CS resulted in increases in power output while TS did not.
Arazi et al., 2013 [89]	Rest-Pause^ /Basic CS	Acute	20 resistance-trained men Strength level not reported	Bench press and leg press with 75% 1RM TS: 4 sets to failure with 3 min inter-set rest CS1: same as TS but with 2 s IRR CS2: same as TS but with 4 s IRR	The only study to show that TS resulted in a greater number of repetitions than CS, most likely due to the subjects supporting the load at full elbow (bench press) or knee (leg press) extension during the IRR periods. Possible that CS where subjects support the load during IRR is more fatiguing than TS.

Keogh et al., [83]	Rest-Pause^ /Basic CS	Acute	12 weight-trained men, Bench press 1RM 1.41x BM	Bench press using 6RM load TS: 6 reps CS: 6 reps with 2 s IRR	Concentric pectoralis major muscle activity was less during CS compared to TS while power output, triceps muscle activity, time under tension, blood lactate, and force were not different between protocols.
Marshall et al., [88]	Rest-Pause	Acute	14 resistance-trained males, Back squat 1RM 2.08x BM	Back squats using 80% 1RM TS1: 5 x 4 with 180 s inter-set rest TS2: 5 x 4 with 20 s inter-set rest CS: sets to failure with 20 s inter-set rest until 20 reps complete	CS resulted in greater muscle activity than TS1 and TS2 with similar amounts of post-exercise fatigue.
Byrd et al., [81]	Rest-Pause^ /Basic CS	10 Weeks	50 untrained males, Bench press 1RM ~1.0x BM Leg press 1RM 2.1-2.6x BM	TS: 6-10RM circuit training x3 CS1: same as TS with 1 s IRR CS2: same as TS with 2 s IRR	CS1 and CS2 resulted in a greater cardiovascular work capacity than TS and all had similar gains in bench press 1RM. Leg press strength increased greater in TS than CS1.

Cluster sets (CS), traditional sets (TS), equal work:rest ratio (EW:R), and rest redistribution (RR). Repetition maximum (RM), body mass (BM), inter-repetition rest (IRR). Arazi et al.^, Keogh et al. ^, and Byrd et al.^ did not perform repetitions to failure as usually described during Rest-Pause, but the IRR was only 1-4 seconds, too short to be classified as only a CS. Therefore, these two studies can be described as CS/Rest-Pause hybrid designs.

Summary

A summary of studies investigating CS, RR, and EW:R is included in Table 2.1. Due to the large degree of variability of protocols between studies and even within studies, the results of each study have been summarized and do not include results for individual repetitions or sets, but include the global response to each protocol as a whole.

Collectively, researchers have compiled a large body of evidence that supports the use of CS to maintain or increase acute power-related variables such as jump height, force, velocity, and power. Additionally, there is compelling evidence that CS structures acutely allow for a greater volume load, and in turn greater external work, by increasing the number of repetitions performed at a given load or increasing the load for a given number of repetitions.

In a training context, researchers have used various protocols inclusive of different exercises on a variety of subjects, but future research should continue to explore the possibilities of different CS structures on hypertrophy, strength, power, and sport-specific performance. Furthermore, research is needed to determine the effects of CS protocols that use different total rest periods and loads compared to TS. Lastly, due to various protocol designs which possibly play a role in the development of inconsistent data within the body of CS literature, the need for consistent terminology when explaining basic CS, RR, and EW:R set structures is of utmost importance.

Practical Applications

According to the present scientific literature, CS structures should be used when:

- Velocity and power maintenance are warranted [10-15, 23, 24, 32, 39, 58, 90-92]
- Aiming to increase the total volume load and TW within a session [10, 24, 54, 91]
- Aiming to increase vertical jump performance [14, 53, 62]

- Aiming to decrease an athlete’s RPE [22, 61, 84]
- Technique and displacement of an exercises is to be maintained [13, 55]
- The SSC plays a large role in the designated movement [57]
- Aiming to acutely decrease cardiovascular stress during resistance-training [96]
- Utilizing post-activation potentiation (PAP) under strict time constraints [56]

Chapter 3

As seen within Chapter 2, the CS terminology had become all-encompassing, including many different types of set structures that did not conform to the TS model of performing a prescribed number of repetitions with rest periods only occurring between sets. Additionally, a large majority of the research had focused on the ability of CS to maintain external power output during power-oriented exercises, meaning that the number of repetitions completed was fairly low and sometimes only included a single set of an exercise. Although such studies provide valuable information, the practical applications of such studies are limited, as resistance-training sessions rarely contain a single set of a single exercise performed for a handful of repetitions. A few studies had investigated the effects of CS on the traditional back squat exercise, and some had included a greater number of repetitions, but no study, to the authors' knowledge, had utilized such protocols using the basic CS model inclusive of extra rest periods. Therefore, the experiment presented in this chapter was conducted to investigate the effects of multiple intra-set rest frequencies during the back squat exercise and to provide baseline data that could be used when comparing the results of the subsequent experiments within this work. In 2016, the following text presented within Chapter 3 was published in the *International Journal of Sports Physiology and Performance*. However, the formatting has been adjusted from the original published manuscript to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Maintenance of velocity and power with cluster sets during high-volume back squats

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Purpose: The purpose of this investigation was to compare the effects of a traditional set structure and two cluster set structures on force, velocity, and power during back squats in strength-trained men. **Methods**: Twelve men (25.8 ± 5.1 y; 1.74 ± 0.07 m; 79.3 ± 8.2 kg) performed three sets of twelve repetitions at 60% of one repetition maximum using three different set structures: traditional sets (TS), cluster sets of four (CS4), and cluster sets of two (CS2). **Results**: When averaged across all repetitions, peak velocity (PV), mean velocity (MV), peak power (PP), and mean power (MP) were greater in CS2 and CS4 compared to TS ($p < 0.01$), with CS2 also resulting in greater values than CS4 ($p < 0.02$). When examining individual sets within each set structure, PV, MV, PP, and MP decreased during the course of TS (effect sizes range from 0.28 – 0.99), while no decreases were noted during CS2 (effect sizes range from 0.00 - 0.13) or CS4 (effect sizes range from 0.00 – 0.29). **Conclusions**: These results demonstrate that CS structures maintain velocity and power whereas TS structures do not. Furthermore, increasing the frequency of intra-set rest intervals in CS structures maximises this effect and should be used if maximal velocity is to be maintained during training.

Introduction

To increase mechanical power, athletes perform resistance-training exercises with maximum intended concentric velocities [32, 50, 107, 108]. Traditionally, repetitions in each set are performed in sequence with no rest between repetitions: a structure that has been defined as a traditional set (TS) structure [13, 16, 17]. When utilising TS, concentric velocity decreases as the number of repetitions increases [12, 13, 23, 30, 31]. Since the external mechanical power of a lift is the product of force and velocity, a reduction in velocity results in a concomitant decrease in power if force remains the same. Patterns of reduced velocity and power across TS have been documented in a variety of complex lifting movements such as the jump squat [14, 32], leg press [29, 30], and weightlifting exercises [12, 13]. These decreases are magnified when multiple sets contain a high number of repetitions [8].

In high-volume resistance training, there are large reductions in movement velocity and power output within sets and across multiple sets [8, 31]. As evidence, Sanchez-Medina et al. [8] reported a 46% reduction in mean velocity (MV) across three sets of 12 back squat repetitions performed to failure with five min of inter-set rest. Ultimately, TS structures that contain many repetitions result in accumulated fatigue, which may result in a reduced capacity to maintain a high velocity throughout a training session.

One potential explanation for the decrease in movement velocity, and ultimately power output, is the combination of reduced adenosine triphosphate (ATP) and phosphocreatine (PCr) availability [29-31], and increased La and ammonia accumulation [30] that occurs when many repetitions are performed over multiple sets. However, if the number of repetitions per set is reduced and more frequent rest periods are provided (e.g. five sets of 10 versus 10 sets of five), the phosphagen system appears to be able to meet the energetic demands of the exercise [29-31]. Specifically, a maintenance of ATP and PCr availability allows movement velocity to remain near maximal. From a programmatic perspective, placing short rest intervals within TS to create what is commonly referred to as a CS [13, 16, 17] may assist in maintaining movement velocity across sets and an entire exercise session.

Since the original investigation of CS structures by Haff et al. [13], research has determined that various intra-set and inter-repetition rest periods acutely maintain force, velocity, and power, blunting the decline that is normally seen when using TS [14, 23, 32, 87]. For example, Hardee et al. [12] reported that by adding 20 s inter-repetition rest intervals, movement velocity and power output decreased less over three sets of six repetitions during the power clean when compared to six successive repetitions. When inter-repetition rest was extended to 40 s, the peak velocity (PV) and peak power (PP) output of each repetition was better maintained than when 20 s of inter-repetition rest was used [12]. Collectively, the acute CS literature utilises set structures with low repetition ranges that are typically associated with maximal strength or power training, leaving the acute effects of CS on high volume resistance training relatively unknown.

Previous CS literature has examined PV [12-14, 32, 87], MV [24, 58], PP [12, 14, 22, 32, 87], mean power (MP) [10, 15, 39, 54, 57, 58], PF [12, 14, 32, 87], and mean force (MF) [54, 57, 58], but none of these studies have investigated all of these variables within the same study. Also, due to the limited number of studies examining the effect of high-volume CS structures on these variables across multiple sets, there is a need for research on this topic. Therefore, the primary purpose of this investigation was to compare the effects of TS and two different CS structures on peak force (PF), MF, PV, MV, PP, and MP during a high-volume back squat session performed at maximal velocity in strength-trained men.

We hypothesised that PV, MV, PP, and MP would be different between the three protocols, but that PF and MF would not.

Methods

Subjects

Twelve strength-trained males participated in this study (age 25.8 ± 5.1 y; height 1.74 ± 0.07 m; body mass 79.3 ± 8.2 kg), had at least six months of strength training experience using the full back squat exercise and could back squat at least 150% of their body mass. Participants were screened using medical history questionnaires and were excluded if they reported any recent musculoskeletal injuries. Participants averaged a 1 repetition maximum (1RM) of 148.8 ± 11.5 kg, a 1RM to body mass ratio of 1.90 ± 0.23, and a peak knee flexion angle at the bottom of the squat of 122.9 ± 11.3°. All procedures were carried out in accordance with the Declaration of Helsinki and were approved by the University Human Research Ethics committee. All participants gave written informed consent prior to participation.

Design

Testing occurred over four sessions: a 1RM session and three experimental sessions. Using a randomised design, participants completed each of the three protocols on separate days, 48-96 h apart, and were instructed to refrain from any type of fatiguing lower body activity for the duration of the study. Each protocol consisted of three sets of 12 back squats using 60% 1RM, and each of the protocols consisted of different set structures defined by different rest periods (Figure 3.1).

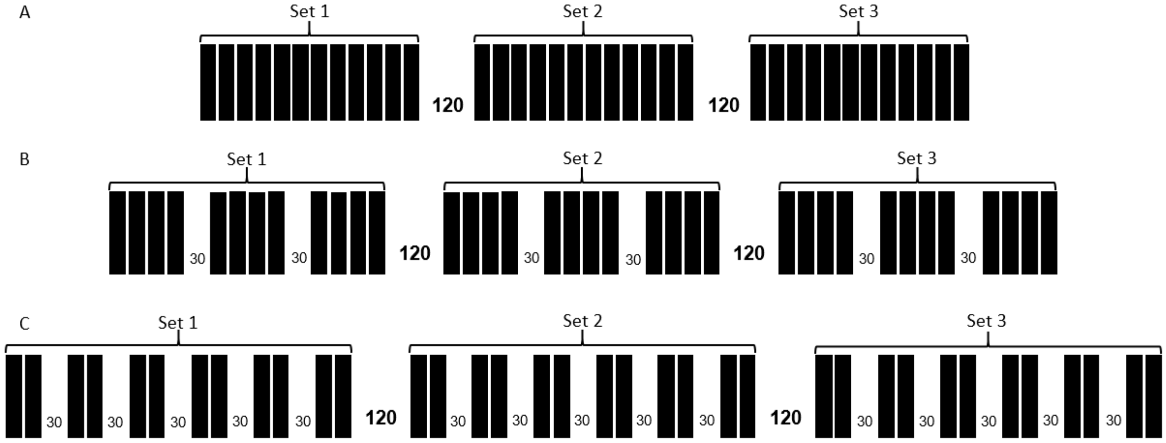

Figure 3.1: Set structure protocols. A) Traditional sets, three sets of twelve with 120 seconds of inter-set rest. B) Cluster sets four, three sets of twelve with 120 seconds of inter-set rest and 30 seconds of intra-set rest after the 4th and 8th repetition of each set. C) Cluster sets two, three sets of twelve with 120 seconds of inter-set rest and 30 seconds of intra-set rest after the even-numbered repetitions of each set.

Previous studies have shown that a load of 70% 1RM equates to roughly a 12RM in the smith machine back squat [8] and that 70% 1RM cannot be maintained during four sets of 10 barbell back squats with 2 min of inter-set rest [58]. During pilot testing, participants were only able to complete all 36 repetitions with 60% 1RM during the TS protocol, described in detail below. Therefore, to ensure that training to failure was avoided, an external load of 60% was chosen. As a result, all participants successfully completed all 36 repetitions in all three protocols.

Methodology

Repetition maximum testing: session one

Participant height was measured using a wall-mounted stadiometer and body mass was measured using a calibrated electronic scale. Participants then completed a warm-up on a cycle ergometer for five minutes at 100 W at 60 revolutions per minute. Warm-up squats consisted of 10 bodyweight squats followed by eight, five, and three repetitions at 25, 50, and 60% estimated 1RM, respectively. Back squat 1RM was then assessed starting at 85% estimated 1RM and load was progressively increased until the 1RM was achieved using previously established methods [109]. Participants' heel and toe locations were recorded on the force plate using a horizontal-vertical grid intersecting every one cm and were maintained throughout all testing sessions.

Experimental testing: sessions two, three, and four

Experimental testing sessions two, three, and four utilised the same warm-up as session one, but included warm-up loads based off of actual 1RM. Each session consisted of a different, randomised protocol. Specifically, TS consisted of three sets of 12 repetitions at 60% 1RM with seated inter-set rest intervals of 120 s (Figure 3.1A). Cluster sets of four (CS4) used the same structure as TS with the exception of an additional 30 s of standing, but unloaded intra-set rest after the 4th and 8th repetition of each set (Figure 3.1B). Cluster sets of two (CS2) used the same structure as TS with the exception of an additional 30 s of standing, but unloaded intra-set rest after the 2nd, 4th, 6th, 8th, and 10th repetition of each set (Figure 3.1C).

During these sessions, an investigator provided participants with a verbal countdown descending from 10 seconds and the participant un-racked the bar when the countdown reached "zero". In an attempt to maximise back squat PP, participants were instructed to perform the concentric phase of each squat as quickly as possible to a standing position [3], while the barbell was lowered under control. In order to ensure that the eccentric velocity was kept constant, each participant used a self-regulated eccentric velocity (no significant differences in eccentric velocity within participants between conditions, $p = 0.18$, $d = 0.29$). Participants were instructed to squat "all the way down" and "explode out of the bottom".

Squat depth was monitored using real-time visual displacement curves to encourage that all repetitions were performed to approximately the same depth (no significant differences in depth within participants between conditions, $p = 0.98$, $d = 0.02$). During all repetitions, the feet were required to maintain contact with the force plate (e.g. no jumping or lifting of the heels) [3] and a slight pause was required at the conclusion of each repetition to ensure full hip and knee extension. Sessions three and four were performed exactly the same as session two, with the exception of completing the remaining two testing protocols in random order.

Force, velocity, and power data acquisition

All kinematic and kinetic data were collected using methodology similar to previous research [110]. Briefly, all squats were performed on a force plate (AMTI BP12001200; Watertown, MA) to obtain PF and MF and two linear position transducers (LPTs) were attached to each side of the barbell originating from the top of the squat rack (Celesco PT5A-250; Chatsworth, CA) to obtain PV and MV. All force plate and LPT data were collected via a BNC-2090 interface box with an analog-to-digital card (NI-6014; National Instruments, Austin TX, USA) and sampled at 1000 Hz. A customized LabVIEW program (National Instruments, Version 14.0) was used to collect and analyze all force and displacement data. Signals were filtered using a 4th order-low pass Butterworth filter with a cut-off frequency of 50 Hz. External mechanical MP and PP of the system were calculated by direct measurement of ground reaction force and bar velocity. The retraction tension of the four LPTs was 23.0 N, which was accounted for in all calculations and all variables were

Equation 3.1

$$Percent\ Decline = \left(\frac{Repetition_{36} - Repetition_{1}}{Repetition_{1}}\right) \times 100$$

Equation 3.2

$$Maintenance_{set} = 100 - \left[\left(\frac{Mean_{set} - Repetition_{1}}{Repetition_{1}}\right) \times 100\right]$$

assessed during the concentric phase. The effect of set structure on MV, PV, MP, and PP across each protocol was determined by a percent decline from the 1st to 36th repetition using Equation 3.1. Further, the ability to maintain MV, PV, MP, and PP during all repetitions within each set was assessed using Equation 3.2. As a result, the variables of mean and peak velocity decline (MVD and PVD), mean and peak power percent decline (MPD and PPD), mean and peak velocity maintenance (MVM and PVM), and mean and peak power maintenance (MPM and PPM) were calculated.

Statistical analyses

Means and standard deviations were calculated for all variables. Individual 3 x 3 (protocol x set) repeated measures analysis of variance (ANOVA) were used to compare means for all variables except percent decline variables and protocol time. In the event of significant main effects and interactions, a Holm's Sequential Bonferroni follow-up test was performed to control for Type I error and assess pairwise comparisons. For decline variables and protocol time, paired t-tests with a Holm's Sequential Bonferroni follow-up were used to control for Type I error. Effect sizes were calculated using Cohen's d and can be interpreted as small, $d = 0.2$; medium, $d = 0.5$; and large, $d = 0.8$. Significance was set at $p \leq 0.05$ for all tests. All statistical analyses were performed using SPSS version 22.0 (IBM, Armonk, NY).

Results

Mean ± SD for MF, PF, MV, PV, MP, and PP are presented in Table 3.1. Repetition PV and PP are presented in Figure 3.2, while MV and MP are in Figure 3.3. Significant interactions are described in the text, while particular p-values and effect sizes are shown in Table 3.3. There were no main effects for protocol when examining MF ($p = 0.884$, $d < 0.01$) and PF ($p = 0.264$, $d < 0.01$) (Table 3.1). As intended by design, the duration of TS

(6:02 ± 0:16 min) was less than CS4 (9:34 ± 0:21 min, $p < 0.001$, $d = 17.78$) and CS2 (15:12 ± 0:28 min, $p < 0.001$, $d = 39.91$); and CS4 was less than CS2 ($p < 0.001$, $d = 23.27$).

There was a protocol*set interaction for MV ($p = 0.001$, $d = 0.29$) and PV ($p < 0.001$, $d = 0.20$) (Table 3.2). There was a protocol*set interaction for MVM ($p = 0.001$, $d = 0.36$) and PVM ($p < 0.001$, $d = 0.45$) (Figures 3.4 and 3.5). For MVD, there was a difference between CS2 and TS ($p = 0.002$, $d = 1.66$), CS2 and CS4 ($p = 0.034$, $d = 0.48$), and CS4 and TS ($p = 0.002$, $d = 1.38$) (Figure 3.6). For PVD, there was a difference between CS2 and TS ($p = 0.004$, $d = 1.47$), and CS4 and TS ($p = 0.003$, $d = 1.29$), but not between CS2 and CS4 ($p = 0.184$, $d = 0.41$) (Figure 3.6).

There was a protocol*set interaction for MP ($p = 0.003$, $d = 0.25$) and PP ($p < 0.001$, $d = 0.25$) (Table 3.2). There was a protocol*set interaction for MPM ($p = 0.002$, $d = 0.33$) and PPM ($p < 0.001$, $d = 0.42$) (Figures 3.4 and 3.5). For MPD, there was a difference between CS2 and TS ($p = 0.003$, $d = 1.67$), CS2 and CS4 ($p = 0.014$, $d = 0.56$), and CS4 and TS ($p = 0.002$, $d = 1.36$) (Figure 3.6). For PPD, there was a difference between CS2 and TS ($p = 0.003$; $d = 1.49$), and CS4 and TS ($p = 0.002$, $d = 1.40$), but not between CS2 and CS4 ($p = 0.269$, $d = 0.22$) (Figure 3.6).

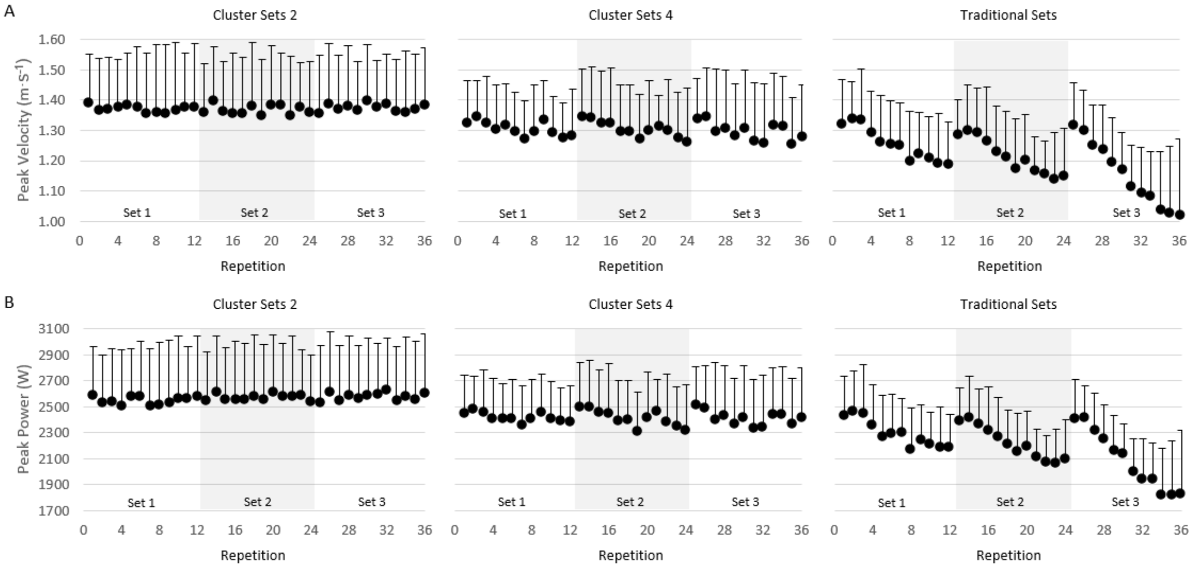

Figure 3.2: Peak velocity (A) and peak power (B) during three sets of twelve repetitions; thirty-six total repetitions. Peak force is not shown, as it did not significantly change across sets or repetitions.

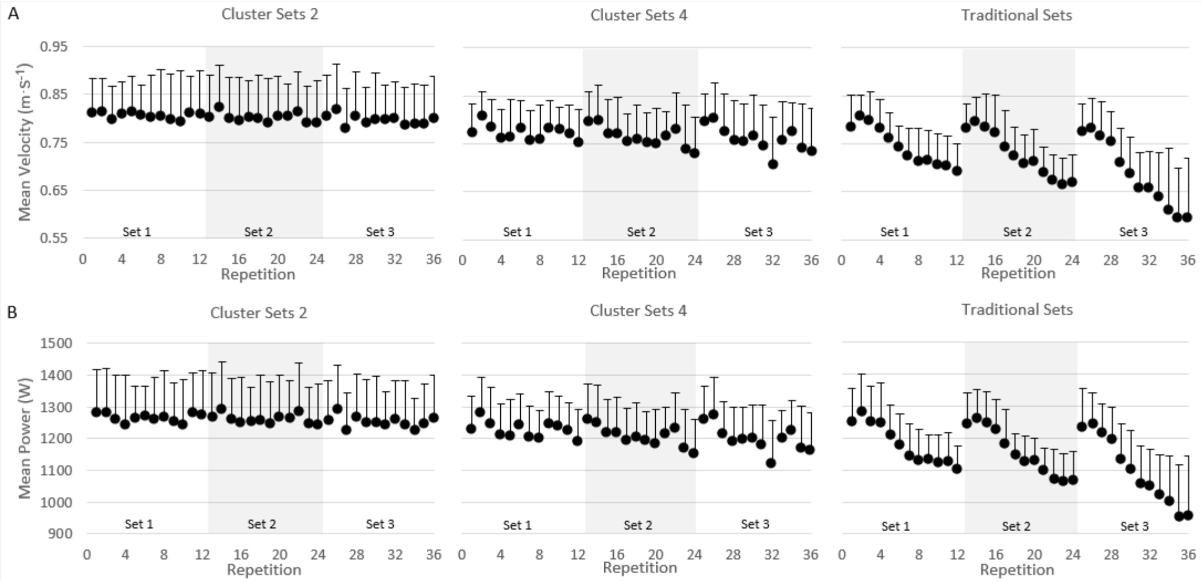

Figure 3.3: Mean velocity (A) and mean power (B) during three sets of twelve repetitions; thirty-six total repetitions. Mean force is not shown, as it did not significantly change across sets or repetitions.

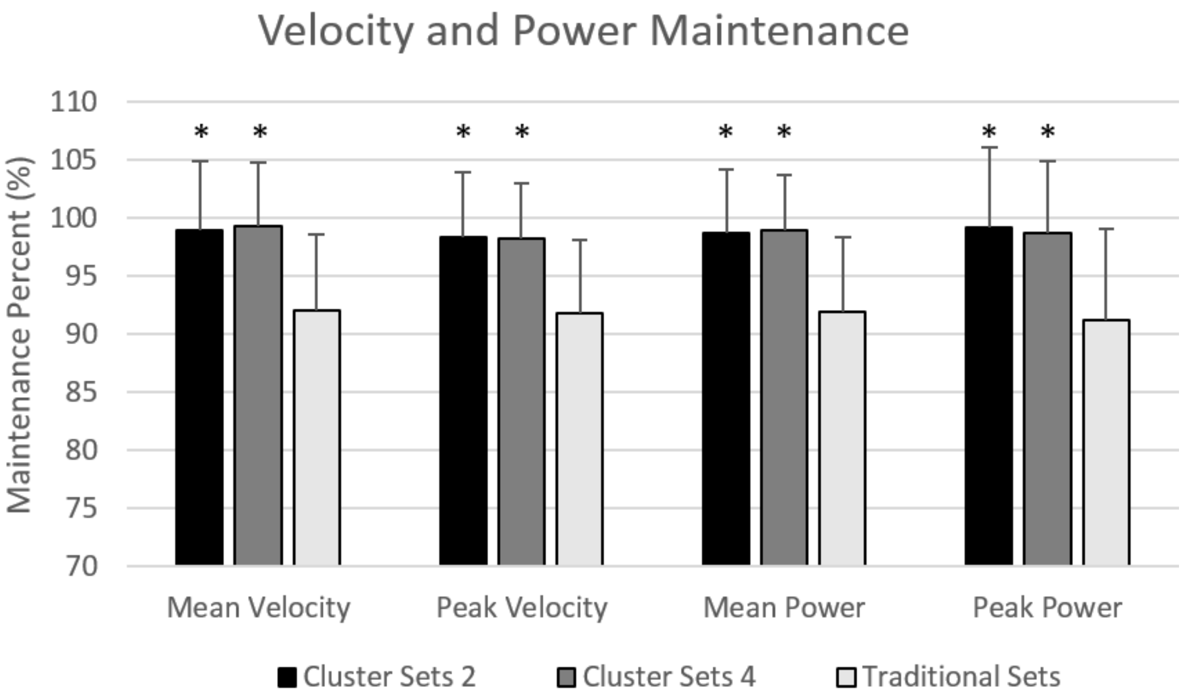

Figure 3.4: Maintenance of mean velocity (MVM), peak velocity (PVM), mean power (MPM), and peak power (PPM) across all 36 repetitions, expressed as a percentage of the 1st repetition during cluster sets two (CS2), cluster sets four (CS4), and traditional sets (TS). Significantly greater than TS (p < 0.01).*

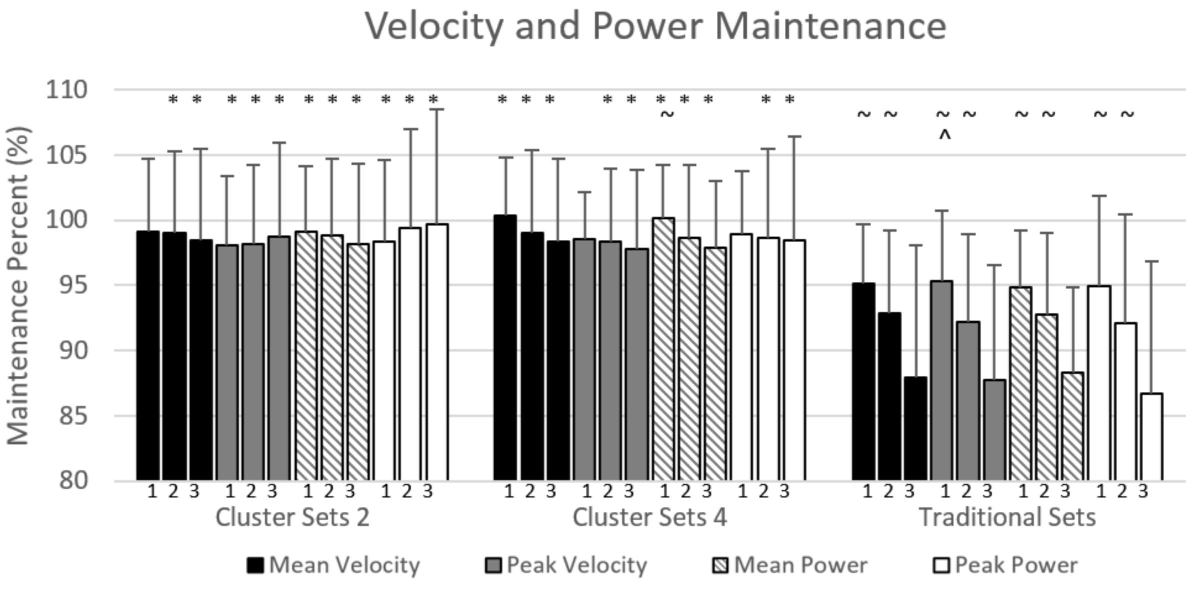

Figure 3.5: Maintenance of mean velocity (MVM), peak velocity (PVM), mean power (MPM), and peak power (PPM) for all three sets, expressed as a percentage of the 1st repetition during cluster sets two (CS2), cluster sets four (CS4), and traditional sets (TS). Significantly greater than TS (p < 0.05), Set 2^ (p < 0.05), and Set 3~ (p < 0.05).*

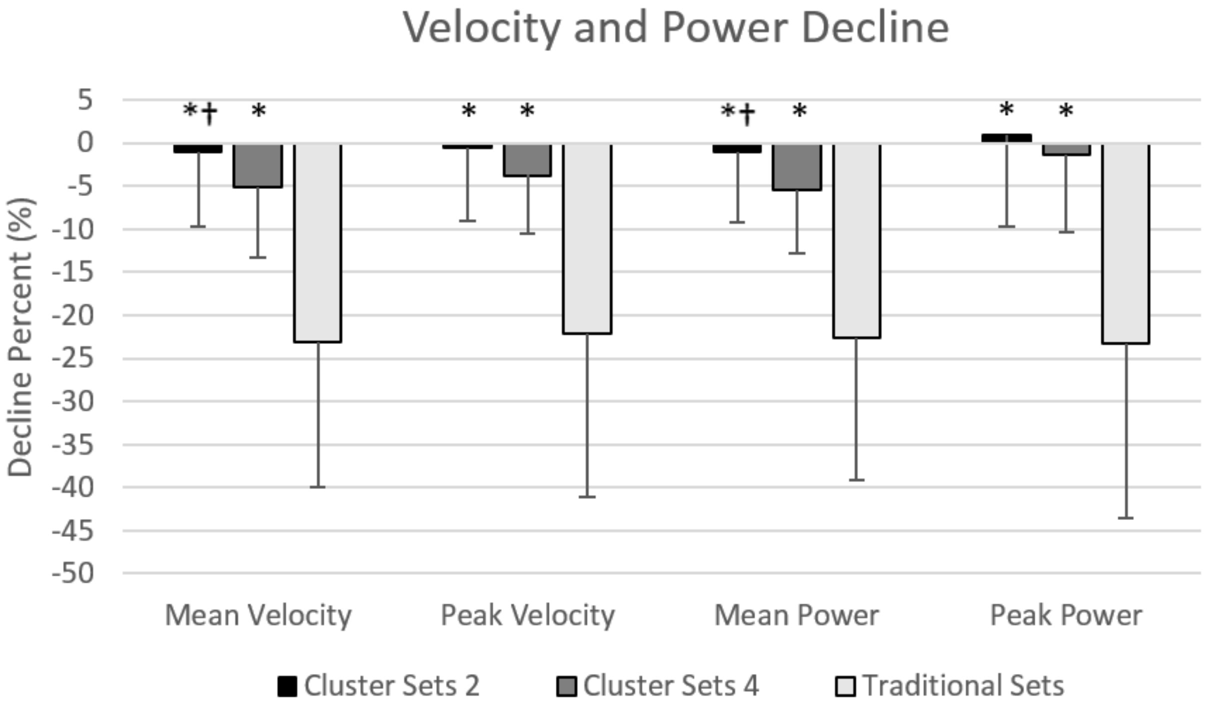

Figure 3.6: Decline of mean velocity (MVD), peak velocity (PVD), mean power (MPD), and peak power (PPD), expressed as a percentage of the quotient of the 36th repetition to the 1st repetition during cluster sets two (CS2), cluster sets four (CS4), and traditional sets (TS). Significantly different than TS (p < 0.01). Significantly different than CS4 (p < 0.05)†.*

*Table 3.1***:** *Force, velocity, and power. Mean ± SD for all 36 repetitions within each protocol.*

	Cluster Sets 2	Cluster Sets 4	Traditional Sets
Mean Concentric Force (N)	1603.6 ± 136.1	1601.4 ± 146.9	1606.1 ± 142.6
Peak Concentric Force (N)	2526.2 ± 237.7	2519.9 ± 248.7	2557.8 ± 248.2
Mean Concentric Velocity ($m \cdot s^{-1}$)	0.80 ± 0.08*†	0.77 ± 0.06*	0.72 ± 0.05
Peak Concentric Velocity ($m \cdot s^{-1}$)	1.37 ± 0.18*‡	1.30 ± 0.14*	1.21 ± 0.13
Mean Concentric Power (W)	1261.2 ± 115.7*†	1213.07 ± 92.3*	1143.8 ± 80.4
Peak Concentric Power (W)	2563.0 ± 403.4*‡	2412.90 ± 306.6*	2207.7 ± 243.0

Significantly greater than TS (p < 0.01). Significantly greater than CS4 (p < 0.01)†; (p < 0.05)‡.*

Table 3.2**:** Force, velocity, and power. Values expressed as Mean ± SD of all twelve repetitions within each set during each protocol.

		Cluster Sets 2	Cluster Sets 4	Traditional Sets
Mean Concentric Velocity (m·s^{-1})	Set 1	0.81 ± 0.07*†	0.77 ± 0.05*	0.75 ± 0.05~
	Set 2	0.80 ± 0.08*†	0.76 ± 0.06*	0.73 ± 0.05~
	Set 3	0.80 ± 0.08*†	0.76 ± 0.07*	0.69 ± 0.07
Peak Concentric Velocity (m·s^{-1})	Set 1	1.37 ± 0.18*	1.30 ± 0.13*	1.25 ± 0.13~^
	Set 2	1.37 ± 0.18*†	1.30 ± 0.15*	1.21 ± 0.14~
	Set 3	1.37 ± 0.18*†	1.30 ± 0.16*	1.15 ± 0.14
Mean Concentric Power (W)	Set 1	1266.63 ± 112.87*†	1228.61 ± 89.25*	1180.89 ± 82.61~
	Set 2	1263.34 ± 123.83*†	1209.46 ± 95.80*	1154.38 ± 77.43~
	Set 3	1253.68 ± 116.56*†	1201.14 ± 97.51*	1096.20 ± 107.04
Peak Concentric Power (W)	Set 1	2545.32 ± 407.92*	2416.43 ± 271.70	2296.55 ± 266.08~
	Set 2	2568.79 ± 405.27*†	2411.06 ± 308.00*	2222.76 ± 252.13~
	Set 3	2574.79 ± 418.41*†	2411.20 ± 351.30*	2088.80 ± 259.03

Protocol differences within set: Significantly greater than TS ($p < 0.05$). Significantly greater than CS4† ($p < 0.05$). Set differences within protocol: Significantly greater than Set 2^ ($p < 0.05$). Significantly greater than Set 3~ ($p < 0.05$).*

*Table 3.3: Protocol*Set and Set*Protocol comparisons shown as:* p*-value (effect size,* d*).*

		Protocol Comparisons			Set Comparisons				
		CS2 – CS4	CS4 – TS	CS2 - TS	1 - 2	2 - 3	1 - 3		
MV	Set 1	0.040 (0.66)	0.014 (0.40)	0.003 (0.99)	0.876 (0.13)	0.199 (0.00)	0.544 (0.13)	CS2	**MV**
	Set 2	0.008 (0.57)	0.001 (0.54)	<0.001 (1.05)	0.127 (0.18)	0.490 (0.00)	0.131 (0.16)	CS4	
	Set 3	0.004 (0.53)	<0.001 (1.00)	<0.001 (1.46)	0.069 (0.40)	0.012 (0.66)	0.010 (0.99)	TS	
PV	Set 1	0.041 (0.45)	0.048 (0.39)	0.004 (0.76)	0.892 (0.00)	0.549 (0.00)	0.824 (0.00)	CS2	**PV**
	Set 2	0.030 (0.42)	0.003 (0.62)	0.001 (0.99)	0.969 (0.00)	0.544 (0.00)	0.678 (0.00)	CS4	
	Set 3	0.006 (0.41)	<0.001 (1.00)	<0.001 (1.36)	0.019 (0.30)	0.017 (0.43)	0.003 (0.74)	TS	
MP	Set 1	0.034 (0.37)	0.006 (0.56)	0.001 (0.87)	0.773 (0.03)	0.141 (0.08)	0.392 (0.11)	CS2	**MP**
	Set 2	0.005 (0.49)	0.001 (0.63)	<0.001 (1.06)	0.064 (0.21)	0.334 (0.09)	0.046 (0.29)	CS4	
	Set 3	0.005 (0.49)	<0.001 (1.02)	<0.001 (1.41)	0.085 (0.33)	0.011 (0.62)	0.011 (0.89)	TS	
PP	Set 1	0.046 (0.37)	0.060 (0.45)	0.009 (0.72)	0.582 (0.06)	0.741 (0.05)	0.588 (0.07)	CS2	**PP**
	Set 2	0.025 (0.44)	0.005 (0.67)	0.001 (1.03)	0.834 (0.02)	0.996 (0.00)	0.888 (0.02)	CS4	
	Set 3	0.016 (0.42)	<0.001 (1.04)	<0.001 (1.40)	0.060 (0.28)	0.014 (0.52)	0.004 (0.79)	TS	
MVM	Set 1	0.400 (0.23)	0.005 (1.15)	0.053 (0.80)	0.911 (0.02)	0.244 (0.09)	0.600 (0.11)	CS2	**MVM**
	Set 2	0.989 (0.00)	0.012 (0.97)	0.006 (0.98)	0.134 (0.24)	0.440 (0.10)	0.130 (0.35)	CS4	
	Set 3	0.940 (0.01)	0.006 (1.24)	0.010 (1.21)	0.076 (0.41)	0.009 (0.59)	0.009 (0.92)	TS	
PVM	Set 1	0.715 (0.09)	0.037 (0.70)	0.064 (0.53)	0.977 (0.01)	0.509 (0.09)	0.723 (0.10)	CS2	**PVM**
	Set 2	0.897 (0.04)	<0.001 (0.99)	0.004 (0.92)	0.887 (0.03)	0.491 (0.10)	0.581 (0.15)	CS4	
	Set 3	0.581 (0.15)	0.001 (1.32)	0.002 (1.37)	0.023 (0.50)	0.015 (0.57)	0.003 (1.03)	TS	
MPM	Set 1	0.442 (0.22)	0.005 (1.26)	0.025 (0.92)	0.742 (0.06)	0.174 (0.11)	0.401 (0.18)	CS2	**MPM**
	Set 2	0.867 (0.04)	0.016 (0.99)	0.006 (1.00)	0.061 (0.31)	0.320 (0.13)	0.048 (0.48)	CS4	
	Set 3	0.831 (0.04)	0.009 (1.64)	0.011 (1.55)	0.086 (0.37)	0.008 (0.71)	0.009 (1.17)	TS	
PPM	Set 1	0.622 (0.09)	0.027 (0.66)	0.070 (0.52)	0.535 (0.15)	0.718 (0.03)	0.542 (0.17)	CS2	**PPM**
	Set 2	0.701 (0.11)	0.001 (0.86)	0.002 (0.92)	0.794 (0.05)	0.900 (0.02)	0.782 (0.06)	CS4	
	Set 3	0.532 (0.15)	0.001 (1.30)	0.001 (1.37)	0.074 (0.37)	0.011 (0.58)	0.004 (0.95)	TS	

Mean velocity (MV), peak velocity (PV), mean power (MP), peak power (PP), mean velocity maintenance (MVM), peak velocity maintenance (PVM), mean power maintenance (MPM), and peak power maintenance (PPM) during cluster sets two (CS2), cluster sets four (CS4), and traditional sets (TS).

Discussion

The major findings of the present study were that the inclusion of 30 s intra-set rest intervals during CS alleviated fatigue-induced decreases in velocity and power over three sets. Specifically, more frequent intra-set rest during CS2 resulted in greater MV, PV, MP, and PP than CS4 while also resulting in less MVD and MPD. As such, velocity and power were maximised when intra-set rest was most frequent and the total rest time was greatest.

The addition of intra-set rest intervals did not have an effect on force production. Specifically, neither MF nor PF changed throughout all three sets during any of the three protocols. These results are in line with other studies comparing MF during the bench press with a 6RM load [54] and PF during bodyweight [14] and 40kg jump squats [32] using traditional and CS structures, but are in disagreement with others [58]. In this study [58], the authors report that MF was greater when using CS compared to TS during four sets of 10 back squats at 70% 1RM; however, that statement is somewhat misleading because the load was decreased in the TS protocol by an average of 8% compared to a constant load used during the CS structure. With a lighter load, the TS structure resulted in a lower MF, which should not be considered a result of a different set structure, but should be attributed to the different loads used in each protocol. Further examination of their data shows that the MF was the same between the cluster and TS structures before the load was decreased during the TS, which agrees with the consistent MF data across all set structures in the present study.

Since MF and PF were not different between groups, any changes in external mechanical power output within the present study should be attributed to changes in movement velocity. Our data revealed distinct differences in velocity and power between TS, CS4, and CS2. Specifically, MV, PV, MP, and PP were less during TS compared to

CS4 and CS2, and decreased during three sets in the TS structure, but did not decrease in CS4 or CS2. These results agree with previous studies in which velocity and power have decreased in response to TS, especially in high volume protocols [8, 24, 58]. Unfortunately, direct comparisons of velocity and power during CS cannot be made to other studies because the only investigations using back squats during CS structures did not provide velocity and power data for individual sets in addition to the entire protocol [10, 23, 39, 58]. Nonetheless, the computation of decline variables (change from the first repetition to the last) in the present study has allowed us to compare our results to those of previous research.

The TS structure in the present study resulted in an MVD, PVD, MPD, and PPD of 23% each. Similarly, Oliver et al. [58] reported an MVD and PPD of ~20% across four sets of 10 back squats using 70% 1RM, Gorostiaga et al. [30, 31] showed a PPD of ~37% during five sets of 10 leg press to failure, and Moreno et al. [14] showed that PVD was ~6% following two sets of 10 bodyweight jump squats. Although MVD, PVD, MPD, and PPD were 23% during TS in the present study, when CS were used, these values were reduced to only 1-5%. In agreement with our data, Hardee et al. [12] showed that while PVD was 10.5% following three TS of six power cleans at 80% 1RM, it was less at 5.5% and 2.5% when 20 s and 40 s of inter-repetition rest was used, respectively. Additionally, Hardee et al. [12] also found a PPD of 18.5% during TS, but only 8.5% and 5% when 20 s and 40 s of inter-repetition rest was used, respectively.

Although not measured in the present study, it can be hypothesised that intra-set rest intervals may have allowed for enhanced clearance of metabolic by-products and replenishment of phosphagen energy substrates in our study. A series of studies by Gorostiaga et al. [29-31] support this by showing that when the leg press was performed to failure (five sets of 10) decreases in power were present, which were also accompanied by increases in La and decreases in ATP and PCr stores. However, when the frequency of rest intervals increased (10 sets of five), La levels were lower and participants maintained power, ATP stores, and PCr stores throughout the exercise session [29-31]. As other authors have hypothesized [10, 16, 17, 32, 39], we believe that the addition of intra-set rest in CS2 and CS4 allowed for superior replenishment of ATP and PCr, resulting in greater movement velocity during latter repetitions of each set compared to TS (Figures 3.2 and 3.3), but this idea remains unexamined in the CS literature.

Since many protocols required participants to train to failure [10, 29-31, 58], and even decrease the load within the protocol to enable all repetitions to be performed, the decreases in velocity and power observed in these studies may not accurately represent what occurs during a normal resistance-training session when athletes do not train to failure and the load remains constant. Data from Sanchez-Medina et al. [8] show that three sets of 12 squats using a 12RM load resulted in a greater decrease in mean propulsive velocity when compared to three sets of 10 using a 12RM load. Since our participants did not reach muscular failure, resulting in less velocity- and power-based fatigue when compared to other studies [8, 23, 31], practical resistance training recommendations may be drawn from the data presented and used in situations where repeatedly training to failure may be unwarranted [59, 60].

Lastly, some studies have failed to report individual repetition data [24, 53, 54], collapsed variables across sets [32, 39, 84], changed the load during the protocol [10, 58], and collapsed variables between protocols [39] making direct comparisons between studies rather difficult. Therefore, percent decline variables were reported in this discussion for the sake of keeping comparisons consistent. However, we would like to highlight the maintenance calculation, unique to the present study, as it describes what happens during the entire protocol. For example, stating that TS resulted in a 23% decline in velocity and power from the first repetition to the last would be a tenuous statement because the remaining 34 repetitions performed within the session would not be accounted for. Therefore, maintenance variables were calculated to show that participants were able to maintain velocity and power by 92% when performing TS, resulting in a decrease of only 8% when all repetitions were accounted for: much less than the 23% decline seen from the first repetition to the last. Hence, future research should address both, decline and maintenance variables, as they may each tell a different story.

Practical Applications

This study indicates that the addition of 30 s intra-set rest intervals maintains velocity and external mechanical power during high volume back squats. Based upon the CS structures assessed, intra-set rest intervals placed after every two repetitions is the most effective at maintaining velocity and power between sets. One drawback to the CS2 structure is that it takes more time than the CS4 and TS structures, meaning that a resistance-training program that is under strict time constraints may not be able to utilize CS2 structures. If a training session requires a compromise between time efficiency and fatigue management, intra-set rest intervals after every fourth repetition may be used, albeit not as effective at maintaining velocity and power as intra-set rest after every two repetitions. Future research should investigate the effects of different CS structures to determine the optimal number of repetitions within each cluster and the minimal amount of intra-set rest needed to maintain velocity and power.

Conclusions

Based on our data, CS allow strength and conditioning professionals to modify set structures in order to achieve different degrees of velocity-based fatigue. With this is mind, it is important for coaches to determine whether or not fatigue management is important and then allocate the frequency of intra-set rest intervals based on the desired training outcomes.

Chapter 4

The data from Chapter 3 showed that the TS protocol was fatiguing and resulted in similar decreases in movement velocity as other studies that were performed with submaximal loads (i.e. not RM loads performed to failure). Therefore, the decision was made to use the same TS protocol in the following study, but also to increase the loads in the CS2 and CS4 protocols. As explained further in this chapter, all of the CS studies thus far had kept the training load and number of repetitions the same between TS and CS protocols and used changes in performance (usually movement velocity) to quantify fatigue. However, the goal of the study presented in this chapter was to take a different approach and explore how CS could be manipulated in order to result in similar changes in velocity with different loads. Therefore, the experiment presented in this chapter was conducted to investigate the effects of three equally fatiguing protocols (i.e. same relative decrease in MV) with different external loads: two different CS protocols and a TS protocol. The idea of this study was to present the idea that CS could be used in other ways than simply reducing acute fatigue, which is what the large majority of previous studies had aimed to show. In 2017, the following text presented within Chapter 4 was published in the *International Journal of Sports Physiology and Performance*. However, the formatting has been adjusted from the original published manuscript to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Cluster sets: permitting greater mechanical stress without decreasing relative velocity

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Purpose: The purpose of this study was to determine the effects of intra-set rest frequency and training load on muscle time under tension, external work, and external mechanical power output during back squat protocols with similar changes in velocity. **Methods:** Twelve strength-trained men (26.0±4.2 y; 83.1±8.8 kg; 1.75±0.06 m; 1.88 ± 0.19 1RM:body mass) performed three sets of twelve back squats using three different set structures: TS with 60% 1RM, cluster sets of four with 75% 1RM (CS4), and cluster sets of two with 80% 1RM (CS2). Repeated measures ANOVAs were used to determine differences in peak force (PF), mean force (MF), peak velocity (PV), mean velocity (MV), peak power (PP), mean power (MP), total work (TW), total time under tension (TUT), percent mean velocity loss (%MVL), and percent peak velocity loss (%PVL) between protocols. **Results:** Compared to TS and CS4, CS2 resulted in greater MF, TW, and TUT in addition to less MV, PV, and MP. Similarly, CS4 resulted in greater MF, TW, and TUT in addition to less MV, PV, and MP compared to TS. There were no differences between protocols for %MVL, %PVL, PF, or PP. **Conclusions:** These data show that the intra-set rest provided in CS4 and CS2 allowed for greater external loads compared to TS, increasing TW and TUT, while resulting in similar PP and %VL. Therefore, cluster set structures may function as an alternative method to traditional strength- or hypertrophy-oriented training by increasing training load without increasing %VL or decreasing PP.

Introduction

Traditional periodization paradigms normally contain blocks of training that target specific adaptations. From a coaching standpoint, some training periods may include high volumes of fatiguing resistance-training to increase skeletal muscle hypertrophy, with little concern for the deleterious effects of fatiguing exercise on other components of fitness such as power output. On the other hand, the application of parallel models of periodization allow for, and may even require, a multi-faceted approach to training in which hypertrophy, strength, and power output are all considered throughout a microcycle. Therefore, there is a need for research examining different resistance-training schemes that aim to simultaneously develop a combination of hypertrophy, strength, and external mechanical (or system) power output.

As a result, researchers have investigated strategies that allow for the maintenance of acute system power output during exercises that are normally performed to elicit strength or hypertrophic adaptations. For example, it has been shown that power output decreases when performing high-volume back squats using traditional set (TS) (i.e. performing repetitions within a set without intra-set rest), but such decreases are ameliorated when using cluster sets (CS) (i.e. including intra-set rest intervals) [10, 11, 39]. Most of the CS literature includes protocols in which the external load and the number of repetitions are kept constant between the experimental (CS) and “control” (TS) protocols [12, 13, 22], making the external load and training volume controlled independent variables and fatigue-induced changes in velocity a dependent variable of interest. However, no research has intentionally prescribed different external loads for the same number of repetitions during traditional and CS structures to make decreases in concentric velocity a controlled independent variable. In doing so, investigators would be able to determine how CS manipulation can allow for increases in training load and the resultant acute power output responses.

If the external resistance is increased, movement velocity will decrease and the ensuing power output may rely more heavily on force production if power output is to be maintained or increased. Since this hypothesis is currently untested in the CS literature, the purpose of this study was to determine the effects of intra-set rest configuration and external load on total work (TW), time under tension (TUT), and power output compared to TS using lighter loads with similar changes in velocity. Based on previous research [3, 11, 39, 58] and the force-velocity relationship, we hypothesized that CS with greater loads would result in slower movement velocities, greater TW and TUT, but similar system power outputs when compared to TS with lesser load and similar changes in velocity.

Methods

Subjects

Twelve strength-trained men (26.0 ± 4.2 y; 83.1 ± 8.8 kg; 1.75 ± 0.06 m) participated in this study and could perform a back squat with the top of the thighs below parallel with a minimum of 150% body mass (mean handheld goniometry knee flexion angle of 120.8 ± 12.4°). The average free weight back squat 1RM was 153.4 ± 18.4 kg, resulting in a 1RM to body mass ratio of 1.88 ± 0.19. Subjects were screened using medical history questionnaires and were excluded if they reported any recent musculoskeletal injuries. All procedures were carried out in accordance with the Declaration of Helsinki, and University Human Research Ethics committee the approved research study. All subjects gave written informed consent prior to participation.

Study design

Subjects reported to the laboratory for a 1RM session and three randomized experimental sessions, each of which included one of the following protocols: Three TS of 12 using 60% 1RM with 120 s of seated inter-set rest; cluster sets of four (CS4), inclusive of three sets of 12 using 75% 1RM with 120 s of seated inter-set rest and 30 s of unloaded standing intra-set rest after the 4th and 8th repetition of each set; or cluster sets of two (CS2), inclusive of three sets of 12 using 80% 1RM with 120 s of seated inter-set rest and 30 s of unloaded, standing intra-set rest after the 2nd, 4th , 6th, 8th, and 10th repetition of each set (Figure 4.1).

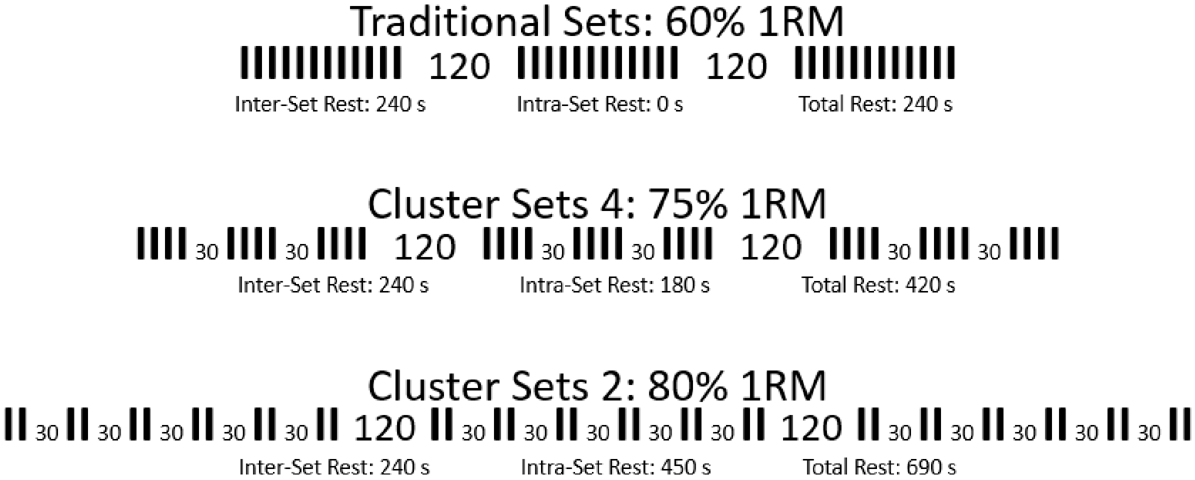

Figure 4.1: Protocol designs for three sets of 12 repetitions using traditional sets, cluster sets of four, and cluster sets of two inclusive of 120 seconds of seated inter-set rest and 30 seconds of standing, but unloaded intra-set rest.

The use of novel protocols, designed to result in similar changes in velocity, required similar relative loading intensities between protocols. Therefore, external loads were assigned at the same relative intensity for each protocol to avoid repetition failure and to provide loading consistency between protocols. Briefly, an RM load of the number of repetitions performed in sequence was multiplied by a factor of 0.84, resulting in a “moderate” load being used for all conditions [111].

Methodology

Repetition maximum testing: session one

Following anthropometric measurements, subjects cycled on an ergometer for five minutes at 60 revolutions·min^{-1} with 100 W of resistance. Next, 10 bodyweight squats were performed, followed by eight, five, and three repetitions at 25, 50, and 60% estimated 1RM. Back squat 1RM was assessed starting at 85% estimated 1RM, and was progressively increased until the 1RM was achieved [109]. Subjects' heel and toe locations were recorded on the force plate using a horizontal-vertical grid intersecting every one cm and foot placement was maintained during all testing sessions. Each session was separated by 48-96 h, and subjects were instructed to refrain from any type of fatiguing lower body activity for the duration of the study.

Experimental testing: sessions two, three, and four

During these randomized sessions, the warm-up was the same as session one, but included warm-up squats using the actual percentages of 1RM. To begin each protocol, an investigator provided verbal 10 s countdown and the subject un-racked the bar when the countdown reached "zero". After stepping backwards onto the force plate and completing the prescribed number of consecutive repetitions (two repetitions in CS2 or four in CS4), subjects re-racked the bar in the squat rack and the intra-set rest timer started. Subjects stepped backward and remained standing unloaded on the force plate during the 30 s intra-set rest period. After 20 s, the next 10 s countdown started and when it reached "five", subjects stepped forward and positioned themselves under the bar, ready to un-rack the bar when the countdown reached "zero". Repetitions during TS were performed in succession, with no intra-set rest. After completing the 12th repetition in all protocols, subjects racked the bar and the 120 s inter-set rest timer started. Subjects then walked to a chair three steps in front of the force plate and remained seated until the next 10 s countdown began to begin the second set. This process was continued until the protocol was complete.

To maximize concentric velocity during the back squat, subjects were instructed to "explode out of the bottom" and perform the concentric phase of each repetition as quickly as possible, back to a standing position [3]. Subjects were instructed to "squat all the way down" while constantly lowering the barbell was under control. Squat depth was monitored using live visual displacement curves in order to ensure that all repetitions were performed to approximately the same depth (no significant differences in mean squat depth within subjects, between conditions: CS2 = 60.12 ± 5.83, CS4 = 60.34 ± 6.30, and TS = 62.37 ± 6.01 cm: F = 3.20, p = 0.061). The feet were required to maintain contact with the force plate at all times [3] (e.g. no jumping or lifting of the heels) and a slight pause was required after every repetition to encourage full hip and knee extension.

Data acquisition

A customized LabVIEW program (National Instruments, Version14.0) was used to collect and manually analyze data received from the force plate (AMTI BP12001200; Watertown, MA) and linear position transducers (LPTs) (Celesco PT5A-250; Chatsworth, CA) via a BNC-2090 interface box with an analog-to-digital card (NI-6014; National Instruments, Austin TX, USA). All signals were sampled at 1000 Hz and filtered using a 4^{th} order-low pass Butterworth filter with a cut-off frequency of 50 Hz. The retraction tension of the four LPTs was 23.0 N, which was accounted for in all calculations.

All kinematic and kinetic data were collected using methodology similar to previous research and all variables were collected during the concentric phase of each lift unless noted otherwise [11]. Briefly, all squats were performed on a force plate to obtain MF and PF and two LPTs were attached to each side of the barbell (four in total) originating from the top of the squat rack to obtain mean velocity (MV), peak velocity (PV), and vertical displacement of the barbell. External mechanical MP and PP of the system were calculated by direct measurement of ground reaction force and bar velocity. The amount of TW was calculated by integrating the area under the force-displacement curve during the eccentric and concentric portions of each repetition.[112] Muscle TUT was computed by summing the time during the eccentric (ETUT) and concentric (CTUT) phases of each repetition [112]. Specifically, the eccentric phase was defined from the moment that descent occurred until maximal (negative) displacement, while the concentric phase was defined as the point of maximal displacement to zero-displacement (standing). Since the protocols in the present study included different loads resulting in different absolute velocities, relative velocities were used [33] to determine the percent change in ML loss (%MVL) and PV loss (%PVL), which were calculated according to Sanchez-Medina and Gonzalez-Badillo [8] using the equation in Figure 4.2A, adapted for CS protocols. In their study [8], the authors calculated the percent loss of mean propulsive velocity from the fastest (usually the first) to the slowest (last) repetition of each set and then averaged over the three sets. However, the final four repetitions of each protocol were averaged together to represent what was occurring near the end of each protocol since the CS structures did not follow a linear decrease in velocity as seen in TS (Figure 4.2B) and in the visual example provided by Sanchez-Medina and Gonzalez-Badillo [8]. The average %MVL ranged between 14-16% and %PVL between 10-13%, indicating that percentage of velocity loss was controlled between protocols.

a

$$MVFT = \left(\frac{AvgMeanVelocity_{Reps\ 33-36} - MeanVelocity_{Rep\ 1}}{MeanVelocity_{Rep\ 1}}\right) * 100$$

b

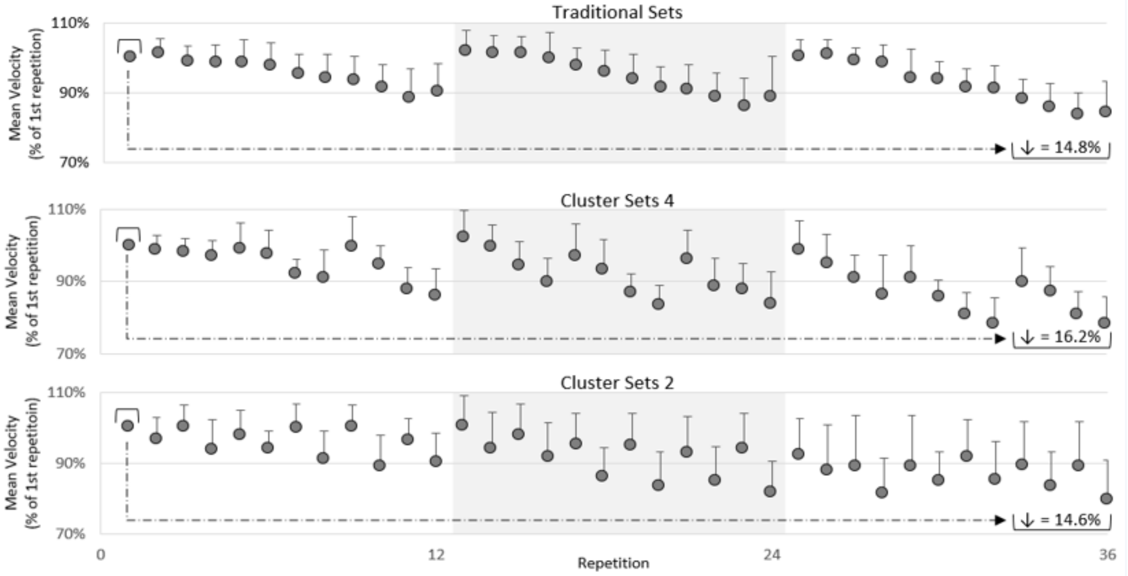

Figure 4.2: Equation used to determine percent mean- and peak-velocity loss (A). Example of percent mean velocity loss (%MVL) calculated by dividing the average of the final four repetitions by the first repetition (B). Percentage decrease in mean velocity (↓) shown in brackets for each protocol. No significant differences between groups.

<u>Statistical Analyses</u>

Means and standard deviations were calculated for all dependent variables and protocol time. For each variable, a repeated measures analysis of variance (ANOVA) was used and a Holm's Sequential Bonferroni follow up test was used to control for Type I error. Significance was set at $p \leq 0.05$ for all tests. Additionally, effect sizes ± 90% confidence intervals were calculated using Cohen's *d* and can be interpreted as small (0.2 - 0.49), moderate (0.5 - 0.79), and large (≥0.8). All statistical analyses were performed using SPSS version 22.0 (IBM, Armonk, NY).

Results

As intended by design, the total time taken to complete each protocol was different (F = 2613, $p < 0.001$). Specifically, CS2 (15:51 ± 0:49 min) was greater than CS4 (10:10 ± 0:38 min; $p < 0.001$, $d = 7.46$) and TS (6:01 ± 0:19 min; $p < 0.001$, $d = 15.40$), while CS4 was also greater than TS ($p < 0.001$, $d = 7.62$). There were also significant differences between protocols for MF, MV, PV, MP, TW, TUT, ETUT, and CTUT (Table 4.1). There were no significant differences between protocols for PF or PP (Table 4.1). For PF, there was a moderate effect for CS2 and TS, a small effect for CS4 and TS, and no effect for CS2 and CS4 (Figure 4.3). For PP, there were no effects for CS2 and TS, CS4 and TS, or CS2 and CS4, (Figure 4.3). Effect sizes for MF, MV, PV, MP, TW, and TUT are also shown in Figure 4.3.

Table 4.1: Mean ± SD for variables during each protocol when averaged across all 36 repetitions.

	CS2	CS4	TS	ANOVA Result	
Mean Force (N)	1968.25 ± 212.63***†††	1884.91 ± 210.79***	1656.40 ± 184.51	F = 725.07	$p < 0.001$
Peak Force (N)	2604.76 ± 250.00	2588.79 ± 301.45	2463.92 ± 257.32	F = 4.51	$p = 0.023^{\wedge}$
Mean Velocity ($m \cdot s^{-1}$)	0.49 ± 0.06***††	0.54 ± 0.06***	0.69 ± 0.07	F = 119.90	$p < 0.001$
Peak Velocity ($m \cdot s^{-1}$)	0.99 ± 0.15***†	1.04 ± 0.17***	1.16 ± 0.16	F = 29.86	$p < 0.001$
Mean Power (W)	944.06 ± 121.19***†	1006.09 ± 108.07***	1114.11 ± 109.18	F = 31.23	$p < 0.001$
Peak Power (W)	2119.79 ± 361.16	2169.90 ± 412.82	2120.50 ± 353.67	F = 0.63	$p = 0.543$
Total Work (kJ)	87.89 ± 8.59***†	84.45 ± 8.03***	76.73 ± 7.44	F = 30.93	$p < 0.001$
TUT (s)	87.69 ±10.35***††	80.58 ± 10.00**	69.55 ± 6.82	F = 41.85	$p < 0.001$
ETUT (s)	39.57 ± 5.39**	37.44 ± 5.95*	34.68 ± 5.62	F = 9.77	$p < 0.001$
CTUT (s)	48.12 ± 6.96***††	43.13 ± 5.47***	34.87 ± 3.48	F = 59.35	$p < 0.001$

Cluster sets of two (CS2), cluster sets of four (CS4), and traditional sets (TS); total (TUT), eccentric (ETUT), and concentric (CTUT) time under tension (TUT). Holm's Sequential Bonferroni follow-up tests revealed: different than TS ($p \leq 0.001$)$***$, ($p \leq 0.01$)$**$, ($p \leq 0.05$)$*$; *different than CS4* ($p \leq 0.001$)$\dagger\dagger\dagger$, ($p \leq 0.01$)$\dagger\dagger$, ($p \leq 0.05$)$\dagger$; *and no differences*$^\wedge$.

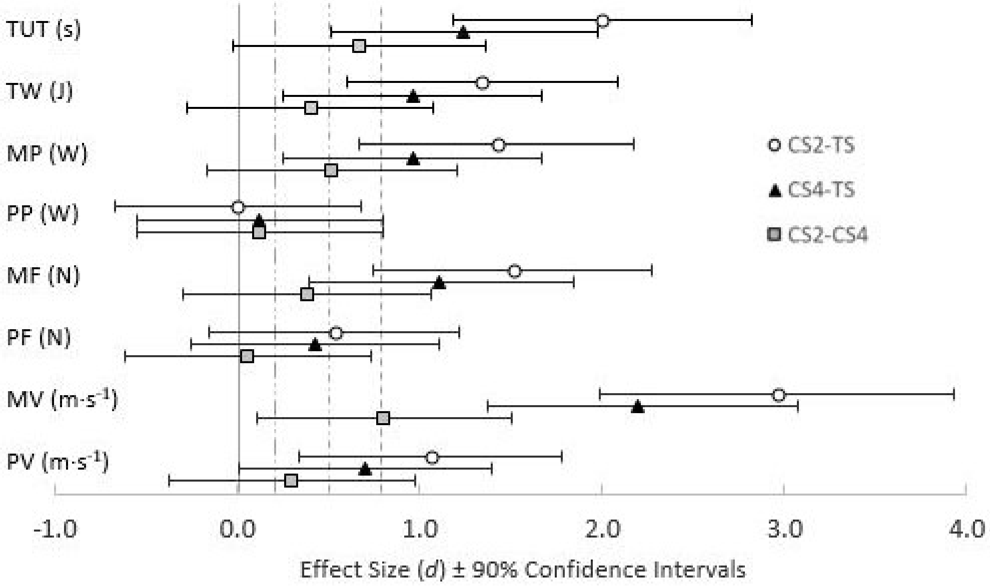

Figure 4.3: Effect size ± 90% confidence intervals comparing cluster sets of two (CS2), cluster sets of four (CS4), and traditional sets (TS). Variables include mean force (MF), peak force (PF), mean velocity (MV), peak velocity (PV), mean power (MP), peak power (PP), total work (TW), and total time under tension (TUT). Dashed lines present at 0.2, 0.5, and 0.8 to indicate a small, medium, or large effects between 0.20-0.49, 0.50-0.79, and greater than 0.80, respectively.

Discussion

The major findings of the present study were: 1) that CS structures allowed greater external loads to be lifted compared to TS while resulting in similar %MVL and %PVL; and 2) using greater loads resulted in slower MV, but resulted in greater TW and TUT while intending to move at maximal velocity; and 3) using greater loads resulted in less MP but did not affect PP. Therefore, data from the present study show that not only can CS structures be designed to reduce fatigue-induced decreases in velocity compared to TS structures with similar training loads as observed in other studies [10, 11, 13, 39], but they can also be manipulated to increase training load and result in greater TW without negatively affecting PP output.

The application of parallel models of periodization may require a multi-faceted approach to training in which the goal is to simultaneously increase strength, hypertrophy, and power output. As increases in muscle mass are associated with increases in strength and strength underpins power output [68], it can be argued that skeletal muscle hypertrophy is of great importance. The realization of hypertrophy is a remarkably complex process, but despite the complexity, there is a reoccurring theme within research that focuses on hypertrophy: protocols that include large amounts of external work (i.e. high-volume protocols) generally elicit greater skeletal muscle hypertrophy compared to protocols with less external work [65, 104, 105]. Ultimately, if a resistance-training program can include greater training loads for a given number of repetitions, increasing TW, it may be plausible that the program may encourage greater skeletal muscle hypertrophy. Although TW can be increased by increasing the load (i.e. force) or the number of repetitions performed (i.e. distance), increasing the external load may result in preferential hypertrophy of Type II fibers [67] which can be beneficial for athletic populations that require strength and size. Therefore, the importance of training load for increasing muscular size and strength is apparent [67, 68].

As load increases, the force required to move the barbell increases and a resultant decrease in movement velocity occurs [3]. In line with this load-velocity relationship, high volumes of fatiguing resistance-training with heavy loads may be unwarranted for improving external mechanical power output, as movement velocity is reduced, negatively affecting system power output [6, 9]. Conversely, CS serve as an alternative method to TS for performing high volumes of resistance-training without negatively affecting power output [11, 39, 58]. The majority of the CS literature includes protocols in which the external load is kept constant between the traditional and CS structures, leaving the influence of CS with various loads unexamined. Therefore, the purpose of this study was to determine the effects of intra-set rest frequency and training load on TUT, TW, and mechanical power output during back squats with similar fatigue-induced changes in movement velocity.

The additional intra-set rest periods during CS2 allowed subjects to successfully lift a greater external load for all 36 repetitions resulting in 19% greater MF, 15% greater TW, and 26% greater TUT than TS. Additionally, CS4 resulted in 14% greater MF, 10% greater TW, and 16% greater TUT than TS. Despite the importance of TW and training load for muscle growth, other factors also contribute to skeletal muscle hypertrophy. Previously, researchers have suggested that TUT should be considered when designing resistance-training programs that aim to increase hypertrophy because increasing the TUT can increase muscle activation [34, 102]. Furthermore, it has been suggested that fatigue is necessary for hypertrophy [104, 113] and that fatigue is a result of the relationship between TUT and TW [36, 114].

However, as fatigue increases, movement velocity decreases, negatively affecting the power output of the system [8, 11, 39, 58]. Although the absolute velocities were different between protocols in the present study, the %VL from the beginning to the end of each protocol was statistically similar. This fact indicates that all three protocols could have been considered as equally fatiguing [8, 115]. Interestingly, PP was similar between the protocols whereas MP was the least when using the greatest load (CS2) and was the greatest when using the lightest load (TS). Despite the CS protocols having greater MF (CS2 > CS4 > TS), slower MV (CS2 < CS4 < TS) negatively affected MP (CS2 < CS4 < TS), indicating that MV had a larger effect on MP than MF did. Although PV followed the same pattern as MV (CS2 < CS4 < TS), PP was not different between groups, possibly explained by greater, but not significantly greater, PF experienced in the CS protocols. Nonetheless, the instance at which PP, PF, and PV occurred was not measured in the present study, leaving the aforementioned hypothesis to be purely speculative.

Our data is in line with data from Oliver et al. [58] who emphasized that MP output was primarily affected by MV, rather than force production. In their study, the total rest time from the TS protocol (four sets of 10 with 120 s of inter-set rest) was redistributed to a CS protocol (four sets of 10 with 90 s of inter-set rest and 30 s of intra-set rest) using ~70% 1RM during parallel back squats. They demonstrated greater MP outputs with CS than TS. However, within the TS protocol, subjects had to reduce the load by an average of 8% to complete all 40 repetitions, and they displayed greater decreases in MV compared to the CS protocol, suggesting that the CS were less fatiguing. This study [58] supports the notion that modifying a set structure to include more frequent rest periods may result in a better maintenance in velocity than TS, which is beneficial in the practical realm of strength and conditioning. However, when unplanned changes to the external load occur during a scientific protocol, the load becomes an uncontrolled, independent variable, which may be perceived as undesirable.

To address the concerns of unintentional changes in external load, other researchers [11] used the same protocols as the ones in the present study with the exception of all protocols using 60% 1RM, and unlike the subjects in the study conducted by Oliver et al. [58], did not have to reduce the load during any of the protocols. As a result, MF was not different between any of the protocols, but MV and MP output were least during TS and greatest during CS with the most intra-set rest [11]. The results of Tufano et al. [11] agree with the findings of Oliver et al. [58], showing that when MF is similar, movement velocity is the main determinant of MP output. However, data from the present study show that even when MF differs in response to intentional alterations in external load, MV still appears to have the greatest influence on MP.

Lastly, a look at the available CS literature shows that many authors discuss either PP [12, 14, 22] or MP output [15, 39, 58], but rarely report both [11]. It is debatable whether MP or PP is more important for different athletes, but the ability to apply large forces at high velocities is widely accepted to be important in many sports. The differing responses between MP and PP in the present study may inspire other researchers to investigate the relationship of PP and MP to various sport performance tasks and resistance-training adaptations.

While CS2 and CS4 appear to be preferable for increasing acute mechanical hypertrophic factors, physiological factors that influence muscle growth were not measured in the present study. It is known that metabolic stress, in addition to mechanical stress, also contribute~~s~~ to skeletal muscle growth [102, 105]. While not within the scope of the present study, it is possible that an increase in total rest time during CS2 and CS4 may have affected metabolite accumulation and energy availability by sparing phosphagen energy stores and decreasing the reliance on glycolytic energy pathways [30, 31]. Therefore, is it possible that although CS2 and CS4 increased mechanical stress compared to TS, additional recovery during the intra-set rest periods may have limited metabolic stress, possibly negating the benefits of increased TW and TUT. Since %MVL and %PVL were not different between protocols in the present study, it could by hypothesized that ATP-PCr energy substrates were expended and restored at similar rates between the protocols based on previous research linking fatigue-induced decreases in velocity to the energetic demands of an exercise [8, 30, 31]. If metabolic stress was in fact similar between protocols but CS2 and CS4 resulted in greater TUT and TW, these CS protocols may provide a superior stimulus for developing skeletal muscle hypertrophy compared to TS without sacrificing PP. However, we did not measure these variables in the present study, warranting the investigation of the mechanisms underlying the force-velocity-power fatigue phenomenon.

Another limitation of the present study is the difference in session duration. By design, the protocol duration for CS2 was greater than CS4, both of which took longer than TS (15:51 ± 0:49, 10:10 ± 0:38, and 6:01 ± 0:19 min, respectively). Therefore, if CS2 is applied across multiple exercises within a training session, either the session's duration would be much longer than TS or the number of exercises performed in the same amount of time would be fewer during CS2. Although CS2 and CS4 resulted in greater TW and TUT than TS in the present study, it could be argued that CS2 and CS4 were less efficient than TS since TW was 15% and 10% greater than TS, but session duration was about 164% and 69% longer during CS2 and CS4, respectively. To abridge these values, the mean training efficiency (total work per unit of time) during TS was 12.8 $kJ\cdot min^{-1}$ whereas CS2 and CS4 resulted in 5.5 and 8.3 $kJ\cdot min^{-1}$, respectively. Therefore, subjects may have been able to perform an additional set or two during TS, increasing mechanical stress. However, this was not investigated within the present study because increasing the number of sets and repetitions in any of the protocols may have affected %VL, resulting in non-fatigue-matched protocols. Nonetheless, the application of such protocols in training environments allows for ad-hoc flexibility that is not allowed in a scientific setting.

Although %VL was similar between protocols, the different loads used in each set structure resulted in different absolute velocities, which may alter the transfer to performance. Keeping this in mind, it is the responsibility of the strength and conditioning professional to determine the importance of absolute velocity during a resistance-training session and to understand that the CS structures in the present study were specifically designed to determine whether CS structures could be manipulated to increase TW and TUT while maintaining PP output, with no concern for absolute movement velocity.

To conclude, our data show that CS can be manipulated in various ways that encourage different acute training responses, not just to result in less fatigue as demonstrated by previous studies [11, 15, 39, 58]. The strength and conditioning professional must be cognizant of the effects of external loads and rest period frequencies on velocity, fatigue, and system power output in order to prescribe training recommendations geared toward various adaptations, and further research should investigate the effects of different loads and intra-set rest durations and frequencies in CS structures.

Practical Applications

The present study shows that CS can be manipulated to include greater training loads, resulting in greater TW and similar PP but less MP without increasing %MVL or %PVL compared to TS. When designed in this manner, CS may serve as an alternative to traditional program design for promoting muscle growth over time during parallel periodization models. The duration of the CS2 session was longer than CS4 and TS due to more frequent intra-set rest intervals, but this allowed for CS2 to have the greatest training load, TW, and TUT. Therefore, the CS4 structure may be warranted when aiming to increase TW and TUT under brief, but not strict, time constraints. Lastly, if the maintenance of MP is of greater importance than PP, caution should be used when utilizing heavier loads during high-volume training, even if CS are used.

Conclusions

The present study shows that if minimizing fatigue-induced changes in velocity is not of paramount importance, CS structures can be designed to utilize greater loads for a given number of repetitions, resulting in greater TW without sacrificing PP. However, it is important that the strength and conditioning professional decide whether maximizing velocity or maximizing mechanical stress is most important during training. Future research should investigate the effects of similar set structures on other acute hypertrophic variables such as muscle activation, metabolic responses, and endocrine responses, ultimately investigating such CS structures over a chronic training period.

Chapter 5

The data presented in Chapter 4 showed that CS could in fact be used to allow for greater training loads for a given number of repetitions, meaning that CS could possibly be used to elicit increases in mechanical stress (i.e. a hypertrophic stimulus) while acutely maintaining PP output. As briefly stated within Chapter 4, MP output was the least in the CS2 protocol and was the greatest during TS, possibly resulting in training implications which should be addressed by the strength and conditioning professional on a case-by-case basis. To refer back to the terminology within Chapter 2, the term "CS" was broken down into sub-categories in order to more accurately describe how rest periods were allocated: two of those categories being the basic CS (where inter-set rest remained untouched and additional intra-set rest was provided) and RR (where the inter-set rest periods were reduced, and the total rest time was redistributed throughout the protocol). To continue exploring the malleability of CS structures, the following study was designed to determine whether a basic CS protocol would result in similar kinetics and kinematics as RR protocols. Previous research had shown that CS structures could maintain power output and movement velocity across the loading spectrum, and that CS could also increase the amount of total external work performed. Therefore, the following experiment was conducted to further investigate the original idea of creating protocols that could provide a hypertrophic stimulus and maintain acute exercise performance, simultaneously targeting multiple training goals. Please note that the formatting has been adjusted from the original manuscript that has been published in the *Journal of Human* Kinetics in 2017 to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Effects of cluster sets and rest redistribution on mechanical responses to back squats in trained men

Tufano JJ, Conlon JA, Nimphius S, Petkovic A, Frick J, and Haff GG.

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Purpose: This study examined the effect of rest period redistribution on back squat kinetics and kinematics. **Methods**: Eight resistance-trained men (1.76±0.22 1RM:body mass ratio) completed three experimental protocols separated by 48-96 hours. The cluster sets of four (CS4) protocol included 30 s of rest after the 4th, 8th, 16th, 20th, 28th, and 32nd repetition in addition to 120 s of rest after the 12th and 24th repetition. For the other two protocols, the total 420 s rest time of CS4 was redistributed to include nine sets of four (RR4) with 52.5 s of rest after every four repetitions, or 36 sets of one (RR1) with 12 s of rest after every repetition. **Results:** Mean (MF) and peak (PF) force, mean and peak velocity (MV and PV), and mean and peak power output (MP and PP) were measured during 36 repetitions and then averaged across 12 repetitions within each protocol. Repeated measures ANOVA 3x12(protocol x repetition) showed a protocol*repetition interaction for PF, MV, PV, MP, and PP (p-values from <0.001 to 0.012). No interaction or main effect was present for MF. During RR1, MV, PV, MP, and PP were maintained, but decreased throughout every 4-repetition group during CS4 and RR4. PF was maintained during RR1, but was less during CS4 and RR4 for repetitions following a rest period compared to subsequent repetitions. **Conclusions:** The present data indicate that if total rest time is redistributed to create shorter but more frequent sets, RR1 may be more beneficial for maintaining consistent kinetics and kinematics during high-volume back squats.

Introduction

Although sport-specific training is paramount for athletes of all sports, periodized resistance training helps foster optimal performance and reduce the risk of injury [116, 117]. To increase the effectiveness of resistance training, acute sessions should include systematic overload stimuli in order for the body to experience and adapt to increases in systemic stress [118]. Oftentimes, this is done by increasing the external training load during resistance training [67]. However, as training load increases, rest periods are generally modified in order to successfully complete a prescribed number of repetitions [69, 119]. Therefore, the modification of inter-set and intra-set rest periods have received considerable attention within the scientific strength and conditioning literature.

Previous research has shown that cluster sets (CS), which contain intra-set rest periods, maintain acute mechanical performance (i.e. force, movement velocity, and power output) better than TS which contain no intra-set rest [11, 12]. Since intra-set rest periods allow for the replenishment of immediate energy stores, the removal of metabolic byproducts from the muscle, and the maintenance of acute performance [10, 53], CS have been used to perform high volumes of external work without resulting in greater acute neuromuscular fatigue [10, 11, 39] in a variety of exercises and populations [24, 93, 95].

To create CS, some researchers have added intra-set rest without changing the inter-set rest duration, increasing the total rest time [11-13]; whereas, others have equated the total rest time between protocols by redistributing the total inter-set rest time throughout the protocol [10, 15, 39]. These studies have generally implemented 30 s of inter-repetition rest [12, 13, 57], with a range from 6 s [90] to upwards of over 40 s [96]. Some studies include a different number of repetitions for each participant, resulting in individualized rest redistribution (RR) that cannot directly be compared to other participants of other studies.

Most studies have compared a single traditional set (TS) protocol to a single CS protocol, and in the few studies that have compared CS protocols to each other [12, 14, 15], comparisons were not made between basic CS with additional intra-set rest periods and the RR technique. Hence, data comparing different CS structures (i.e. the addition of intra-set rest versus the redistribution of total rest time) is lacking. By examining such protocols, valuable information may be gathered regarding how the duration and frequency of rest periods influence neuromuscular fatigue during resistance training.

Therefore, the purpose of this study was to determine the effect of a basic CS inclusive of a standard inter-set rest period with the addition of intra-set rest and two different RR protocols with different rest period frequencies on mechanical variables during back squats in trained men. Based on previous literature [14], we hypothesized that the protocol with the most frequent, but shortest, rest periods would result in greater movement velocities and power outputs compared to protocols with longer but less frequent rest periods when the total rest time was equated between protocols.

Methods

Eight resistance-trained males participated in this study (25.2 ± 4.1 y; 76.7 ± 5.1 kg; 1.75 ± 0.07 m). All participants had at least six months of strength training experience using the back squat exercise and were able to perform a free weight back squat (top of the thighs at or below parallel) with at least 150% of their body mass. Participants were screened using medical history questionnaires and were excluded if they reported any recent musculoskeletal injuries. Participants averaged a 1RM of 135.0 ± 16.8 kg, a 1RM to body mass ratio of 1.76 ± 0.22, and a peak knee flexion angle at the bottom of the squat of 129.5 ± 11.5°. All procedures were carried out in accordance with the Declaration of Helsinki, were approved by the university’s Human Research Ethics committee, and all participants gave written informed consent prior to participation.

Participants reported to the laboratory for a 1RM session and three randomized experimental sessions. Each of the experimental sessions included 36 back squat repetitions using 75% of 1RM. The total assigned rest time was equal between protocols, but the distribution of rest varied. The cluster sets of four (CS4) protocol included 30 s of rest after the 4th, 8th, 16th, 20th, 28th, and 32nd repetition in addition to 120 s of rest after the 12th and 24th repetition. For the other two protocols, the total rest time was redistributed to include nine sets of four (RR4) with 52.5 s of rest provided after every four repetitions, or 36 sets of one (RR1) with 12 s of rest provided after every repetition. Therefore, all three protocols included 36 repetitions at 75% 1RM with 420 s of standing, unloaded rest (Figure 5.1). Each session occurred at the same time each morning and was separated by 48-96 h. Participants were instructed to avoid all other forms of exercise for 48 h leading up to data collection for the duration of the study and abstained from eating and drinking during the protocols.

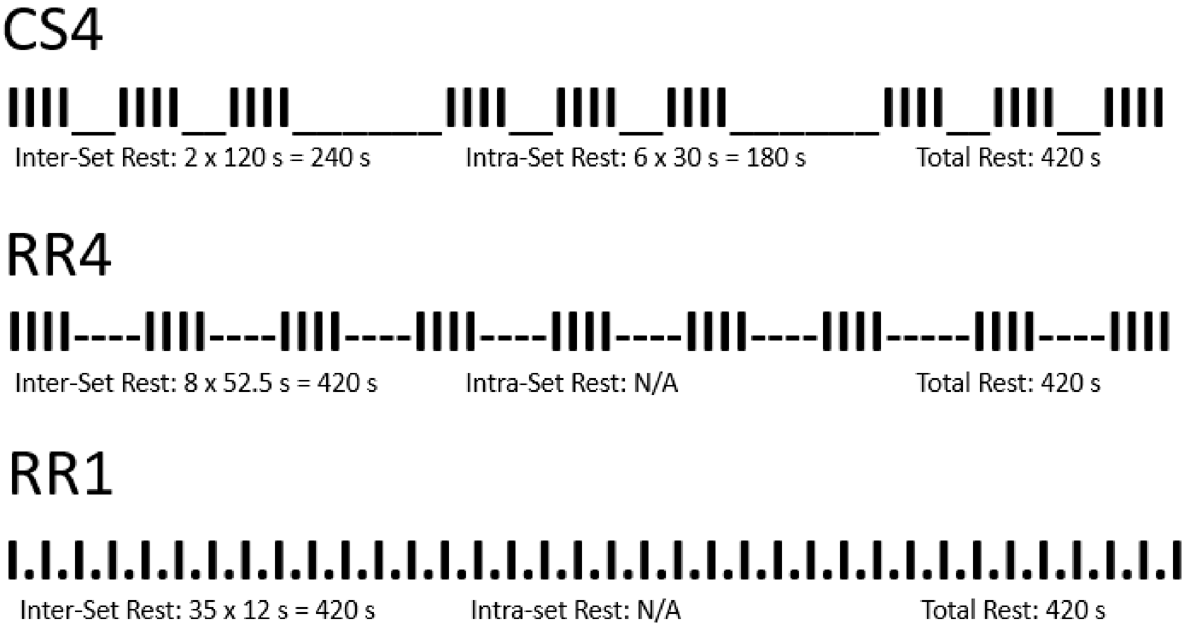

Figure 5.1: Cluster set protocol with 420 seconds of total rest (CS4), redistributed to create nine sets of four repetitions with 52.5 seconds of inter-set rest (RR4) and to create thirty-six sets of one with 12 seconds of inter-repetition rest (RR1).

During each of the experimental sessions, participants were instructed to "squat all the way down" by lowering the barbell under control and to "explode out of the bottom" by performing each squat as quickly as possible during the concentric phase without jumping and without the bar leaving the shoulders [110]. Each participant's foot placement was kept constant for every repetition during every session using a horizontal-vertical grid with individualized visual markings. Following a standard dynamic warm-up inclusive of stationary cycling, dynamic warm-up, and squats with progressively increasing loads, each protocol began when participants positioned themselves under the barbell at the beginning of a verbal five-second countdown. When the countdown reached zero, the participants un-racked the bar and stepped backwards onto the force plate to perform the desired number of consecutive repetitions according to the assigned protocol. After completing one (RR1) or four (CS4 and RR4) repetitions, the participants re-racked the bar in the squat rack and remained standing, unloaded during the rest period. The participants positioned themselves under the barbell when the next five-second countdown began and the process was repeated until the protocol was finished.

A customized LabVIEW program (National Instruments, Version14.0) was used to collect and manually analyze data received from the force plate (AMTI BP12001200; Watertown, MA) and linear positon transducers (LPTs) (Celesco PT5A-250; Chatsworth, CA) via a BNC-2090 interface box with an analog-to-digital card (NI-6014; National Instruments, Austin TX, USA). All signals were sampled at 1000 Hz and filtered using a 4th order-low pass Butterworth filter with a cut-off frequency of 50 Hz. The retraction tension of the four LPTs was 23.0 N, which was accounted for in all calculations.

All kinematic and kinetic data were collected using methodology similar to previous research [110] and all variables were collected during the concentric phase of each lift. Specifically, the concentric phase was defined as the point of maximal displacement (bottom of the squat) to zero-displacement (standing). All squats were performed on a force plate to measure MF and PF and two LPTs were attached to each side of the barbell (four in total) originating from the top of the squat rack to obtain MV and PV. External mechanical MP and PP of the system were calculated by direct measurement of ground reaction force and bar velocity.

Means and standard deviations were calculated for all dependent variables for 36 repetitions, and after averaging all repetitions into 12-repetition segments within each protocol (i.e. repetition 1=(1+13+25)/3; repetition 2=(2+14+26)/3; etc.), 3x12 (protocol x repetition) repeated measures ANOVAs were used within SPSS version 22.0 (IBM, Armonk, NY). In the event of a significant protocol*repetition interaction, the 12 repetitions were compared in 4-repetition segments due to the design of the RR4 and CS4 protocols and follow-up pairwise comparisons were made to determine differences. Significance was set at $p \leq 0.05$ for all tests.

Results

Means and standard deviations for all variables are shown in Table 5.1. There were no significant differences between protocols for any variable when all 36 repetitions were averaged together. However, a protocol*repetition interaction was present for PF, MV, PV, MP, and PP (Table 5.1). Significant differences are shown throughout Figure 5.2. There was neither an interaction nor a main effect for protocol for MF.

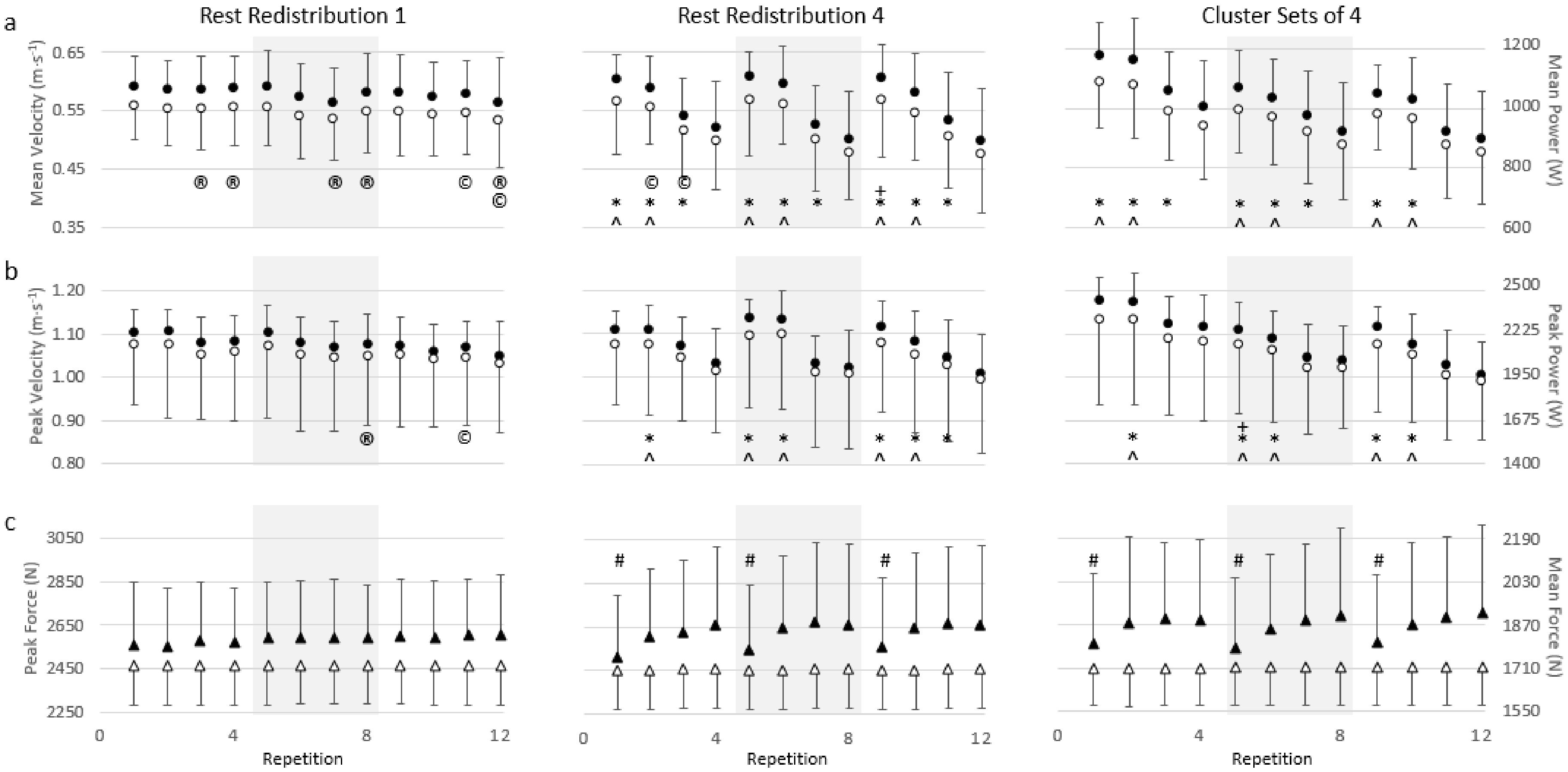

*Figure 5.2: Mean velocity and power output (A); peak velocity and power output (B); and peak force output collapsed across twelve repetitions for each protocol (C). Closed circles indicate velocity data on the primary vertical axis and open circles for power data on the secondary vertical axis. Closed triangles show peak force and open triangles show mean force. Significantly greater than the *4th, ^3rd, and +2nd repetition of each segment; Significantly different from the same repetition of the ©CS4 protocol and the ®RR4 protocol; Peak force significantly less than the following three repetitions #.*

Table 5.1: Mean ± standard deviation of kinetic and kinematic data with ANOVA results.

	CS4 **Mean ± SD**	**RR4** **Mean ± SD**	**RR1** **Mean ± SD**	**ANOVA Result Protocol**		**ANOVA Result Protocol*Repetition**	
Mean Force (N)	1712.48 ± 139.29	1715.34 ± 146.45	1722.84 ± 145.65	F = 3.16	p = 0.074	F = 2.04	p = 0.116
Peak Force (N)	2640.22 ± 364.65	2621.73 ± 333.09	2581.14 ± 266.93	F = 1.15	p = 0.344	F = 3.62	p = 0.012[a]
Mean Velocity ($m \cdot s^{-1}$)	0.56 ± 0.06	0.56 ± 0.06	0.58 ± 0.06	F = 0.82	p = 0.459	F = 10.60	p < 0.001[c]
Peak Velocity ($m \cdot s^{-1}$)	1.09 ± 0.13	1.07 ± 0.13	1.08 ± 0.12	F = 0.22	p = 0.806	F = 4.00	p = 0.007[b]
Mean Power (W)	955.08 ± 159.44	945.31 ± 160.11	982.18 ± 129.94	F = 1.01	p = 0.388	F = 10.80	p < 0.001[c]
Peak Power (W)	2101.39 ± 433.09	2062.96 ± 432.00	2081.35 ± 428.77	F = 0.25	p = 0.779	F= 3.78	p = 0.010[b]

*ANOVA – analysis of variance; CS4 – cluster sets of four protocol; RR1 – rest redistribution one protocol; RR4 – rest redistribution four protocol. Significant protocol*repetition interaction: $p < 0.05$a; $p \leq 0.01$b; $p < 0.001$c.*

Discussion

Basic CS and RR protocols have been investigated independently within the scientific literature, but to the authors knowledge, have never been compared within the same study. Therefore, the purpose of this study was to determine the effect of a basic CS inclusive of a standard inter-set rest period with the addition of intra-set rest and two different RR protocols with different rest period frequencies on mechanical variables during back squats in trained men. The main finding of the present study was that when using the same load and number of repetitions, the mean acute kinetic and kinematic responses to free-weight back squats were similar regardless of how the rest periods were distributed within the session, but the patterns of each variable were different between protocols, with the exception of MF. Specifically, the first repetition following a rest period in RR4 and CS4 displayed less PF than the following three consecutive repetitions: a pattern that was not present in RR1. Additionally, MV, PV, MP, and PP all progressively decreased throughout every 4-repetition segment, which did not occur during RR1.

The primary finding was that despite mean MV and PV of all 36 repetitions being statistically similar between protocols, there were unique velocity and power output responses between the protocols (Figure 5.2A and 5.2B). Furthermore, MP and PP mirrored the MV and PV responses, supporting the hypothesis that movement velocity underpins the production of external power output [58]. In RR1, velocity and power output remained fairly steady; but, when four repetitions were performed in a row regardless of the protocol (RR4 and CS4), a decrease in velocity and power output occurred in each 4-repetition segment. Therefore, despite a lack of significant differences in the global kinematic responses, the patterns observed in the protocol*repetition interactions of the present study should be considered by strength and conditioning professionals as the data indicate that practical training implications may arise when prescribing resistance exercises if acute movement velocity is of interest.

In order to discuss the practical applications of such observations, the role of monitoring velocity during acute resistance-training should be understood. To abide by the training principle of specificity, some athletes and coaches strive to acutely achieve maximal movement velocity and power output, hypothesizing that chronic exposure to such stimuli will result in positive training adaptations that translate into heightened performance. Therefore, some coaches and researchers implement "velocity-based training" protocols in which a minimum velocity threshold (i.e. 80% of the maximal attainable velocity for a given load) must be maintained to avoid overly fatiguing the neuromuscular system [18, 120, 121]. According to the recommendations of previous research [18, 120, 121], velocity-based training with a minimum velocity threshold of 80% maximal attainable velocity would have resulted in a minimum velocity threshold of approximately 0.52 $m \cdot s^{-1}$ in the present study. Despite the redistribution of rest during RR4 allowing MV to return to a baseline value after each 52.5 s rest period, only 28 out of 36 repetitions had a MV greater than 0.52 $m \cdot s^{-1}$. Additionally, 120 s and 30 s of rest were enough to allow MV to return to baseline during CS4, but only 32 out of 36 repetitions achieved a MV above 0.52 $m \cdot s^{-1}$. In RR1, participants were able to complete 36 out of 36 repetitions at a velocity equal to or greater than 0.52 $m \cdot s^{-1}$, indicating that RR1 would have allowed for a greater number of repetitions resulting in greater TW and possibly a greater acute training stimulus. Similarly, other researchers have highlighted the effectiveness of inter-repetition rest periods for maintaining velocity [90] and have suggested that inter-repetition rest periods may be preferential to TS for increasing mechanical stress without decreasing acute performance [23, 24]. Although the purpose of this study was not to implement or define velocity-based thresholds, the readers of this manuscript are likely interested in acute kinematics during resistance-training and should consider the aforementioned points when implementing basic CS or RR protocols during training. In this regard, it appears as though the shorter but more frequent rest intervals used in RR1 may be most beneficial for maintaining movement velocity and power output.

Since the relative external load was the same during each protocol, there was no difference in MF between protocols, in line with previous research [11, 54, 57]. There is a lack of PF data within the CS literature, but previously, Hardee et al. [12] showed that PF was better maintained when longer inter-repetition rest periods were used during three CS of six power cleans performed with a load of 80% of 1RM. On the other hand, Hansen et al. [32] showed that PF was not different between RR protocols during four sets of six jump squats with a fixed load of 40 kg. Considering that one study implemented extra rest periods during a heavily loaded concentric movement whereas the other redistributed the total rest time during a relatively light exercise with a countermovement, it would be difficult to compare the PF results of either of those studies to the data in the present study. However, in a previously published study, PF has been reported to be similar between cluster and TS protocols inclusive of the same load during the back squat exercise when using different rest period configurations [11], but a comparison of individual repetitions was lacking, making the present study the first to compare the differences in PF between individual back squat repetitions during CS.

Although PF averaged across 36 repetitions was not different between the current study's protocols, a protocol*repetition interaction indicates that practical training implications may in fact be present within the data. Specifically, data in Figure 5.2C show that the repetition that was preceded by a rest period in the CS4 and RR4 protocols displayed less PF than repetitions that were preceded by another repetition. Therefore, PF remained fairly steady during RR1, but was greater during successive repetitions compared to the first repetition of each 4-repetition segment in RR4 and CS4 (Figure 5.2C). Despite this being the first study to compare PF between individual repetitions of the back squat using CS, the results from a previous study may shed light on this PF phenomenon [57]. In a study conducted by Moir et al. [57], participants performed four repetitions of the deadlift in a row (i.e. a TS), a CS of four individual repetitions with 30 s of inter-repetition rest, and a CS of four repetitions with 30 s of intra-set rest after every two repetitions. The authors concluded that the additional rest periods during CS had a negative effect on power output and culminated in greater concentric TUT compared to the TS [57]. A lack of PF data does not allow for a direct comparison with the present study, but an increase in TUT (and a hypothesized decrease in movement velocity stated by the authors) in the repetitions that followed a 30 s rest period led the authors to believe that the stretch-shortening cycle was not as profound in the CS protocols compared to the TS when a repetition was preceded by another repetition [57]. The authors concluded that the competing mechanisms of fatigue and potentiation resulted in different mechanical responses and that such relationships should always be considered when designing a resistance-training program, especially as inter-set rest periods are employed.

Similar to the protocols used by Moir et al. [57], the CS4 and RR4 protocols of the present study contained a minimum of 30 s rest before the repetition that exhibited less PF. Alternatively, the RR1 protocol included only 12 s of rest between repetitions and did not show the same pattern of decreased PF after a rest period. Therefore, it is possible that there may have been a force-potentiation mechanism involved that lasted up to 12 s, but not 30 s during dynamic resistance training with maximal effort in the present study and the study conducted by Moir et al. [57]. In a practical sense, inter-repetition rest periods approaching

30 s may not result in optimal force production during loaded back squats performed for many repetitions. However, it is important to consider that in addition to PF, other factors such as movement velocity most likely play a larger role for determining acute exercise performance and developing power output [58].

To conclude, previous studies have shown that the redistribution of rest periods maintains the kinetic and kinematic characteristics of resistance training [14, 32, 58], and the data in the present study also support those findings. Although there were no statistical differences between variables when all 36 repetitions were averaged together within each protocol, it is important that the strength and conditioning professional be cognizant of the competing physiological mechanisms of fatigue and potentiation, and consider the protocol*repetition interaction patterns of velocity and power output when rest periods are redistributed within a protocol.

Conclusions

The present study demonstrated that redistributing total rest time did not affect the overall kinetics and kinematics of back squats in trained men, but resulted in different patterns of force, velocity, and power output throughout the session. Further research may examine such protocols using different exercises and external loads in addition to determining the effect of various RR protocols on acute physiological responses that occur during resistance training.

Practical implications

- Redistributing total rest time results in similar gross mechanical responses during barbell back squats in strength-trained men
- The frequency and duration of redistributed rest results in different patterns of PF, movement velocity, and power output

- Rest periods of 30 seconds or greater may dissipate the potential for “priming” the stretch-shortening cycle to produce maximal PF, which seems to be present when performing up to four successive repetitions, or when performing single repetitions separated by 12 seconds of rest
- If a minimum velocity threshold must be met, a protocol similar to RR1 may allow for the greatest number of repetitions to be performed

Chapter 6

The data presented in Chapter 5 showed that when considering all of the repetitions performed in the protocols, the kinetic and kinematic responses to back squats were similar regardless of how the rest periods were redistributed. However, the patterns of velocity and power output were unique to each set structure. From a practical standpoint, all of the protocols were able to maintain movement velocity equally; but, as noted within the previous chapter's practical implications, only the RR1 protocol with inter-repetition rest allowed for the maintenance of at least 80% of maximal MV. However, the maintenance of acute movement velocity and power output are not typically associated with hypertrophy-based workouts, even when large volumes of work are performed. Hence, it would be fair to state that RR1 may not have been sufficient to stimulate an acute hypertrophic response. To address this, information regarding anabolic mediators other than mechanical stress could shed light on whether or not these protocols could maintain acute performance while resulting in a physiological environment indicative of stimulating skeletal muscle hypertrophy. Therefore, the information in this chapter is a continuation of the data presented in the previous chapter. Specifically, this chapter includes data that came from the same experiment as the previous chapter, but places a major focus on the physiological responses to exercise rather than solely the mechanical responses. Please note that the formatting has been adjusted from the original manuscript that has been published in 2019 in the *Journal of Strength and Conditioning Research* to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Different cluster sets result in similar metabolic, hormonal, and perceptual responses in trained men

Tufano JJ, Conlon JA, Nimphis S, Oliver JM, Kreutzer A, and Haff GG

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Purpose: The purpose of this study was to compare the metabolic, endocrine, and perceptual responses of three back squat protocols with equal loads, number of repetitions, and total rest duration. **Methods**: Eight strength-trained men performed 36 back squats using 75% 1RM and 420 s of total rest during basic cluster sets of 4 (CS4), rest-redistribution sets of 4 (RR4), and rest-redistribution sets of 1 (RR1). Ratings of perceived exertion (RPE), blood lactate (La), mean velocity maintenance (MVM), and mean velocity loss (MVL) were measured during exercise. Total testosterone (TT), growth hormone (GH), cortisol (C), and sex-hormone binding globulin (SHBG) were measured before exercise and 15, 30, and 60 min post-exercise. **Results**: There were no differences between protocols for MVM. However, MVL was less during RR1 compared to RR4 ($p = 0.032$), and neither protocol was different than CS4. All protocols resulted in similar increases in RPE and La, which remained elevated up to 30 min post-exercise ($p<0.05$). In all protocols, GH increased and returned to baseline by 60 min post-exercise ($p<0.05$). At 60 min post-exercise, TT was less than all other time points ($p<0.05$). There were no main effects for time for SHBG or C. **Conclusions**: The data from this study suggest that rest period distribution may not affect perceived effort or metabolic and hormonal changes as long as the external load, number of repetitions, and total rest time are equalized. Additionally, this study shows that different types of cluster set protocols can result in pro-anabolic physiological responses to resistance-training.

Introduction

Resistance-training performed with a traditional set (TS), in which lifters consecutively perform repetitions within a set, is fatiguing and results in decreased energy availability [30, 31], increased metabolic stress [10, 31], and decreased movement velocity [8, 11]. To combat such fatigue-induced decreases in acute performance (i.e. movement velocity and power output), researchers have begun to investigate the effects of intra-set rest periods in set structures known as a cluster set (CS) [122]. There are many different ways in which CS can be made, including the addition of intra-set rest periods, known as a basic CS, and the redistribution of rest in which total rest time is divided to create shorter but more frequent rest periods [122]. Although these two sub-types of CS have been investigated independently, to the authors' knowledge, they have never been compared to each other within the same study. Nonetheless, it has been hypothesized that the use of all types of CS allow for the frequent and partial replenishment of adenosine triphosphate (ATP) and phosphocreatine (PCr) stores, resulting in a better ability to maintain velocity and power output when compared to TS [16, 122].

Previous research has shown that various types of CS performed with different exercises and intensities generally result in better performance maintenance (i.e. velocity, power output, jump height, force output) during an acute exercise bout when compared to TS [14, 39, 53, 58, 122]. In addition to the positive effects of CS on acute performance, research has indicated that implementing less-fatiguing protocols during training can result in similar gains in strength compared to more fatiguing protocols [59, 61, 123]. Although these examples indicate that fatigue may not be necessary to induce gains in strength, it should not be forgotten that some degree of acute fatigue is needed to continually stress the body and stimulate neuromuscular adaptations [118] and that fatigue is often warranted when seeking to increase skeletal muscle hypertrophy [105, 121, 124].

In order to acutely increase fatigue and stimulate the anabolic process, classic body-building programs include moderately heavy loads performed for many repetitions with short rest periods [40, 102, 119]. Historical works from various laboratories have shown that such body-building regimes inclusive of high training volumes and short rest periods result in large amounts of external work, increased metabolic stress, and changes in acute hormonal concentrations [125-127], resulting in associations to be made between these variables [124, 128, 129]. Despite a plethora of data showing that high-volume resistance training increases acute endocrine responses during and after exercise and that such responses play a role in anabolism, some researchers have begun to question the importance of acute endocrine responses for inducing skeletal muscle hypertrophy [130]. Nevertheless, previous evidence relating acute increases in hormone concentrations to skeletal muscle growth and tissue regeneration should not be disregarded [124], and new theories open the door for unconventional training methods which use a variety of loads and rest period frequencies and durations [61, 131, 132].

The ability to create a seemingly infinite combination of external loads, rest periods, and training volumes allows for novel training stimuli to be introduced at various times within a training program. Specifically, additional rest periods provided during CS can allow for greater training loads and a greater amount of total work (TW) compared to TS protocol of equal relative fatigue [133]. Such increases in mechanical stress could possibly affect acute metabolic demands during exercise [105], post-exercise endocrine responses [45, 46], and skeletal muscle growth [65]. To date, there are a few studies that have investigated the effect of CS on metabolic and endocrine responses, but these studies have used varying protocols, making direct comparisons between studies difficult [10, 53, 134]. For example, Oliver et al. [10] employed a rest redistribution (RR) protocol during 4 sets of 10 back squats using 70% of 1RM, whereas Girman et al. [53] implemented an RR protocol during upper- and lower-body circuit training using a wide variety of exercises and training loads. While Girman et al. [53] and Oliver et al. [10] utilized RR protocols, Goto et al. [134] implemented a basic CS protocol inclusive of 30 s intra-set rest periods during 3-5 sets of machine exercises with a 10RM load. Despite a lack of uniformity among the protocols used, all of the protocols increased La, but the response was always greater in response to TS [10, 53, 134]. Additionally, RR and TS resulted in increased growth hormone (GH) concentrations after exercise [10, 53] whereas basic CS inclusive of intra-set rest periods did not [134].

Together, the data from these three studies [10, 53, 134] indicate that RR and basic CS protocols both have the ability to increase lactate (La), but RR may also increase acute endocrine responses whereas basic CS may not. In addition, neither study reported the differences in subjects' rating of perceived exertion (RPE) between protocols, which may serve as a simple method of subjectively reporting perceptual effort levels that relate to physiological fatigue [22, 84, 135]. Compared to TS, previous research has shown that RR [84] and basic CS protocols [22] result in lower RPE, and it has been hypothesized that these set structures may also result in less La and a lesser endocrine response [17]. However, to the authors' knowledge, La, RPE, and endocrine responses have not been collected during the same study using different types of CS protocols. Therefore, the purpose of this study was to compare the effects of a basic hypertrophy-oriented CS protocol [133] to two different RR protocols on the hormonal, metabolic, and perceptual responses of back squats in trained men.

Methods

Subjects

Eight resistance-trained men (25.2 ± 4.1 y; 76.7 ± 5.1 kg; 1.75 ± 0.07 m) with at least six months of strength training experience using the full back squat exercise participated in this study. All subjects could perform a free weight back squat (top of the thighs below parallel) with at least 150% of their body and were excluded if they reported any recent musculoskeletal injuries or recent use of ergogenic aids that may have affected endocrine function. Specifically, subjects must not have had any history of anabolic steroid use, and could not have used any other supplements that are marketed to influence hormone or insulin levels. The average 1RM was 135.0 ± 16.8 kg, 1RM to body mass ratio was 1.76 ± 0.22 kg:kg, and peak knee flexion angle at the bottom of the squat was 129.5 ± 11.5°. All procedures were carried out in accordance with the Declaration of Helsinki and were approved by the University Human Research Ethics committee at Edith Cowan University, and all subjects gave written informed consent prior to participation.

Experimental design

Using a repeated measures design, subjects reported to the laboratory four times. Prior to the three randomized experimental sessions, subjects completed a 1 repetition maximum (1RM) session, immediately after which they were familiarized with the procedures of the subsequent experimental testing sessions. Two to three days after the 1RM session and after 48 hours of no physical activity, the first experimental session took place. Each of the experimental sessions included 36 back squat repetitions using a load of 75% of 1RM. The total assigned rest time was equal between protocols, but the distribution of rest varied [10, 32]. The cluster sets of four (CS4) protocol included 30 s of rest after the 4th, 8th, 16th, 20th, 28th, and 32nd repetition in addition to 120 s of rest after the 12th and 24th repetition [133]. For the other two protocols, the total rest time was redistributed to include nine sets of four repetitions (RR4) with 52.5 s of rest provided after every fourth repetition, or 36 sets of one repetition (RR1) with 12 s of rest provided after every repetition. Therefore, all three protocols included 36 repetitions at 75% 1RM with 420 s of standing, unloaded rest (Figure 6.1). Subjects were instructed to avoid all other forms of exercise during the study period and abstained from eating and drinking during the protocols. All subjects completed all 36 repetitions in each protocol.

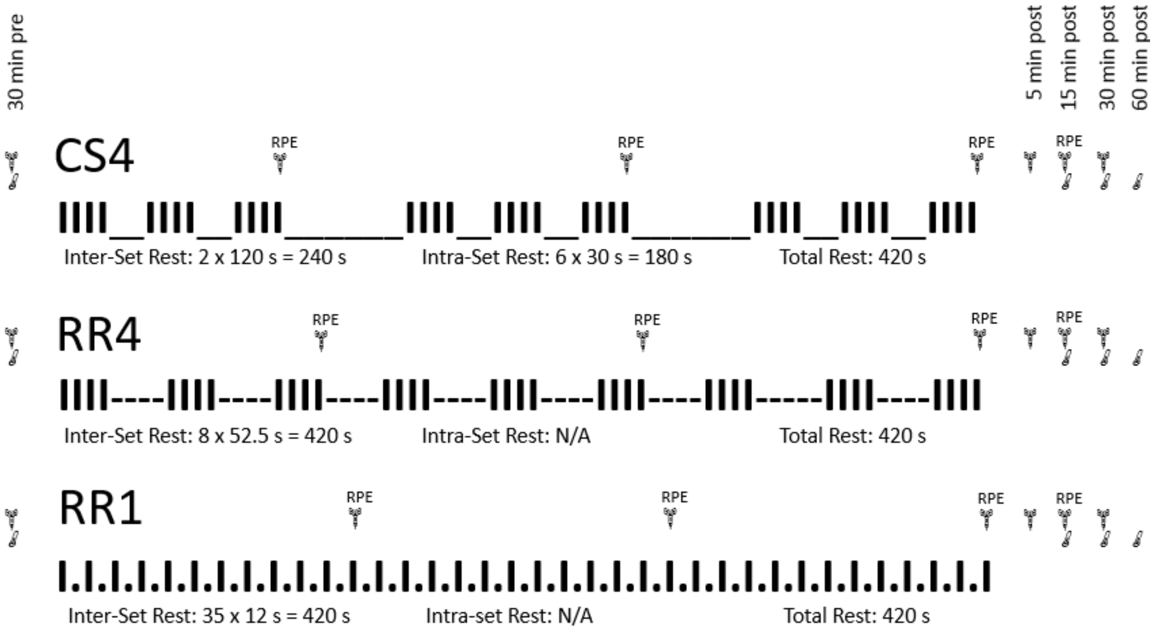

Figure 6.1: Protocol design for cluster sets of 4 (CS4), rest redistribution 4 (RR4), and rest redistribution 1 (RR1). Time-sensitive data collection included blood lactate (⊤); vacutainer blood collection for growth hormone, cortisol, total testosterone, and sex-hormone binding globulin (🧪); and rating of perceived exertion (RPE).

<u>One-repetition maximum testing</u>

Subjects reported to the laboratory at the same time of day as the upcoming experimental sessions (in the morning between 06:00 and 10:00). Following anthropometric measures, subjects completed a 5 min stationary cycle warm-up, pedaling at 60 revolutions per minute with 100 W of resistance. Subjects then completed a 5 min dynamic warm-up consisting of bodyweight squats, leg swings, and various marching exercises followed by eight, five, and three back squat repetitions with 25, 50, and 60% of estimated 1RM. Next, subjects began free-weight back squat 1RM attempts starting at 85% estimated 1RM, resting 2-5 min between sets of increasing progressively increasing loads. Each subject's heel and toe locations were recorded using a horizontal-vertical grid intersecting every 1 cm and were kept constant for all remaining sessions.

Experimental sessions

After refraining from physical activities outside of normal daily tasks for 48-72 h, subjects reported to the laboratory in the morning after a 12-h fast. Subjects were then seated for 15 min before pre-exercise blood samples (PRE) were obtained. The warm-up protocol was identical to the 1RM session, and after 5 min of rest, subjects positioned themselves under the barbell. Following a verbal 5-second countdown, subjects un-racked the bar from the squat rack when the count reached "zero". Once in position on the force plate, subjects performed the desired number of repetitions (four repetitions in CS4 and RR4, and one repetition during RR1). Subjects were instructed to perform the eccentric portion under control and "explode out of the bottom" returning to a standing position as quickly as possible without jumping or the bar leaving the shoulders [11]. After completing the prescribed number of repetitions, subjects re-racked the bar and remained standing, unloaded during the rest period. When the next 5-second countdown began, the subjects positioned themselves under the barbell, ready to repeat the process when the countdown reached "zero". This was repeated until the final repetition was completed. Upon completion of the final repetition, subjects were seated and remained quietly seated for 60 min. Post-exercise blood draws were obtained 15 (P15), 30 (P30), and 60 (P60) min after the final repetition was completed. All experimental sessions were separated by 48-96 hours and occurred at the same time of day within a two-hour time frame.

Kinematic data collection and analysis

All data were collected using a customized LabVIEW program (National Instruments, Version14.0) and were manually analyzed after data collection. Four linear position transducers (LPTs) (Celesco PT5A-250; Chatsworth, CA) were positioned above the squat rack at all four corners, sending raw voltage data via a BNC-2090 interface box with an analog-to-digital card (NI-6014; National Instruments, Austin TX, USA). All signals were sampled at 1000 Hz and filtered using a 4th order-low pass Butterworth filter with a cut-off frequency of 50 Hz.

Using time and displacement from the LPTs, mean velocity (MV) was calculated for all back squat repetitions. From these values, MV maintenance (MVM) [11] was calculated to show the average MV of all 36 repetitions in relation to the fastest repetition of each protocol, expressed as a percentage of the fastest repetition. Additionally, MV loss (MVL) was calculated by determining the percentage decrease in MV from the fastest repetition (usually the first or second) to the 12th, 24th, and 36th repetition to quantify the degree of neuromuscular fatigue at equal repetitions within each protocol, similar to previous studies [8, 11].

Rating of perceived exertion

During the 1RM session, subjects were familiarized with a printed 0-10 OMNI-RES scale: a resistance-training specific RPE scale where 0, 2, 4, 6, 8, and 10 were anchored using the descriptions of “extremely easy”, “easy”, “somewhat easy”, “somewhat hard”, “hard”, and “extremely hard”, respectively [135]. Subjects were then shown the printed scale after repetitions 12 (R12), 24 (R24), and 36 (R36) during experimental sessions, and were asked how difficult the previous repetition was.

Blood sampling and analysis

A certified phlebotomist sterilized the area surrounding the medial cubital vein according to standard procedures and collected a 5 mL blood sample in a vacutainer tube containing no additives (BD Biosciences, San Jose CA) for the analysis of serum total testosterone (TT), cortisol (C), sex-hormone binding globulin (SHBG), and GH. After gently inverting the tube with no additive five times, the samples remained at room temperature for approximately 45 min and were then stored in a refrigerator for up to three hours. The same blood sampling procedures were repeated at P15, P30, and P60. All samples were centrifuged at 3000 revolutions per minute for 10 minutes in a swing-bucket centrifuge. Serum was then aspirated, aliquoted into Eppendorf tubes, and stored at -80°C until analysis.

Using radioimmunoassay (RIA; MP Biomedicals, Orangeburg, NY), all T and GH samples were run in duplicate on an ISO Data 100 gamma counter (Titertek; Pforzheim, Germany). The inter-assay coefficient of variation (CV) was 11.88% and 9.74% for T and GH, respectively. Additionally, C and SHBG samples were run in duplicate using an Enzyme-linked immunosorbent assay (ELISA; ALPCO, Salem NH). The inter-assay CV for C was <5% and was 15% for SHBG.

A certified phlebotomist also performed finger stick blood sampling at the following time points: PRE, R12, R24, R36, 5-min post exercise (P5), P15, and P30. These samples were used for the analysis of La using a Lactate Pro 2 device (Arkray Global Business Inc., Kyoto, Japan). The first drop of blood was wiped away using medical gauze and a subsequent drop was used as the blood sample. The device instantaneously analyzed each sample and the values were recorded for analysis.

Statistics

Descriptive statistics were calculated for RPE, MVM, MVL, La, C, GH, TT, and SHBG. Separate 3 (protocol) x 4 (time) repeated measures analysis of variance (ANOVA) were used for C, GH, TT, and SHBG. A 3 (protocol) x 7 (time) repeated measures ANOVA was used for La. Separate 3 (protocol) x 3 (time) repeated measures ANOVA were used for RPE and MVL, whereas a 3 (protocol) x 1 (time) repeated measures ANOVA was used for MVM. The alpha level was set at $p \leq 0.05$ and all statistical analyses were performed using SPSS 22.0 (IBM, Armonk, NY). In addition to these statistics, the magnitude of effect was assessed to determine practical differences in performance variables due to set structures. Therefore, Hedge's g effect sizes were calculated for performance variables (i.e. MVM and MVL) and were interpreted as small (0.2 - 0.49), moderate (0.5 - 0.79), and large (≥0.8).

Results

Repeated measures ANOVA tests showed that there were no differences between protocols ($p = 0.733$) for MVM (CS4 = 84.3 ± 6.8%; RR4 = 84.5 ± 6.6%; RR1 = 85.8 ± 6.0%) and only negligible to small effects were present: RR1-CS4, 0.23 (-0.76 to 1.21); RR1-RR4, 0.19 (-0.79 to 1.17); and RR4-CS4, 0.04 (-0.94 to 1.02). There were significant main effects for protocol ($p = 0.026$) and time ($p = 0.017$) for MVL (Figure 6.2). Effect sizes indicated that different protocols had different effects on MVL. The effect of RR1 on MVL was large compared to CS4, 1.01 (-0.03 to 2.05), and RR4, 1.00 (-0.04 to 2.04) at the beginning of the protocol from the fastest repetition to the 12th, decreasing to moderate by the end of the protocol 0.56 (-0.44 to 1.56) and 0.38 (-0.61 to 1.36) for RR1-CS4 and RR1-

RR4, respectively. In contrast, the effect of RR4 and CS4 were negligible at the beginning and end of the session 0.08 (-0.90 to 1.06) and 0.18 (-0.81 to 1.16), respectively. For C, there was a main effect for protocol ($p = 0.038$), but not for time ($p = 0.079$) (Figure 6.3). There was a main effect for time ($p = 0.002$) for GH, but there were no differences between protocols ($p = 0.418$) (Figure 6.5). Similarly, there was a main effect for time ($p = 0.008$) for TT, but there were no differences between protocols ($p = 0.523$) (Figure 6.6). For SHBG, there was neither a main effect for protocol ($p = 0.995$) nor time ($p = 0.389$) (Figure 6.6). For both La and RPE, there was a main effect for time ($p \leq 0.001$), but not for protocol ($p = 0.089$ for La; $p = 0.766$ for RPE) (Figure 6.4). There were no protocol*time interactions present for any variable ($p > 0.05$; range $p = 0.221$ to 0.917).

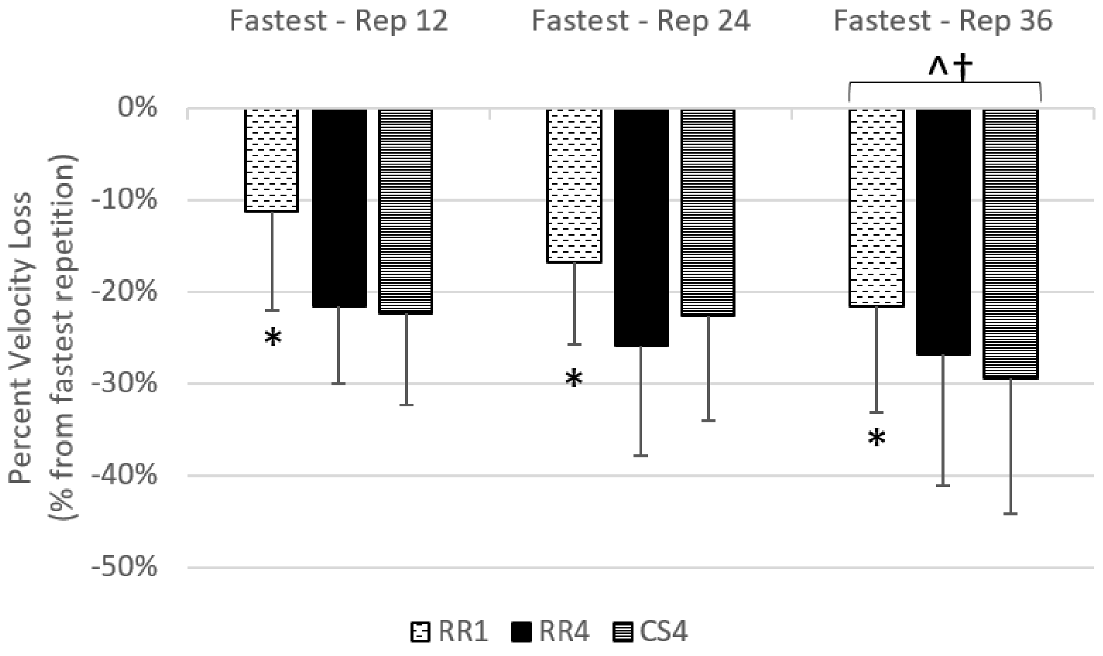

Figure 6.2: Percent of mean velocity loss (MVL) from the fastest repetition to the 12th, 24th, and 36th during the rest redistribution 1 (RR1), rest redistribution 4 (RR4), and cluster sets of 4 (CS4) protocol. When collapsed across time, MVL was significantly less in RR1 than RR4 (p = 0.032). When collapsed across protocols, MVL from the fastest repetition to Rep36 was significantly greater than the MVL from the fastest to Rep12 (p = 0.020)^ and the fastest to Rep 24 (p = 0.011)†.*

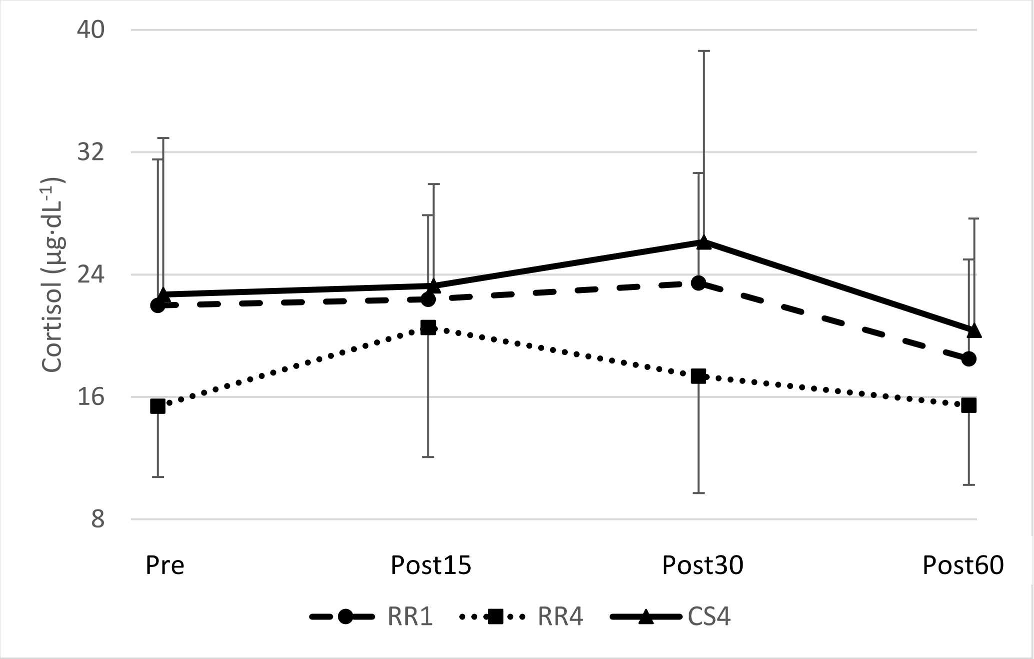

Figure 6.3: Cortisol before (Pre), 15 (Post15), 30 (Post30), and 60 (Post60) minutes after exercise. When collapsed across all time points, rest redistribution 4 (RR4) was significantly than rest redistribution 1 (RR1) and cluster sets of 4 (CS4) ($p < 0.05$). No significant interactions or differences between time points.

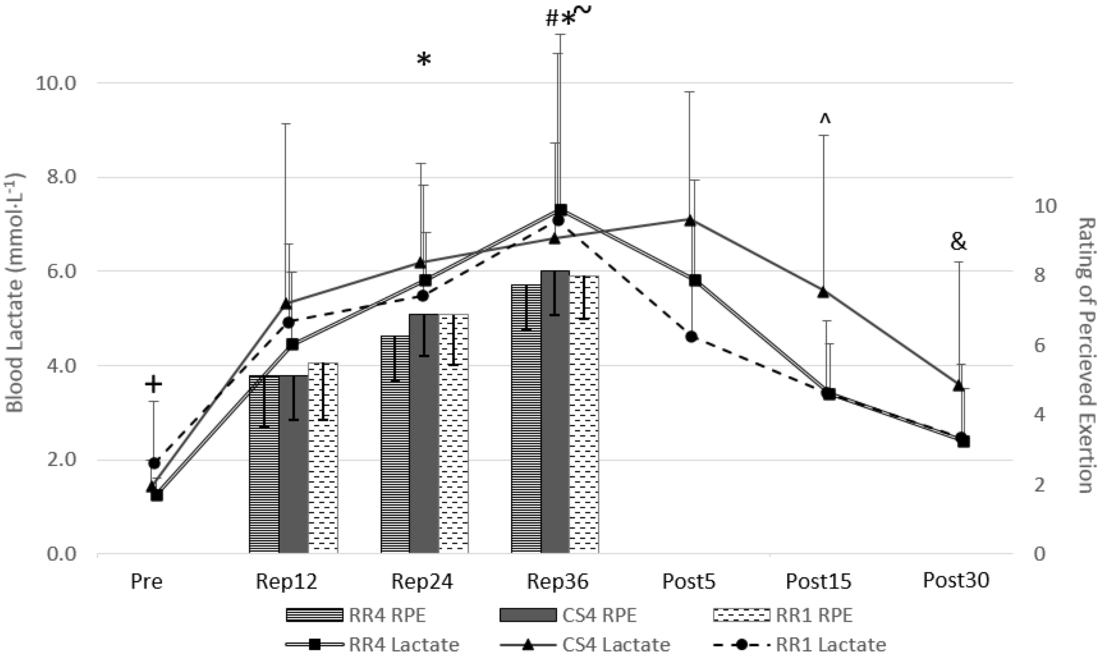

Figure 6.4: Whole blood lactate (primary vertical axis on the left, represented by line graph) and rating of perceived exertion (secondary vertical axis on the right, represented by bar graph) during the rest redistribution 1 (RR1), rest redistribution 4 (RR4), and cluster sets of 4 (CS4) protocol.

When collapsed across protocols, significantly less lactate than all other time points ($p < 0.05$)+, less than all time points but Pre ($p < 0.05$)&, less than Rep24, Rep36, and Post5 ($p < 0.05$)^, and greater than Rep12 ($p < 0.05$)#. When collapsed across protocols, significantly greater rating of perceived exertion (RPE) than Rep12 ($p < 0.001$) and Rep24 ($p < 0.001$)~. All differences are collapsed across protocols, with no differences between protocols for any variable and any time point.*

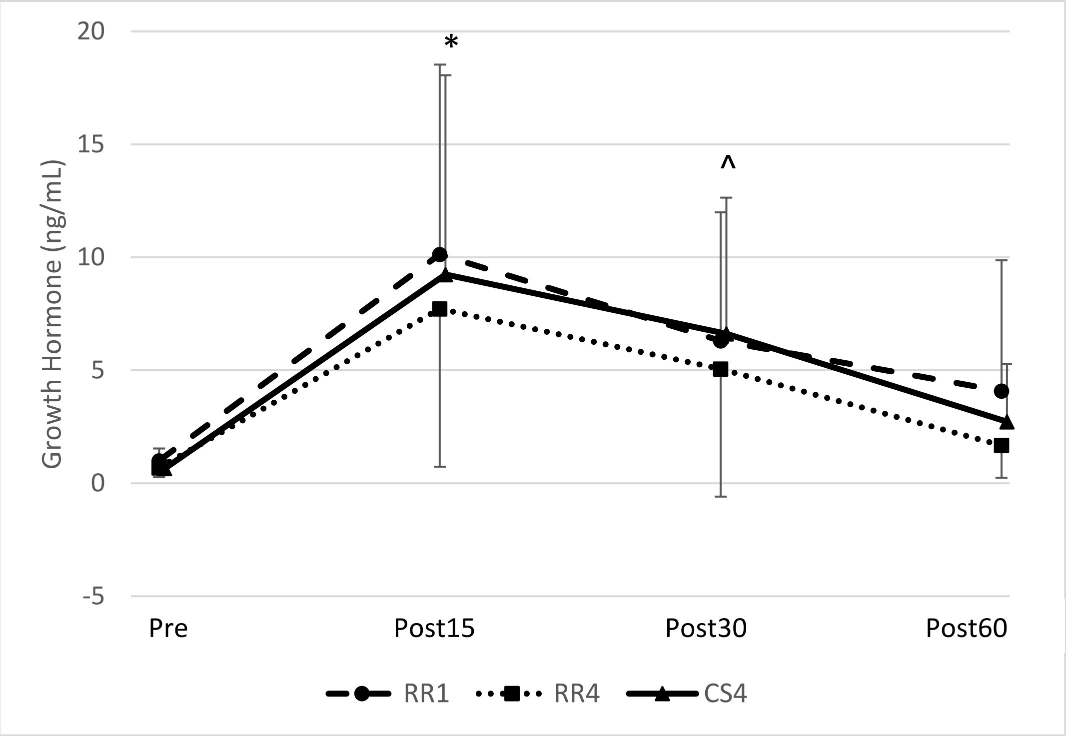

Figure 6.5: Growth hormone before (Pre), 15 (Post15), 30 (Post 30), and 60 (Post60) minutes after exercise during cluster sets of 4 (CS4), rest redistribution 1 (RR1), and rest redistribution 4 (RR4). Significantly greater than all other time points ($p < 0.05$), and significantly greater than Pre ($p < 0.05$)^.*

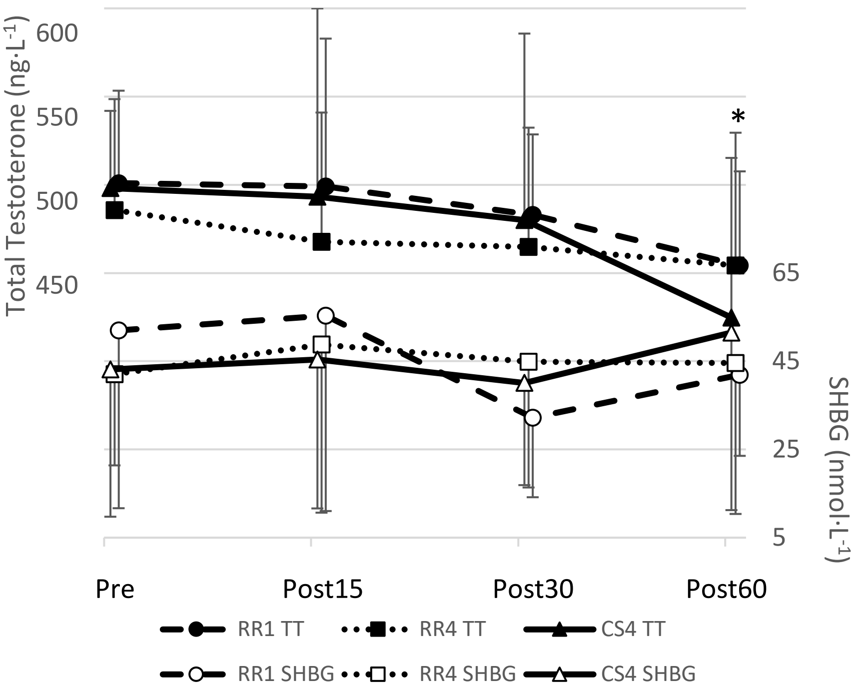

Figure 6.6: Total testosterone (TT) and sex-hormone binding globulin (SHBG) before (Pre), 15 (Post15), 30 (Post 30), and 60 (Post60) minutes after exercise. When collapsed across protocols, significantly less TT than all other time points ($p < 0.05$). No significant differences for SHBG at any time point for any protocol.*

Discussion

The purpose of this study was to compare the effects of a basic hypertrophy-oriented CS protocol [133] to two different RR protocols on the hormonal, metabolic, and perceptual responses of back squats in trained men. The main finding was that when using the same load and number of repetitions, the perceptual, metabolic, and hormonal responses to back squats were similar regardless of how the rest periods were distributed within the session. Additionally, all protocols resulted in similar MVM. However, the effect of RR1 on MVL in the beginning stages of the protocol was large compared to CS4 and RR4, but decreased to a moderate effect by the end of the protocol. Therefore, these data collectively show that shorter but more frequent rest intervals may spare neuromuscular performance in the beginning stages of a resistance-training session, but such an advantage decreases as the session's duration increases, with all protocols being equally fatiguing and resulting in similar RPE values and metabolic and hormonal changes.

Simultaneous increases in RPE, decreases in movement velocity, and increases in La during resistance-training are evident throughout the literature [8, 22, 31], with the same occurring in the present study. As the protocols within the present study were designed to avoid RM loading and muscular failure [133], RPE was not expected to reach maximal values despite performing the concentric movements with maximal intent [22]. Specifically, RPE increased equally throughout each protocol from 5.3 after the 12th repetition, to 6.7 after the 24th repetition, and up to an average value of 8.0 out of 10 following the final repetition, indicating that each protocol could be considered as "hard" [135]. Previous research has shown similar RPE values during basic CS protocols inclusive of inter-repetition rest [22]. In the study by Hardee et al. [22], subjects performed three TS of six power cleans using 80% 1RM, resulting in RPE scores of approximately 6.0, 7.5, and 9.0 after each set, respectively. However, RPE was significantly less during CS, resulting in RPE scores of approximately 5.5, 6.5, and 7.5 when 20 s of inter-repetition rest was used, and values of 4.0, 5.0, and 6.0 when 40 s of inter-repetition rest was used. Therefore, the 20 s inter-repetition rest protocol used by Hardee et al. [22] resulted in similar RPE values as those seen in the present study; and, although a direct comparison between these two studies is not possible as a result of different exercises, loads, and number of repetitions, RPE served as an accurate measure of perceived effort in both studies, evidenced by decreases in power output [22] and MVL in the present study. Furthermore, other research [84] has shown that when the work-to-rest ratio of five sets of squats using a 10RM load is divided to create a protocol similar to that of the present RR1 protocol, RPE values decreased compared to TS and were similar to those of the present study. Therefore, as a subjective measure of perceived effort that is linked to neuromuscular fatigue, RPE has again proven to be a valid tool which is quick and easy to use [135]. However, as coaches and researchers may be more interested in the mechanical and physiological responses that coincide with increases in RPE, more objective measures of fatigue could be useful.

The data in Figure 6.4 show that increases in RPE throughout the exercise sessions were indicative of increases in La, in agreement with previous research [44, 136, 137]. The La values of the present study were greater than [54] and less than [53] other studies most likely due to differences in exercise choice, order, and external loading parameters. Nonetheless, a gradual increase in La during exercise and the return of La to near-baseline levels 30 min after exercise in the present study was similar to the response seen in other studies [10, 53, 54, 134]. In a study by Oliver et al. [10], subjects completed four sets of 10 back squats with 70% 1RM using either TS (4x10 with 120 inter-set rest) or an RR protocol (4x10 with 90 s inter-set rest and 30 s intra-set rest after the 5th repetition of each set). Similar to the present study, both protocols resulted in increased blood La during exercise and up to 30 min after exercise, but La was greater at all time points in response to the TS protocol [10]. Goto et al. [134] showed that La, although not measured during exercise, was greater following a TS protocol using 10RM loads during the lat pull down, shoulder press, and knee extension exercises compared with a basic CS design in which the load and number of repetitions were equalized to the TS protocol. Together, the previous research shows that RR [10, 53, 54] and basic CS [134] protocols result in less La than TS. Additionally, the present study shows that basic CS and RR protocol designs result in similar metabolic responses, suggesting that the protocols used in present study may have also resulted in less La compared to a TS protocol had one been implemented in the study. Although not measured in any of the previously mentioned studies, it is likely that changes in La occurred in response to ATP/PCr availability [8, 29, 31]. Along these lines, changes in energy availability typically affect performance, as evidenced in many studies [28, 30, 31, 54].

Specifically, decreases in ATP/PCr availability and increases in La have been associated with decreases in power output and movement velocity [8, 10, 29]. The same held true during the present study, as all protocols resulted in increases in La and decreased movement velocity, as indicated by MVL. Despite La being similar between protocols, RR1 had a large effect on MVL compared to RR4 and CS4, indicating that MV decreased less during RR1 in the beginning stages of the session. However, by the end of the protocol, the effect of RR1 compared to RR4 and CS4 was only moderate. Additionally, RR1 experienced less MVL than CS4 when measurements were collapsed across time, indicating that MVL during RR1 was less than CS4. On the other hand, MVM showed that when the MV of all 36 repetitions is taken into consideration, all of the protocols maintained MV to a similar extent. Therefore, it is important for the strength and conditioning professional to determine what is most important when designing a resistance-training program using different CS configurations: the global response (i.e. MVM and similar measures that account for all repetitions) or the response at specific time points (i.e. MVL and other measures that are time-sensitive). Previous research has shown that MV is better maintained during basic CS structures compared to TS [11] and when RR is compared to TS [14, 58]. However, this is the first study to show that although basic CS and RR result in similar MVM, redistributing the rest periods of a basic CS protocol can affect MVL at different stages within a resistance-training session. Therefore, researchers and practitioners should acknowledge that all CS sub-types [122] may not result in the same acute responses to exercise, bearing in mind that future research should further investigate such effects before a conclusive statement on the topic can be made.

Lastly, the decision to investigate the CS4 protocol, which served as the "reference" protocol from which the RR1 and RR4 protocols were created, was based on previous data demonstrating that this specific protocol was able to increase mechanical stress compared to a TS protocol without inducing greater neuromuscular fatigue, assessed by relative decreases in movement velocity [133]. From a purely mechanical perspective, it is possible that such a protocol could induce an acute response indicative of skeletal muscle anabolism. However, the development of hypertrophy is a complex process, of which shifts in the acute hormonal milieu play a role [45, 124, 125]. Research has shown that as La increases, there is usually a concomitant increase in GH [127, 138], resulting in associations to be made between La and the anabolic process. Therefore, the initial scientific reviews of CS did not recommend CS for hypertrophy-based workouts, as the additional rest periods were thought to result in less La and a blunted hormonal response compared TS [16, 17]. On the contrary, more recent research suggests the opposite [62, 121], indicating that when designed appropriately, CS protocols may be just as effective as TS at developing muscle hypertrophy [122].

In support of this, the present study showed that CS4, RR1, and RR4 resulted in similar increases in La, increases in post-exercise GH levels, and decreases in post-exercise TT levels. Since GH plays a role in tissue regeneration [124, 138], equivalent increases in GH after exercise shows that all three protocols may have resulted in similar anabolic stimuli. Furthermore, an increased GH response paired with no change in post-exercise C levels further shows that the mechanical stress provided during each of the protocols most likely favored anabolism over catabolism. Although decreases in TT can be considered as unwarranted for hypertrophy, there was a significant decrease in TT at P60. Despite a lack of significant changes in SHBG, an apparent increase in SHBG from P30 to P60 combined with a significant decrease in TT (Figure 6.6) indicates that the transport of TT via SHBG may have increased, resulting in a possible increased uptake of TT into the muscles, which may actually result in the increase of muscle growth. Therefore, these data indicate that RR and CS protocols can create a physiological environment indicative of skeletal muscle hypertrophy, but other research using CS does not agree. Despite the basic CS protocol used by Goto et al. [134] resulting in significant increases in La, the apparent elevations in post-exercise GH were not significant and TT remained unchanged compared to pre-exercise values. The lack of post-exercise endocrine response documented in that study [134] infers that the stimulus provided during their protocol, which included cadence-controlled machine-based lat pull down, shoulder press, and knee extensions, may not have been sufficient to increase La enough to stimulate a subsequent endocrine response [124, 138]. However, data from other research agrees with data of the present study, showing that RR protocols inclusive of maximal velocity compound lower-body movements have resulted in pro-anabolic shifts in TT [10] and GH [53] concentrations, albeit to a lesser extent than a TS protocol [10]. The lack of a TS protocol within the present study does not allow for a comparison to be made between TS and the CS sub-types used in the present study, but the hormonal data presented are comparable to that of previous studies using similar hypertrophic protocols of 4 sets of 10 back squats with 70-75% 1RM using TS [10, 46]. Therefore, when designed appropriately, basic CS and RR protocols may result in acute hormonal responses comparable to TS protocols designed to stimulate hypertrophy.

Conclusions

In conclusion, this is the first study to investigate the effects of a basic CS protocol to two RR protocols on the hormonal, metabolic, and perceptual responses of back squats in trained men. Collectively, these data show that when using the same load, total rest time, and number of repetitions, the perceptual, metabolic, and hormonal responses to back squats were generally similar regardless of how the rest periods were distributed within the session. Comparable increases in RPE and La between the protocols also support that redistributing rest periods within a resistance-training session can result in similar exertion and energetic demands. The large effects of RR1 on MVL indicate that shorter but more frequent rest intervals may spare performance in the beginning stages of a longer protocol, but such an advantage is reduced as the protocol continues: hinting that mechanical changes may occur in the absence of metabolic or hormonal changes. Lastly, this study provides further evidence that different types of CS protocols can be designed in a way to increase the acute hormonal response to exercise, possibly stimulating the anabolic process. However, further research must investigate the effectiveness of such protocols within a chronic training environment.

Chapter 7

The data presented in Chapter 5 showed that as long as the total rest time is equal, redistributing total rest time to create shorter but more frequent sets did not affect acute neuromuscular performance, and the data in Chapter 6 showed that the same holds true for hormonal, perceptual, and metabolic responses. To date, researchers had only examined the effect of rest redistribution to create very small sets, with a maximum of 4 or 5 repetitions. Additionally, the traditional sets that those rest redistribution sets were compared to were always quite fatiguing. However, modern research trends indicate that velocity-based training, where sets are truncated before excessive fatigue ensues, can result in greater neuromuscular and hypertrophic adaptations compared to sets performed to failure. With that in mind and taking into account the information from the previous chapters of this document, the purpose of the following study was to determine whether performing more repetitions per set would reduce (or improve) the effectiveness of rest redistribution, and to determine whether rest redistribution is still effective compared to traditional sets that are not very fatiguing. Previous research has indicated that no more than 5 repetitions should be performed in a row when the aim is to increase power output. Therefore, the purpose of the following study was to determine whether redistributing total rest time to include sets of 6 repetitions also results in similar acute kinetic and kinematic responses. Please note that the formatting has been adjusted from the original manuscript that was published in 2019 in the *Journal of Human Kinetics* to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the actual references have not been altered in any way.

Shorter but more frequent rest periods: no effect compared to traditional sets not performed to failure

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Performing traditional sets to failure is fatiguing but redistributing total rest time to create short frequent sets lessens the fatigue. Since performing traditional sets to failure is not always warranted, we compared the effects of not-to-failure traditional sets and rest redistribution during free-weight back squats in twenty-six strength-trained men (28 ± 5.44 y; 84.6 ± 10.5 kg, 1RM-to-body-mass ratio of 1.82 ± 0.33). They performed three sets of ten repetitions with 240 s inter-set rest (TS) and five sets of six repetitions with 120 s inter-set rest (RR6) at 70% of one repetition maximum. Mean velocity ($p > 0.05$; d = 0.10 (-0.35, 0.56)) and mean power ($p > 0.05$; d = 0.19 (-0.27, 0.64)) were not different between protocols, but the rating of perceived exertion (RPE) was less during RR6 ($p < 0.05$; d = 0.93 (0.44, 1.40)). Also, mean velocity and power output decreased (RR6: 14.10% and 10.95%; TS: 17.10% and 15.85% respectively) from the first repetition to the last, but the percent decrease was similar (velocity: $p > 0.05$; d = 0.16 (-0.30, 0.62); power: $p > 0.05$; d = 0.22 (-0.24, 0.68)). These data suggest that traditional sets and rest redistribution maintain velocity and power output to a similar degree when traditional sets are not performed to failure. However, rest redistribution might be advantageous as RR6 displayed lower RPE.

Introduction

As the importance of high power outputs during sport-specific movements is well-established, the ability to express high power outputs is considered to be one of the most important characteristics of an athlete [139, 140]. Therefore, power output seems to be the determining factor that differentiates the performance between athletes in a variety of sports [141, 142], and to increase power output, resistance training (RT) is often implemented using a variety of loads and exercises. As a result, it is important to understand the effects of different RT protocols on power output to optimize training adaptations.

Regardless of how an RT protocol is designed, maintaining movement velocity seems to be the key for maintaining power output over the course of an acute RT session, especially when the force requirements remain relatively unchanged [11, 143]. In addition, it has been shown that decreases in movement velocity during RT is a valid indicator of neuromuscular fatigue [8], which can be detrimental to power development. Furthermore, fatigue is exacerbated when performing multiple repetitions in sequence (i.e. traditional sets) [14, 29, 58], which is why a growing body of literature is investigating the effects of different strategies to dissipate fatigue and maintain movement velocity and power output during RT.

One of the most basic yet effective methods for maintaining power output is the use of cluster sets that include short (e.g. 15-45 sec) intra-set rest periods in addition to longer (e.g. < 1 min) inter-set rest periods [11, 13, 122]. Despite their effectiveness, it can be argued that some of the cluster set structures that have been used in research are not practical, as they can extend total training time by up to 64-169%, depending on the frequency and duration of the intra-set rest intervals [133]. Oftentimes, the time constraints of an individual training session or even of the phase of the season may be a limiting factor to consider when aiming to optimize RT sessions. Therefore, one alternative to these lengthy cluster set structures is to redistribute the total rest time of traditional set structures by abbreviating the inter-set rest but including shorter and more frequent rest intervals.

This strategy, known as rest redistribution, has been shown to be effective in numerous studies [39, 58, 144] that collectively show that when total rest time is the same, shorter but more frequent rest periods are the most effective for maintaining acute RT performance. However, relatively few studies have examined such set structures in high-volume free weight RT, [39, 58, 143] many of which included traditional sets that were performed to failure [23, 39, 58]. In doing so, these study designs resulted in fewer repetitions, a decrease in external load, or both during traditional sets performed to failure. Another study compared a cluster set protocol to two different rest redistribution protocols using sets of 1 and 4 repetitions, but this study did not have a traditional set protocol [144]. Additionally, studies that examined explosive exercises like bench throws and plyometric jumps [14, 145] suggested that no more than five repetitions should be performed in a row in order to avoid decreases in velocity and power outputs and to allow for maximal recovery. However, no studies have investigated the effect of high volume rest-redistribution sets compared to traditional sets not performed to failure (i.e. with equal training load and volume) in a free weight exercise.

Examining such protocols would shed light on the influence of both rest period frequency and duration on neuromuscular fatigue as well as velocity and power measures during RT when compared to traditional protocols. Since strength and conditioning professionals must often operate under time constraints, and given the importance of power development for athletic performance, it is logical to continue investigating the most efficient ways to induce power adaptations and maintain high movement velocities during training. Therefore, the purpose of our study was to compare the effects of a traditional set structure not performed to failure and a rest redistribution protocol on the velocity, power output, and perceptual responses during a high-volume free-weight back squat session where the number of repetitions and load were both equal. Based on one study [58], it was hypothesized that the rest redistribution protocol would allow for greater movement velocity and power output maintenance as well as a lower fatigue perception compared to traditional sets.

Methods

Participants

Twenty-six strength-trained men (amateur weightlifters and track and field athletes) participated in this study (age 28 ± 5.4 y, body mass 84.6 ± 10.5 kg), had at least 1 year of strength training experience using the free weight back squat exercise, and could back squat at least 100% of their body mass. Participants were excluded if they reported any recent musculoskeletal injuries. Participants averaged a 1-repetition maximum (1RM) of 152.7 ± 25.9 kg, resulting in a 1RM-to-body-mass ratio of 1.82 ± 0.33.

All procedures were carried out in accordance with the Declaration of Helsinki and were approved by the University Human Research Ethics Committee. All participants gave written informed consent prior to participating.

Study Design

Testing occurred over 3 sessions: a 1RM session and 2 experimental sessions. Using a randomized counterbalanced design, participants completed each of the 2 protocols on separate days, 5-7 days apart, and were instructed to refrain from any type of fatiguing lower body activity for at least 48 hours before sessions. Each protocol consisted of 30 repetitions of free-weight back squats using 70% 1RM, and each of the protocols consisted of a different set structure defined by different rest periods (Figure 7.1). Participants were asked 1 minute after the completion of each protocol for their rating of perceived exertion (RPE) scores. Previous studies have shown that a load of 70% 1RM equates to roughly a 12RM in the Smith machine back squat [8]. Therefore, to ensure that training to failure was avoided and that the total number of repetitions was equal between conditions, an external load of 70% was chosen. As a result, all participants successfully completed all 30 repetitions in both protocols.

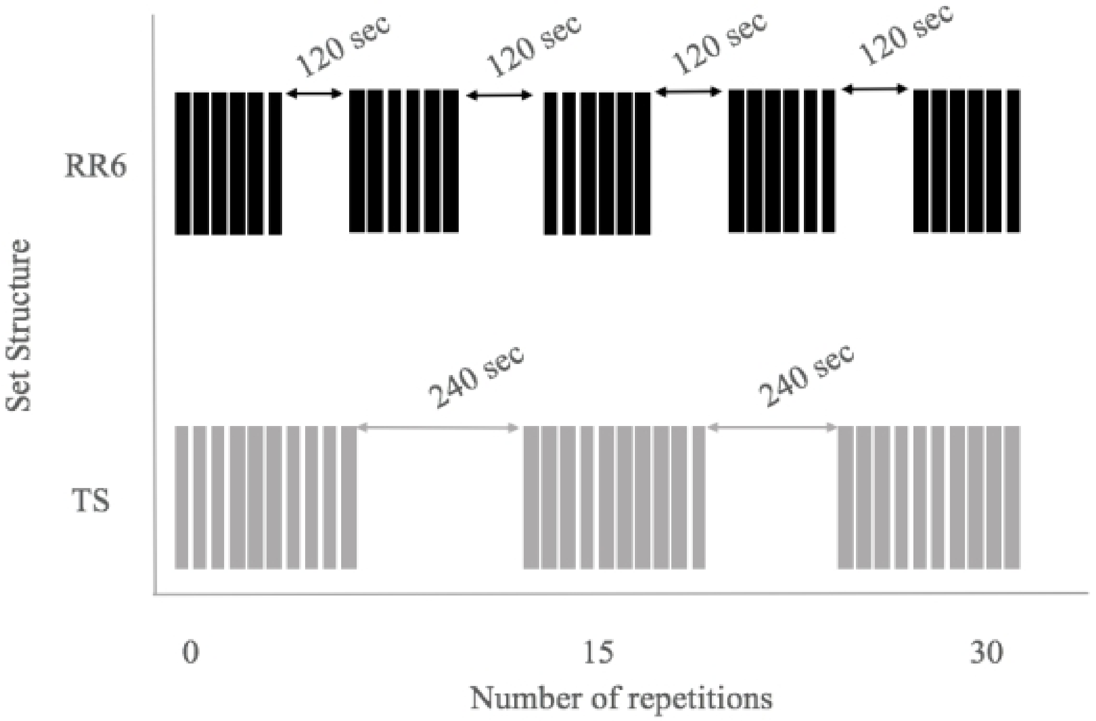

Figure 7.1 Set structure protocols. A – Rest Redistribution sets, five sets of six repetitions with 120 seconds of inter-set rest. B – Traditional sets, three sets of ten repetitions with 240 seconds of inter-set rest.

Repetition-Maximum Testing: Session 1

Participants were familiarized with the protocols and anthropometrics were measured. After a dynamic warmup (6-8 minutes), participants performed 20 barbell squats followed by 8 repetitions at 50%, and 5 repetitions at 60% of their estimated 1RM, respectively. Back squat 1RM was then assessed starting at 80% estimated 1RM with 2-3 minutes of rest between each successive attempt, and load was progressively increased until the 1RM was achieved using previously established methods [109]. Participants were required to reach a depth of the squat at which the top of the thighs were at least parallel to the floor as determined by investigators for an attempt to be considered successful. During the 1RM session, subjects were also familiarized with the 0-10 OMNI-RES scale: a resistance training specific RPE scale [146].

Experimental Testing: Sessions 2 and 3

These sessions used the same warm-up as Session 1, but included warm-up loads based on the actual 1RM. Each session consisted of a different, counter-balanced protocol. Specifically, the traditional set protocol (TS) consisted of 3 sets of 10 repetitions with 70% 1RM with inter-set rest intervals of 240 seconds, and the rest-redistribution protocol (RR6) consisted of 5 sets of 6 repetitions at 70% 1RM with inter-set rest periods of 120 seconds. Schematic view of described set structures can be seen in Figure 7.1.

In an attempt to maximize back squat velocity and power output, participants were instructed to perform the concentric phase of each squat as quickly as possible to a standing position [3] while the barbell was consistently lowered under control during all repetitions in both protocols. To ensure natural squatting patterns in these experienced resistance-trained men, each participant adopted a shoulder width stance and used a self-regulated eccentric velocity and immediately upon reaching the bottom of their squat, participants were instructed to perform the concentric (upward) portion of each repetition "as explosively as possible". Verbal encouragement was provided throughout all trials. Participants were again required to reach a depth of the squat at which the top of the thighs were at least parallel to the floor as determined by the investigators for a repetition to be considered successful, however, there were no repetitions that the investigators deemed unsuccessful, indicating that the experienced participants maintained their full-squat technique throughout the entire experiment. During all repetitions, the feet were required to maintain contact with the floor (i.e. no jumping or lifting of the heels) [3] and a slight pause was required at the conclusion of each repetition to ensure full hip and knee extension. One minute after completing each protocol, participants were asked to rate their session on a 0-10 RPE scale.

Data Acquisition and Preparation

All 30 repetitions during the back-squat exercise in each of the set structures were measured with the PUSH band, which is a smartphone-based wearable device designed to track movement velocity during a variety of resistance exercises (PUSH Inc., Toronto, Canada). According to the manufacturer's guidelines, the PUSH band was worn on the participant's dominant forearm, with the hand supinated, on top of the ulna, 1–2 cm distal to the elbow, and with the main button located proximally. PUSH determined velocity by measuring the linear accelerations and angular velocities of the movement where vertical velocity was calculated by the integration of acceleration with respect to time. Force estimations by the PUSH were calculated from the system mass multiplied by the acceleration data whereas power values were determined from the product of the force and velocity curve data [147]. The PUSH band's sampling rate was 200 Hz, and to record the measured data with the PUSH band, the system was linked to an iPod (Apple, Inc., California, US) running the PUSH application v.3.1.7 using a Bluetooth 4.0 LTE connection. Further, raw data were exported from the PUSH portal Internet Cloud to Microsoft Excel (Microsoft, Seattle, WA, USA) where they were prepared for later statistical analysis. The device has been proven valid and reliable in previous research [147, 148].

From each repetition, mean velocity (MV) and mean power output (MP) were recorded. Similar to previous research [11], the percentage decline of both MV (MVD) and MP (MPD) were calculated as a percentage of the quotient of the 30th repetition to the first repetition during RR6 and TS. Additionally, to provide a more holistic view of MV and MP throughout each protocol, the overall maintenance of MV (MVM) and MP (MPM) were calculated by dividing each repetition (1-30) by the first repetition and then averaging those values. Similar to previous research [149], we divided our participants into stronger (>150kg 1RM squat) and weaker (≤ 150kg 1RM squat) groups using an arbitrary value of 150kg 1RM to ensure an equal number of subjects in both groups. Finally, the differences in duration of the eccentric phase (ECC) of all repetitions between the protocols (TS = 1.14 ± 0.38 s; RR6 = 1.05 ± 0.28 s) were not present ($p > 0.05$; $d = 0.30$ (-0.16, 0.76). Therefore, the potential different durations of the ECC phase of the lift that might influence the fatigue (Wilk et al. 2018a, 2018b) were assumed to be negligible.

Statistical Analysis

All data were normally distributed as determined by the Shapiro-Wilk test of normality. Means and SDs were calculated for MV, MP, RPE, MVM, MPM, MVD, and MPD. Repeated-measures analysis of variance (ANOVA) was used to compare means between protocols for all variables. In addition, one-way ANOVA was used to examine the differences between stronger and weaker participants for each variable. When a significant main effect or interaction was determined, a Bonferroni post-hoc test was conducted. Cohen's *d* effect sizes with 90% confidence intervals (90%CI) were used to determine practically relevant magnitudes of difference, which can be interpreted as: $d < 0.2$ (trivial),

$d = 0.2–0.5$ (small), $d = 0.5–0.8$ (moderate), and $d > 0.8$ (large). All statistical analyses were performed using SPSS, version 23.0 (IBM, Chicago, USA) with an *a-priori* level of significance set at $p < 0.05$.

Results

Mean ± SDs for MV, MP, and RPE are presented in Figure 7.2 and Figure 7.3. There were no differences between RR6 and TS in MV (Figure 7.2A; $p > 0.05$; $d = 0.10$ (-0.35, 0.56)), MP (Figure 7.2B; $p > 0.05$; $d = 0.19$ (-0.27, 0.64)), MVD (Figure 7.4; $p > 0.05$; $d = 0.16$ (-0.30, 0.62)), MPD ($p > 0.05$; $d = 0.22$ (-0.24, 0.68)), MVM (Figure 7.5; $p > 0.05$; $d = 0.12$ (-0.34, 0.56)), or MPM ($p > 0.05$; $d = 0.09$ (-0.36, 0.55)).

RPE was significantly lower in RR6 compared to TS (Figure 7.3; $p < 0.05$; $d = 0.93$ (0.44, 1.40)). Similarly, no differences were observed when participants were divided into stronger and weaker groups during RR6 in MV ($p > 0.05$; $d = 0.37$ (-0.28, 1.03)), MP ($p > 0.05$; $d = 0.15$ (-0.50, 0.80)), MVD ($p > 0.05$; $d = -0.41$ (-1.07, 0.24)), MPD ($p > 0.05$; $d = -0.46$ (-1.12, 0.20)), MVM ($p > 0.05$; $d = -0.24$ (-0.89, 0.41)), MPM ($p > 0.05$; $d = -0.28$ (-0.93, 0.37)), RPE ($p > 0.05$; $d = -0.59$ (-1.25, 0.08)) as well as during TS in MV ($p > 0.05$; $d = 0.17$ (-0.48, 0.82)), MP ($p > 0.05$; $d = -0.08$ (-0.73, 0.56)), MVD ($p > 0.05$; $d = -0.23$ (-0.88, 0.42)), MPD ($p > 0.05$; $d = -0.35$ (-1.00, 0.30)), MVM ($p > 0.05$; $d = -0.20$ (-0.85, 0.45)), MPM ($p > 0.05$; $d = -0.37$ (-1.03, 0.28)), RPE ($p > 0.05$; $d = -0.13$ (-0.78, 0.51)).

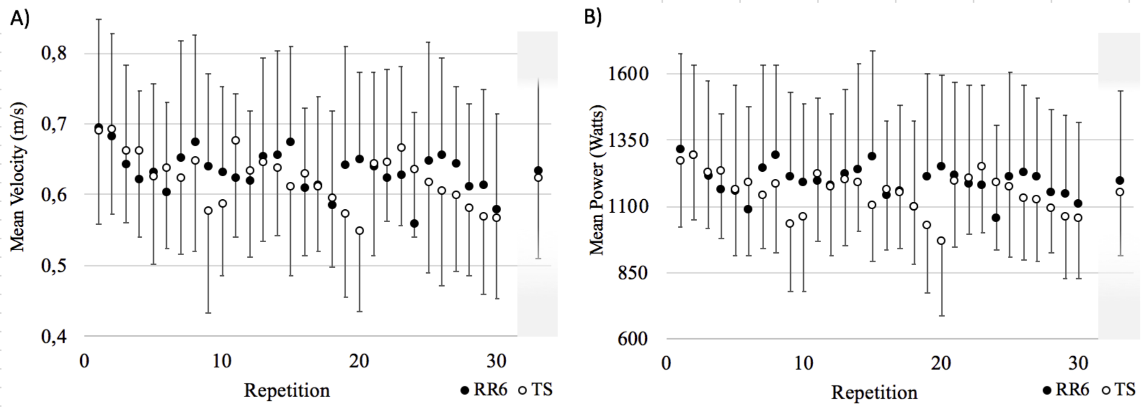

Figure 7.2 Means and standard deviations during rest redistribution sets (RR6) and traditional sets (TS) across 30 repetitions for: A) mean velocity output and B) mean power output. Open circles indicate velocity and power data for the TS while closed circles represent velocity and power data for the RR6. The shaded region shows that no significant differences were present between the protocols (p > 0.05) when averaging all 30 repetitions together.

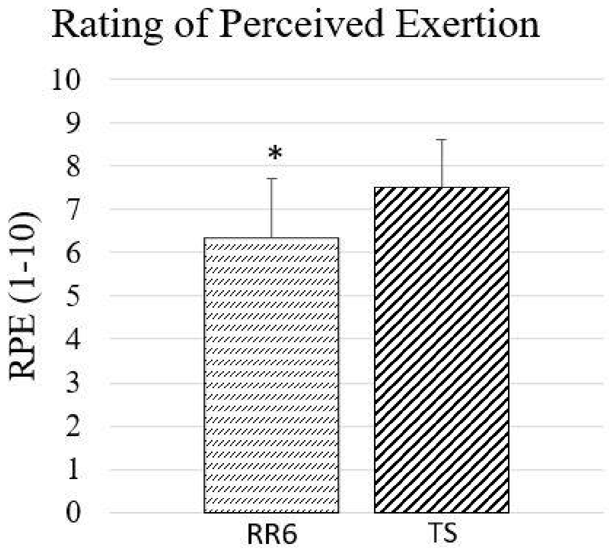

Figure 7.3 Means and standard deviations for rating of perceived exertion (RPE) in both rest redistribution sets (RR6) and traditional sets (TS). Significantly less than TS (p < 0.05)*

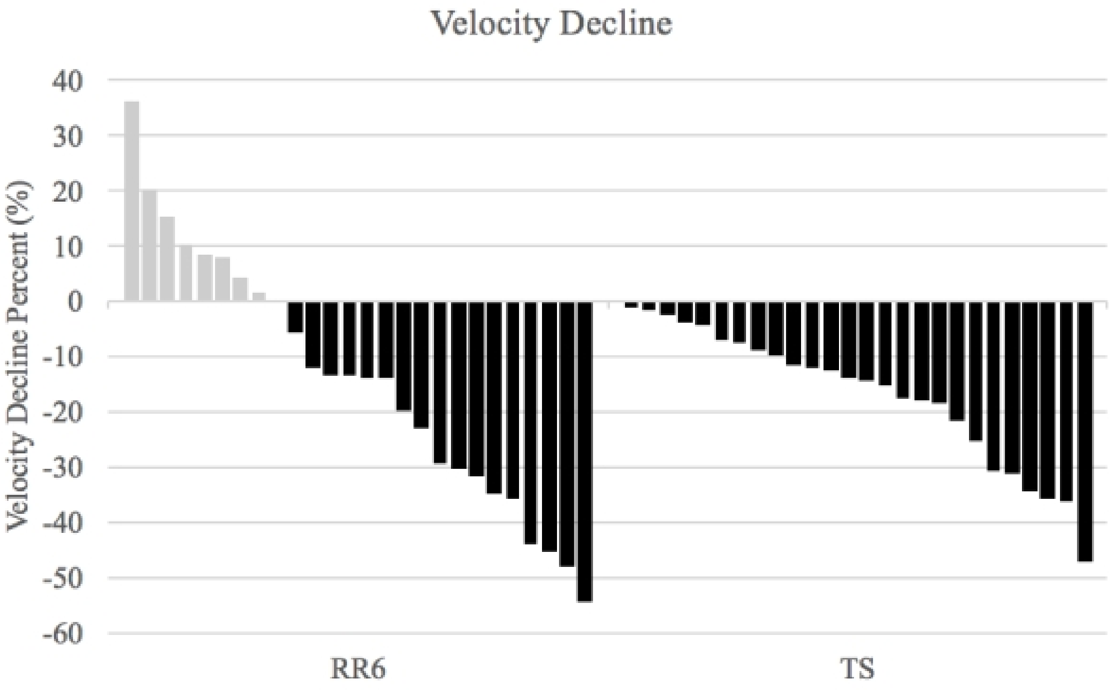

Figure 7.4 Individual data for mean velocity decline (MVD) expressed as a percentage of the quotient of the 30th repetition to the 1st repetition during RR6 and TS. Each bar represents the MVD for a single subject. For the sake of simplicity, mean power decline is not shown, as it followed the exact same pattern as MVD.

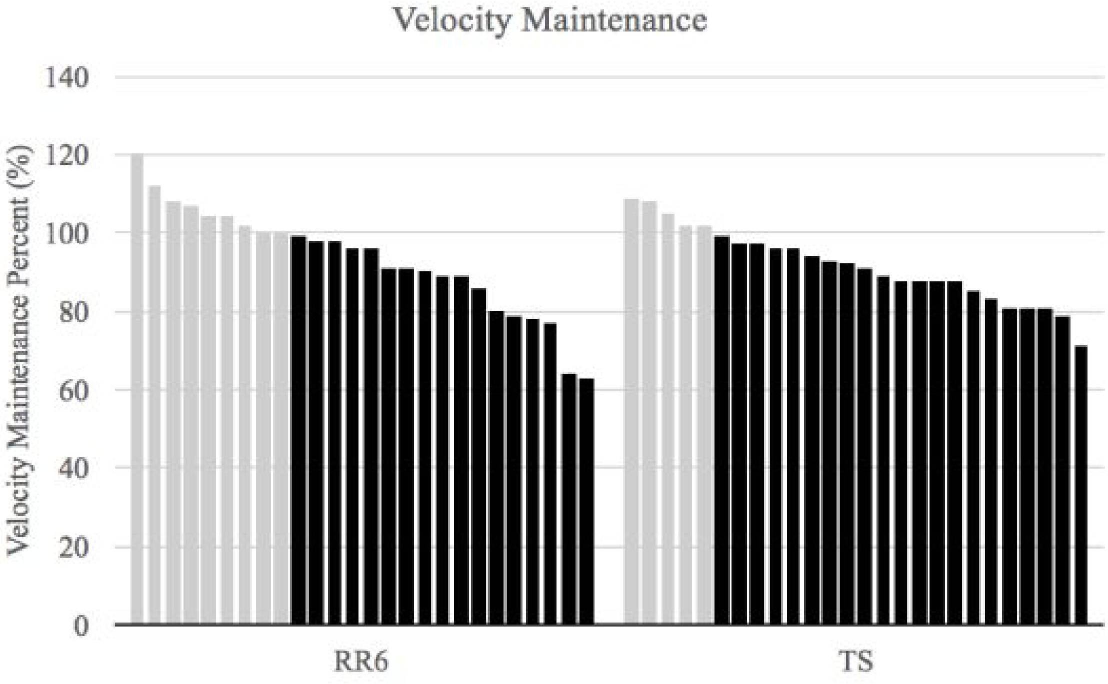

Figure 7.5 Individual data for mean velocity maintenance (MVM) across all 30 repetitions expressed as a percentage of the 1st repetition, then averaged together. Each bar represents the MVM for a single subject. For the sake of simplicity, mean power decline is not shown, as it followed the exact same pattern as MVD.

Discussion

The main finding of this study was that redistributing rest intervals, while performing high volume RT, did not affect fatigue-induced decrements in velocity and power measures. Despite TS having a greater RPE, the redistribution of rest periods to include more frequent but shorter sets during RR6 resulted in similar MV, MP, MVM, MPM, MVD, and MPD between the protocols. Hence, velocity and power output decreased in both protocols, but were not better maintained when more frequent inter-set rest periods were implemented with respect to the same load and total training volume while the perceptional fatigue was decreased. These results are in contrast with a large majority of studies in which higher frequency rest intervals allowed for a greater maintenance of mean velocity and mean power output during RT [58, 143, 144, 150]. There are a few potential explanations for our contradictory and novel findings.

Firstly, the number of repetitions per set may have played a role. In one study [144], researchers compared rest redistribution protocols that consisted of either 36 one-repetition sets or 9 four-repetition sets, showing that although both protocols maintained movement velocity and power output better than a cluster set structure with longer and less frequent rest periods, the protocol with the most frequent rest periods (i.e. performing one repetition at a time) was superior for maintaining movement velocity. On the other end of the spectrum, redistributing rest periods to create six repetitions per set, which was the number of repetitions in RR6 of this study, was not effective at maintaining velocity and power output better than TS with more repetitions per set. This is in line with the findings of others [14, 145] who suggested that executing more than five repetitions is detrimental to power development. This is likely the case due to adenosine triphosphate (ATP) and phosphocreatine (PCr) availability reduction [29-31], and increased lactate and ammonia accumulation [30] that has been shown to occur when multiple consecutive repetitions are performed over multiple sets. However, the same authors suggested that increasing the frequency of rest intervals can lower lactate levels and allow for greater power output, ATP stores, and maintenance of PCr stores throughout RT. Thus, all of these factors seem to play an important role in modulating both peripheral and central fatigue [151]. Although such data were not measured in the present study, our data (e.g. similar MVD and MPD as well as MVM and MPM across the 30 repetitions during RR6 compared to TS) further indicate that coaches should aim for implementing a lower number of repetitions (≤ 5) in the set during RT when the goal is to maximize power adaptations [14]. Therefore, it is likely that it may be optimal to redistribute total rest time by creating sets of up to four repetitions, but no more than six. Although the current data support this hypothesis, more research is needed to substantiate this claim.

Secondly, although one study [152] showed that shorter but more frequent rest periods in the leg press exercise can positively impact MV when compared to traditional sets that do not lead to failure, many studies in free weight exercises that compared rest redistribution set structures to traditional sets had to either exclude some participants from the analysis [39] or decrease the load due to some subjects reaching momentary failure during traditional sets [58, 143]. As subjects in our study were able to complete all repetitions (3 sets of 10 repetitions with 70% 1RM) with RPE values averaging 7.5 out of 10 (versus an assumed 10 out of 10 during high-volume training to failure in other studies), it is possible that the effects of rest redistribution on performance maintenance is not as pronounced when sets are not performed to (or nearing) concentric muscular failure. Therefore, rest redistribution is likely advantageous when performing high-volume free weight RT performed to or near concentric failure; but likely does not have as large of an effect when resistance training is not performed to failure.

The TS protocol of this study was likely not as fatiguing as the traditional set protocols of other studies because of the greater total rest time in our study. The TS protocol included 240 s of rest between sets, which is double than what has been used in other similar studies. Specifically, one study [58] compared the effects of rest redistribution protocols that consisted of traditional sets with 120 s inter-set rest and another protocol with 30 s intra-set rest and 90 s of inter-set rest. As expected, their traditional set protocol was extremely fatiguing, even requiring some subjects to decrease the load during testing to ensure that the prescribed number of repetitions could be completed. Similar to their organization of the set structures and findings in general, another study [39] showed greater power outputs after traditional sets with 120 s inter-set rest were divided into twice as many sets with half of the inter-set rest period (60 s, instead of 120 s). Although both of these studies used 70-75% of the participants' back squat 1RM, only 2 minutes of rest in total were provided to execute four sets of ten repetitions with that load. This was considerably lower than the total amount of rest in the RR6 and TS protocols of the present study. Additionally, another study [23] also showed greater velocity and power outputs after a rest redistributed set configuration with a 4RM load in the parallel back squat when compared to traditional set. Although the differences were profound between the protocols, this was likely the case due to the traditional set being intentionally performed to mechanical failure, based on which the number and length of rest periods in rest redistribution set configuration was determined [23]. Moreover, only one repetition was performed during rest redistribution protocol per set. Collectively, these data indicate that a lack of differences in velocity and power output of our study may have been due to the lack of extreme fatigue during TS. Therefore, it can again be concluded that redistributing rest periods to create shorter but more frequent sets only brings a significant advantage when a comparative traditional set structure is extremely fatiguing.

Despite both the TS and RR6 protocols being seemingly similar in terms of movement velocity and power output, RPE was significantly greater for TS compared to RR6, which suggests that it is perceptually harder to perform ten than six repetitions during multiple sets when the total rest time is equal. In addition, RPE has been shown to simultaneously increase as movement velocity decreases [84, 153], which further highlights the relationship between velocity loss during RT and the degree of fatigue. However, as the maintenance of mechanical variables were similar between the protocols and RPE was significantly different, perhaps the number of repetitions in each protocol played a role in the difference in RPE. Studies that have investigated the relationship between the RPE and the number of repetitions being performed in a set support this [154-156]. Participants in these studies, which had similar study designs, were asked to rate their exertion levels following various numbers of repetitions during RT at a target voluntary contraction intensity, and it was found that the RPE increased with the number of repetitions at the target voluntary contraction intensity [154-156]. Therefore, it is possible that the greater number of repetitions performed in sequence during TS simply felt more difficult compared to performing more sets, but with only six repetitions per set. Furthermore, despite the fact that protocols were prescribed relative to an individual’s 1RM, the stimulus of RT could differ between the protocols since individual muscular endurance also plays an important role in determining the RT stimulus [157]. Perhaps the TS protocol was perceived as more intense to the majority of the participants due to them being closer to mechanical failure than when they performed the RR6 protocol.

To further explain why RPE may have been lower during RR6, we can delve further into the comparisons between stronger (back squat 1 RM > 150 kg) and weaker participants (back squat 1RM ≤ 150kg). Of all the variables measured in this study, differences (moderate effects) were only present between stronger and weaker participants for RPE and only during RR6, where stronger participants perceived it easier (RPE of 5.9) as opposed to their weaker counterparts (RPE of 6.7). The lack of differences between stronger and weaker subjects for all other variables is in agreement with the findings from one study [58] that showed similar patterns in all mechanical variables between trained and untrained people during both cluster and traditional set structures. However, RPE was not measured in that study, making it difficult to attribute strength level or training experience to the difference in RPE during RR6. Nevertheless, both stronger and weaker participants in the present study experienced the same level of fatigue during TS protocol which also potentially explains the fact that 8 participants in this study reacted positively to RR6 protocol (Figure 7.4).

Although these explanations for our findings are logical, this study is not without limitations. For example, when looking at the data from individual subjects, it can be seen that a considerably higher proportion of the participants experienced lower MVD and MPD during RR6 compared to TS (Figure 7.4). Furthermore, Figure 7.5 also shows that participants responded differently to each protocol because a greater number of participants actually improved their velocity outputs towards the 30th repetition during RR6 which was not the case in TS where all subjects experienced a decrease. Therefore, although the mean changes across all subjects indicate that RR6 and TS were essentially equal, perhaps some individuals would benefit from implementing protocols similar to RR6. Additionally, due to its rising popularity, portability, and ease of use, we decided to use the PUSH device in the present study. However, it should be noted that although it has previously been shown to be valid and reliable [147], slight deviations compared to gold standard measurements may mask differences between protocols that might be seen using direct velocity and power measurements (e.g. force plates and linear position transducers). As such, it is up to the strength and conditioning professional to determine whether using gold standard devices are worth the cost and space, or whether more affordable and user-friendly devices such as PUSH are to be used.

Finally, based on the findings of the present study, it seems that rest redistribution protocols performed at 70% of 1RM are not very beneficial for maintaining movement velocity compared to traditional structures when traditional sets are not extremely fatiguing. In contrast, when traditional protocols are performed very close to mechanical failure, rest redistribution might be very beneficial, as previous studies have suggested [39, 58, 143]. Considering these points, cluster sets with extra intra-rest periods are still likely the best option when wanting to maximize acute movement velocity and power output [11, 13, 122, 133], provided that time efficiency is not an issue. Future research should continue to investigate the most efficient ways to organize set structures during RT in order to increase training efficiency and to prevent detrimental effects of fatigue on velocity and power, which can further lead to insufficient training adaptations.

Conclusions and Practical Implications

The present study shows the inability of RR6 to maintain MV and MP to a greater extent when compared to TS while performing free weight back squats at 70% of 1RM. Because of that, six consecutive repetitions may be too much in a single set when designing rest redistribution protocols, especially when derived from another protocol that is not extremely fatiguing. Therefore, strength and conditioning professionals should aim to implement a lower number of repetitions (≤ 5) in a set when designing rest redistribution set structures to prevent velocity and power decrement during RT and ultimately maximize power adaptations in athletes.

Chapter 8

The data presented in Chapter 7 showed that, as hypothesized, rest redistribution did not play a significant role in managing acute neuromuscular fatigue when the number of repetitions per set reaches 6 and when the comparative traditional set protocol does not include extreme fatigue. As power output varies between exercises and individuals, it would be logical to utilize loads at which an individual's maximum power output occurs when determining the effects of cluster sets on power output. Additionally, it would be useful to combine the ideas of CS and velocity-based training to investigate the effect of CS structures not only in repetitions to failure or across a prescribed number of repetitions, but during a training session that employs a power-based threshold where the traditional set structure also utilizes the threshold, possibly "levelling out the playing field". Therefore, the purpose of this study was to investigate the effects of cluster sets and traditional sets on velocity, power output, and training volume when using individualized loads at which mean power output is maximized. Also unique to this study, the protocols were based on a velocity-based training approach whereby a decrease in mean power output below a certain threshold truncated each set, meaning that the number of total sets was prescribed, but the number of total repetitions was not. Please note that the formatting has been adjusted from the original manuscript that has been published in 2019 in *PlosOne* to allow for continuity throughout the entire document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Cluster sets vs. traditional sets: levelling out the playing field using a power-based threshold

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Abstract: Cluster sets allow for velocity and power output maintenance, but the literature routinely uses highly fatiguing traditional set protocols. Although such studies have merit, others suggest fatigue should be avoided when training to improve power output, making those cluster set studies less practical. Therefore, the purpose of this study was to compare these set structures when truncating sets using a power-based threshold. Nine males (23.4 ± 0.6 yr) with various sport backgrounds performed 6 sets of back squats with individualized loads that elicited the greatest mean power (MPmax) output (112.7 ± 12.1% of body mass). Each set during the traditional set (TS) protocol included as many repetitions as possible until two consecutive repetitions dropped below 90% MPmax, which was followed by 120 s inter-set rest. The design was identical for cluster sets (CS) but with an additional 20 s intra-set rest after every 2 repetitions. The number of repetitions performed, mean velocity, and mean power output, were analyzed using 2(protocol)*6(set) repeated measures ANOVA. The number of repetitions during CS (51.8 ± 14.4) was greater than TS (31.9 ± 3.7) ($p = 0.001$), but the average velocity (CS = 0.711 ± 0.069, TS = 0.716 ± 0.081 $m \cdot s^{-1}$; $p = 0.732$) and power output (CS = 630.3 ± 59.8, TS = 636.0 ± 84.3 W; $p = 0.629$) of those repetitions were similar. These data indicate that CS are a viable option for increasing training volume during contemporary training where sets are ended when repetitions drop below velocity or power thresholds.

Introduction

As an athlete's ability to produce force quickly is important during many athletic movements, strength and conditioning professionals implement various exercises during training that should ultimately enhance the power-generating abilities of muscles during competition. For example, it has been suggested that resistance training should include a variety of exercises spanning across the entire force-velocity spectrum [108, 158], meaning that a well-rounded program could include exercises ranging from heavy squats and deadlifts to moderately heavy Olympic weightlifting derivatives to bodyweight jump squats and even assisted movements [3, 108, 159]. Regardless of the exercise or the external load, performing multiple repetitions with maximal concentric effort results in fatigue and a concurrent decrease in movement velocity and power output [11, 122, 133]. To ameliorate fatigue and combat these acute decreases in performance, the use of cluster sets has become increasingly popular within the strength and conditioning literature and within training environments [122].

Contrary to traditional sets where repetitions within a set are performed consecutively, a long inter-set rest period is provided, and another set of repetitions is performed consecutively, cluster sets include short, intra-set rest intervals, which likely allow for immediate energy stores and subsequent performance to be better maintained [[30, 31, 122]. Likely as a result of more constant energy stores within the active muscle, recent research has identified that intra-set rest intervals can allow for greater loads for a given number of repetitions [133] or a greater number of repetitions for a given load [24]. Although these findings may play a role in developing strength, hypertrophy, or both, cluster sets are often implemented during power-focused training [122], where repeated exposure to maximal-velocity movements against a given load is desired. In support of this, the cluster set literature has repeatedly shown that movement velocity and power output are better maintained when utilizing intra-set rest or having more frequent inter-set rest periods [13, 14, 58, 144]. Although adding intra-set rest intervals is easy to implement (i.e. only needing a mental countdown or, at most, a stopwatch), coaches who prefer to utilize technology during training may wish for a more objective approach for monitoring or guiding training. Therefore, this valid concern could mean that the addition of intra-set rest intervals using cluster set methods may reduce acute training stressors and fatigue so much that athletes may unwittingly elude an overload stimulus, resulting suboptimal adaptations. Therefore, to counteract any inadvertent and extreme over- or under-loaded stimuli, coaches may wish to monitor movement velocity or power-output to allow for training to be adjusted using objective data.

The recent surge of velocity-based training (VBT) in the literature and in practice serves as evidence to support the desire of coaches to objectively assess an athlete's performance during training sessions [115, 120, 160-163]. Among these studies, velocity- or power-based thresholds are often used to truncate an exercise once a certain amount of fatigue has ensued, something that has not been implemented during traditional sets in cluster-set-focused research. Although VBT studies make use of recent technological advancements, some coaches may err on the side of caution and may not implement VBT due to its heavy reliance on technology and the fact that technology can fail unexpectedly. In these cases, it is possible that cluster sets could be used as an "a-priori" alternative to VBT, as a recent study showed that 12-second inter-repetition rest periods allowed for 36 consecutive back squat repetitions to be performed with 75% 1RM without dropping below a 20% velocity-decrease threshold [144], which has been suggested by previous VBT researchers [18, 121]. When the same study implemented 52.5 s of rest between 9 sets of 4 repetitions, only 28 of the 36 repetitions were performed above the 20% velocity-decrease threshold, indicating that more frequent rest periods are beneficial for maintaining movement velocity when the total rest time and number of repetitions are equal. Paradoxically, that study [144] as well as many others have utilized either the same loads for all subjects [14, 32] or loads relative to a subject's 1 repetition maximum (1RM) [11, 58, 153], but aim to investigate the effects of cluster sets on maximizing power-output, with no studies utilizing loads that maximize power output [12, 13, 90, 122]. As power output varies between exercises and individuals, it would be logical to utilize loads at which an individual's maximum power output occurs when determining the effects of cluster sets on power output. Additionally, it may be useful to combine the ideas of cluster set training and VBT to investigate the effect of cluster set structures not only in repetitions to failure or across a prescribed number of repetitions [122], but during a training session that employs a power-based threshold [121] where the traditional set structure also utilizes the threshold, possibly "levelling out the playing field".

Therefore, the purpose of this study was to investigate the effects of cluster sets and traditional sets on velocity, power output, and training volume when using individualized loads at which mean power output is maximized. Also unique to this study, the protocols were based on a VBT approach whereby a decrease in mean power output below a certain threshold truncated each set, meaning that the number of total sets was prescribed, but the number of total repetitions was not. Based on previous research [24], we hypothesized that cluster sets would allow for greater movement velocities, greater power outputs, and greater total training volume compared to traditional sets, even when both protocols adopt the same power-threshold approach.

Materials and methods

To investigate the effects of set structure on velocity, power output, and training volume when using power-based thresholds, this study employed a repeated measures research design. First, subjects completed a familiarization session where each subject performed back squats with progressively increasing loads to determine the individualized load at which mean power output was the greatest (MPmax). This load was then used during the traditional set (TS) and cluster set (CS) protocols, which were performed in a counter-balanced order and occurred approximately 72 hours apart.

During the TS protocol, subjects performed 6 sets of back squats with their individualized MPmax load. Subjects completed each set with as many repetitions as possible until mean power output dropped below 90% of MPmax for two consecutive repetitions, as previous researchers have recommended that when developing "speed-strength" abilities, resistance training should be adjusted to maintain at least 90% of maximal mean power output [164-167]. After two consecutive repetitions were performed below 90% of MPmax, the set was concluded, and 2 min of inter-set rest was provided. This procedure was repeated for the remaining 5 sets (Fig 8.1).

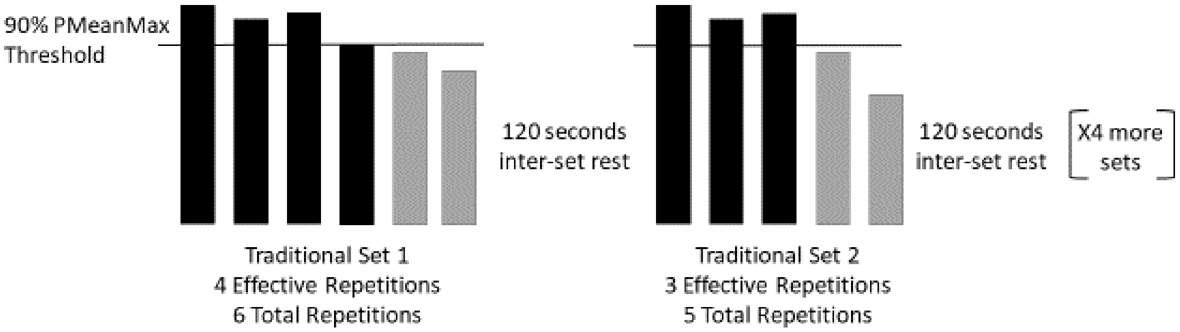

Figure 8.1: Example of the traditional set (TS) protocol with a threshold set at 90% of an individual's maximal mean power output (PMeanMax). Each set was truncated when two consecutive repetitions dropped below 90% PMeanMax. The y-axis is theoretical mean velocity and each bar represents an individual repetition.

During the CS protocol, an undetermined number of clusters of 2 repetitions were performed with 20 s intra-set rest until both repetitions in each cluster were performed below 90% of MPmax. When this happened, the set was concluded, and 2 min of inter-set rest was provided. This procedure was repeated for the remaining 5 sets (Fig 8.2).

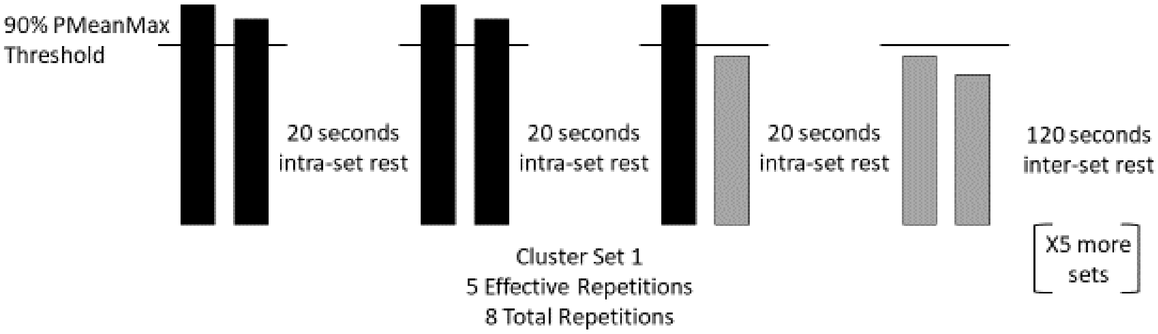

Figure 8.2: Example of the cluster set (CS) protocol with a threshold set at 90% of an individual's maximal mean power output (PMeanMax). Each set was truncated when two consecutive repetitions within the same cluster dropped below 90% PMeanMax. The y-axis is theoretical mean velocity and each bar represents an individual repetition.

Subjects

Ten university-aged males (23.4 ± 0.6 yr, 182.8 ± 2.7 cm, 79.39 ± 5.83 kg) with various specialized sport backgrounds (mainly track & field and soccer) participated in the study. All subjects routinely performed resistance training as part of their general training program for a minimum of at least 18 months prior to the commencement of this study, had no recent musculoskeletal injuries, and must have been able to perform a full barbell back squat with the hips descending below the knees with more than 100% of their body mass. The load with the greatest mean power output was 112.7 ± 12.1% of body mass. Subjects were instructed to refrain from any type of fatiguing lower body activity for the duration of the study, and all subjects read and signed an informed consent form that was approved by the Comenius University in Bratislava, Faculty of Physical Education and Sport ethics committee (project 4/2018).

Measurements and procedures

Back squat exercise

Contrary to most cluster set studies where subjects were instructed to keep their feet flat on the floor to control the distance and technique of each squat [10, 11, 58, 144, 168], this study utilized a high-bar back squat with a calf raise. Considering the purpose of this study was to maximize power output, subjects were instructed to control the eccentric phase of the squat, and then to perform the concentric phase as explosively as possible, even forcefully plantar-flexing the ankles so that acceleration during the concentric phase was maximized. The average eccentric phase of each squat (i.e. depth of the squat) was 72.46 ± 5.90 cm, and the total displacement during the concentric phase was 84.69 ± 6.08 cm, meaning that the average displacement of the barbell after the completion of the squat (i.e. from the starting position until the highest point of the lift which occurred at the end of the calf raise) was approximately 12 cm. As this exercise included triple extension of the hips, knees, and ankles, the principle of training specificity indicates that the squats performed in this study were executed as a “speed-strength” exercise compared to a standard back squat that doesn’t involve ankle plantar flexion.

Warm-up

Before all sessions, subjects performed a 5 min general warm-up, followed by 5 bodyweight lunges on both legs, 5 bodyweight squats with a calf-raise, and 5 bodyweight jump squats with maximal effort in the concentric phase. Next, in the TS and CS sessions, subjects performed 2 repetitions with a barbell (20 kg) followed by 2 repetitions with 50%, 75%, and 100% of their individualized MPmax load, which was determined during a familiarization session described below. Between each warm-up set, 1 min of rest was provided, and every warm-up repetition was performed with maximal concentric effort.

Familiarization and diagnostic session

This diagnostic session was performed to determine each subject's MPmax load and included a progressive loading test whereby the barbell load increased by 10 kg increments, starting with a 20kg barbell [169]. After completing the general (e.g. 15 minutes that included jogging and dynamic stretches of the lower limbs) and exercise-specific warm-up (e.g. bodyweight lunges, calf raises, squats, and jump squats) subjects un-racked the bar, stepped backwards onto a standardized line to ensure similar foot placement, and started the repetition on a verbal signal from the researcher. At each load, subjects performed a single repetition with the eccentric phase under control and maximal concentric effort finishing with plantar flexion without jumping. A linear position transducer (details below) was used to provide instantaneous computations of mean velocity and mean power output. This process continued with 90 s of rest between each repetition until a subject's individual load-power graph displayed a decrease in power output at two consecutive 10 kg increments. On average, subjects reached their MPmax of 763.2 ± 77.9 W with 89.5 ± 11.7 kg with a mean velocity of 0.86 ± 0.06 $m \cdot s^{-1}$, values that are somewhat lower than previous studies, but can likely be explained by the training status of our subjects (track and field athletes and soccer players) compared to previous studies that used resistance-trained men [10, 153]. Although we did not assess maximal strength (i.e. 1RM) in this study, it is possible that the MPmax loads were below the 70% or 75% 1RM loads that were used in previous studies. Additionally, as this was the first study to investigate the effects of back squats with a calf raise, the presence of plantar flexion, intent of plantar flexion, or both may influence strength, movement velocity, or power output compared to traditional back squats that are often used in research.

Traditional sets and cluster sets sessions

As explained above, the TS protocol consisted of 6 sets with 2 min inter-set rest intervals, stopping each set when MPmax dropped below 90% for two consecutive repetitions. The CS protocol was identical to TS, but repetitions were performed two at a time with 20 s of intra-set rest. During each protocol, subjects casually walked around the laboratory during their 2 min inter-set rest periods until about 10 s remained, at which point they began to return under the bar. During the CS protocol, subjects also casually walked around the laboratory during their 20 s intra-set rest periods. When there was 7 s left (in both the intra- and inter-set rest periods), subjects un-racked the bar, took one step backwards, and waited to perform the first repetition when the researcher's countdown reached "0", upon which the subject immediately started to perform the eccentric phase of the first repetition. As repetitions were performed consecutively, there was approximately a 1 s pause between each repetition to allow the subjects to reset themselves before the next repetitions and to allow the transducer to recognize the completion of one repetition and the beginning of the next. As soon as the bar was re-racked, the appropriate intra- or inter-set timer started. Like during the diagnostic session where all of the subjects were familiarized with the protocols and procedures, the start of each repetition of every set was verbally signaled by the researcher.

Data acquisition

All data were collected using a FiTROdyne Premium linear position transducer (FiTRONiC, Bratislava, Slovakia), which is a reliably method for measuring velocity and power output [170]. Time and vertical velocity were directly measured, and power output was calculated as the product of force (barbell load) and velocity. Total work was measured using force (barbell load) and distance of the entire range of motion, including the calf raise.

Immediate feedback was provided to the researchers after every repetition and subjects were informed whether the previous repetition was above or below 90% of their MPmax threshold. Verbal encouragement was provided throughout the protocols, but neither visual nor any other forms of feedback were provided to the subjects. After each protocol, the number of effective repetitions (i.e. above the 90% threshold), ineffective repetitions (i.e. below the 90% threshold), and total number of repetitions were recorded.

Statistical analyses

When analyzing the number of total repetitions performed, one subject was an outlier and performed over two standard deviations more than the average. Therefore, this subject was excluded from all analyses and data from the other 9 subjects were analyzed. Descriptive statistics were calculated for mean velocity (MV), mean power output (MP), eccentric depth (ECC), total work per repetition (TW), number of effective repetitions (NER), and number of total repetitions (NTR). Individual 2(protocol)x6(set) repeated measures ANOVA were used to evaluate MV, MP, ECC, TW, NER, and NTR, with an LSD post-hoc test when necessary. The alpha level was set at $p \leq 0.05$ and all statistical analyses were performed using SPSS 22.0 (IBM, Armonk, NY). Effect sizes were calculated using Cohen's *d* and can be interpreted as small (0.20 - 0.49), moderate (0.50 - 0.79), and large (≥0.80). A post-hoc power analysis using G*Power (3.1.9, Dusseldorf, Germany) revealed a power of 0.99 using the number of total repetitions as the main variable of interest, an alpha level of 0.05, and an f-value of 0.945 [171].

Results

The NER during CS (30.1 ± 11.7 repetitions) was greater ($p = 0.009$, $d = 1.27$) than TS (19.1 ± 3.7 repetitions), but the MV ($p = 0.317$) and MP ($p = 0.276$) of the NEF were similar. However, TW and ECC of NER were greater ($p = 0.025$ and $p = 0.017$, respectively) in TS than CS. Means, standard deviations, and effect sizes are shown in Table 8.1.

The NTR performed during CS (51.8 ± 14.4 repetitions) was greater ($p = 0.001$, $d = 1.89$) than TS (31.9 ± 3.7 repetitions), but the MV ($p = 0.732$) and MP ($p = 0.629$) of the NTR were similar. However, TW and ECC of NTR were greater ($p = 0.006$ and $p = 0.014$, respectively) in TS than CS. Means, standard deviations, and effect sizes are shown in Table 8.1.

Set-by-set data for NTR and NER, MV, and MP can be found in Fig 3, Fig 4, and Fig 5, respectively. Despite a greater NTR during CS in the first two sets ($p = 0.011$ and 0.027, respectively) and a greater NER during CS in the first set ($p = 0.027$), these protocol*set interactions were not significant ($p = 0.120$ and 0.118, respectively). There were no interactions for MV or MP for either NTR or NER. The corresponding effect sizes are listed in Table 8.2.

Table 8.1 Effect sizes (d) for all variables during the traditional set (TS) and cluster set protocols (CS). Effective repetitions include all repetitions performed over 90% MPmax,

	Number of Effective Repetitions	Number of Total Repetitions
Mean Velocity ($m \cdot s^{-1}$)	CS: 0.751 ± 0.073 TS: 0.763 ± 0.082 *d* = 0.15 in favor of TS	CS: 0.711 ± 0.069 TS: 0.716 ± 0.081 *d* = 0.07 in favor of TS
Mean Power (W)	CS: 664.5 ± 57.0 TS: 677.1 ± 79.4 *d* = 0.18 in favor of TS	CS: 630.3 ± 59.8 TS: 636.0 ± 84.3 *d* = 0.08 in favor of TS
Total Work (J)	CS: 741.11 ± 74.77 TS: 752.21 ± 78.97* *d* = 0.14 in favor of TS	CS: 737.73 ± 75.45 TS: 751.32 ± 80.05** *d* = 0.17 in favor of TS
Eccentric Depth (cm)	CS: 72.07 ± 6.42 TS: 73.02 ± 6.01* *d* = 0.15 in favor of TS	CS: 71.97 ± 6.44 TS: 72.98 ± 6.05* *d* = 0.16 in favor of TS

and total repetitions include effective repetitions and all repetitions performed below 90% MP max. Symbols indicate a significant difference between protocols $p < 0.05$*, $p < 0.01$**.

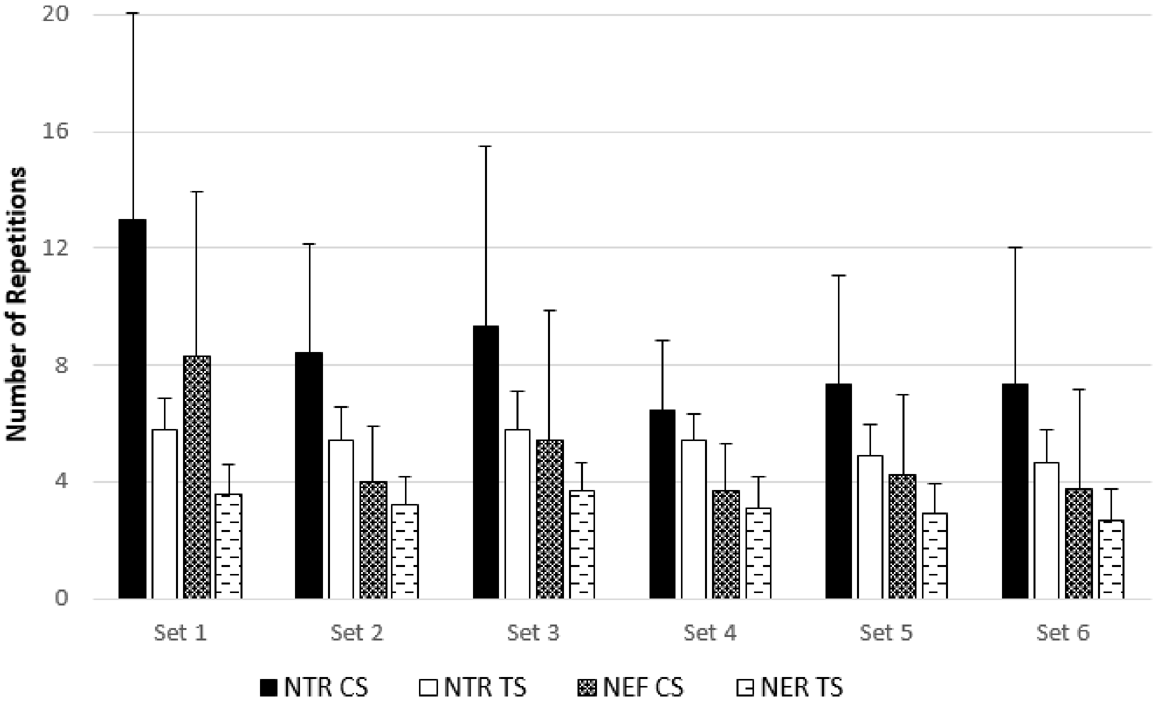

Figure 8.3: The number of total repetitions (NTR) and effective repetitions (NER) for the cluster set (CS) and traditional set (TS) protocols. Data are presented as mean ± standard deviation.

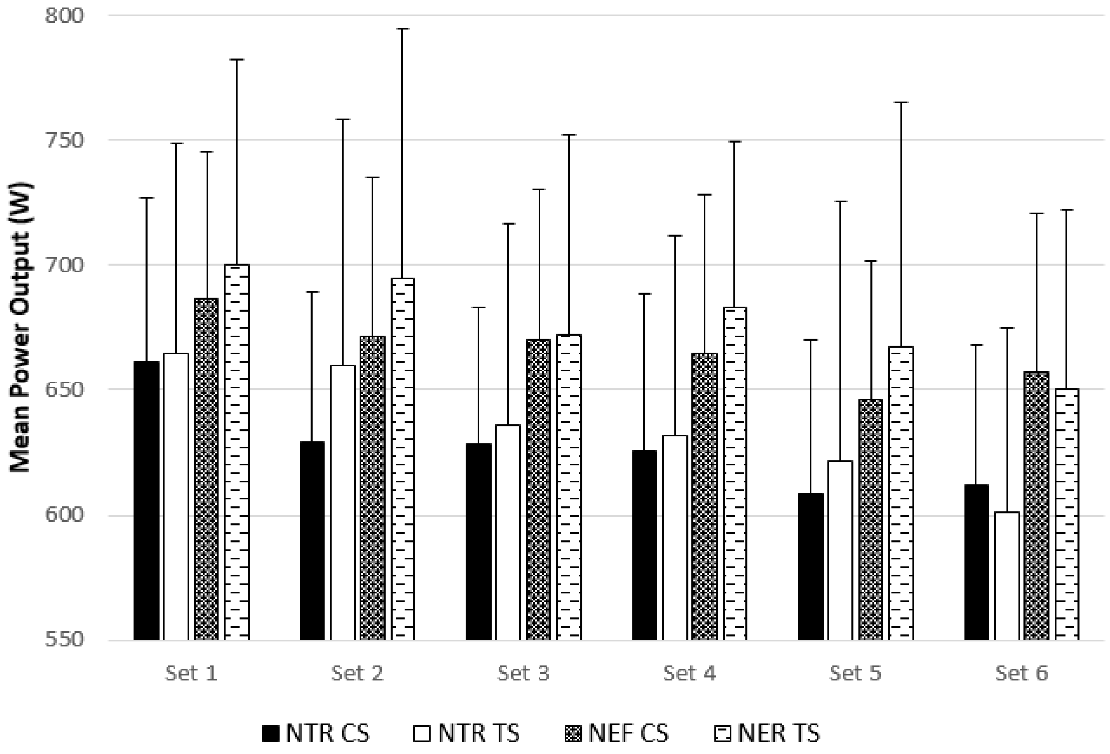

Figure 8.4: Mean power output for the number of total repetitions (NTR) and effective repetitions (NER) for the cluster set (CS) and traditional set (TS) protocols. Data are presented as mean ± standard deviation.

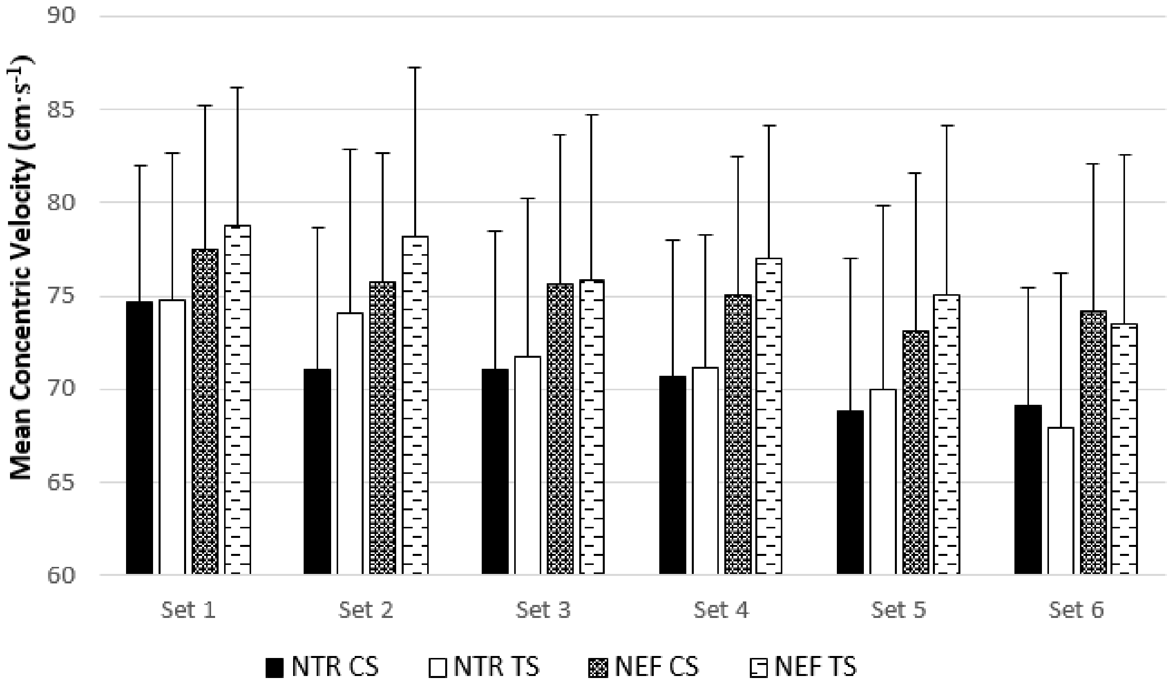

Figure 8.5: Mean concentric velocity for the number of total repetitions (NTR) and effective repetitions (NER) for the cluster set (CS) and traditional set (TS) protocols. Data are presented as mean ± standard deviation.

Table 8.2 Set-by-set effect sizes (d) for all variables between the traditional set (TS) and cluster set protocols (CS).

		Number of Repetitions	Mean Power Output	Mean Velocity
Total Repetitions (CS - TS)	Set 1	1.42	0.04	0.02
	Set 2	1.09	0.37	0.37
	Set 3	0.80	0.11	0.09
	Set 4	0.55	0.09	0.07
	Set 5	0.88	0.15	0.12
	Set 6	0.78	0.16	0.16
		Number of Repetitions	Mean Power Output	Mean Velocity
Effective Repetitions (CS - TS)	Set 1	1.18	0.19	0.17
	Set 2	0.51	0.28	0.30
	Set 3	0.55	0.04	0.02
	Set 4	0.40	0.28	0.27
	Set 5	0.63	0.27	0.22
	Set 6	0.44	0.10	0.08

Discussion

The current body of evidence overwhelmingly supports cluster sets over traditional sets when velocity and power maintenance are desired [122]. However, the large majority of these studies were designed so that the traditional set protocols were extremely fatiguing [11, 58, 133, 168]. This classical training approach has become challenged by research indicating that less-fatiguing resistance-training strategies impose similar, and at times superior, strength and power adaptations [60, 172]. Therefore, our study took a novel approach and implemented TS that were, by design, not extremely fatiguing. In doing so, our data show that when using a power-based threshold to truncate resistance-training sets, CS and TS resulted in similar movement velocities and power outputs by design.

Interestingly, the effect sizes of the present study show a slight possible advantage (insignificant p-values and negligible-to-small effect sizes) for TS, which is in stark contrast to previous studies that often highlight the extreme fatigue that occurs in traditional sets. When repeatedly reading about the fatiguing-nature of traditional sets [122], readers ultimately believe that traditional sets are arduous and malevolent and that cluster sets are fatigue-resistant and steadfast. Although the present study indicates that CS and TS are in fact quite similar in terms of movement velocity and power output when using a power-based threshold, as expected, CS resulted in a significantly greater NER and NTR, indicating that total training volume was significantly greater during CS without decreasing acute repetition performance.

This study is not the first to show that more repetitions can be performed using cluster sets compared to traditional sets. Previous research that used cluster sets to redistribute rest periods and approximately equalize the work-to-rest ratio that occurred during traditional sets also showed that cluster sets enable more repetitions to be performed compared to traditional sets [24]. In that study, subjects performed 3 traditional sets of back squats to failure using a 4RM load with 3 min of inter-set rest. They later performed individual repetitions with the same work-to-rest ratio and number of repetitions as their traditional set protocol but were then allowed to continue performing individual repetitions with the same work-to-rest pattern until failure. As a result of having more frequent rest intervals, subjects were able to complete approximately 5 times the number of repetitions (45.0 ± 32.0) as they completed with traditional sets (9.3 ± 1.9) [24]. The present study shows that CS resulted in approximately 1.6 times more NER and NTR than TS, values that are comparatively dwarfed by the 5-fold increase noted in the aforementioned study. This discrepancy further illustrates the necessity of the present study, as using cluster sets to train to failure results in an anomalous number of repetitions compared to performing traditional sets to failure. By using velocity- or power-based thresholds in practice, cluster sets would likely not result in 5 times the number of repetitions as traditional sets, but rather a more modest but significant increase, possibly of about 1.6 times as seen in the present study. However, it is worth mentioning that the intra- and inter- subject variability for the number of repetitions performed during CS was quite large. For example, the NER in the first CS set ranged between 2 and 21 repetitions, with the NTR ranging between 4 and 28, whereas the NEF in the first TS set ranged between 2 and 5 with the NTR ranging between 4 and 7. Specifically, one subject who completed 21 NER during the first CS completed 7 NER during the second set and only 2 NER during the final set. With this in mind, it is possible that the greater volume experienced during the first set of CS may have affected the performance of the subsequent CS in some subjects, despite having 2 min of inter-set rest. This notion is supported by the largest pro-TS effect sizes during the 2nd set, when the accumulated fatigue of the 1st CS set may have affected performance during the 2nd CS set (Table 8.2). Therefore, strength and conditioning professionals should consider these individual differences and the possibility of accumulated fatigue when implementing similar protocols with their athletes.

Generally, performing more repetitions during cluster sets may seem intuitive, especially when the total rest time is greater. Moreover, previous research has shown that not only do cluster sets allow for more repetitions compared to traditional sets, but those additional repetitions are performed with greater movement velocities and presumably greater power outputs [24]. However, this this was not observed in the present study. In fact, although not significantly different, it is possible that the CS structure used in the present study may have had a slight negative effect on MV and MP compared to TS, demonstrated by effect sizes reaching up to 0.37 in NTR and up to 0.29 in NER, both in favor of TS for MV and MP. As these differences were not significant, it would be inaccurate to claim that TS had greater MP and MV than CS. Nevertheless, it is possible that the greater NTR performed during CS may have resulted in slightly more accumulated fatigue throughout the session. Although ECC and TW per repetition were statistically greater during TS, a 1 cm change in squat depth is likely not practically significant, and likely does not indicate any more or less fatigue for either protocol. Therefore, it seems as though coaches must perform a balancing act between increasing training volume and maintaining power output, even when using power-based thresholds in traditional set and cluster set settings.

Unique to our study is the use of a MPmax load combined with a power-based threshold approach, two things that have not been investigated in the cluster set literature to date. Our data show that when using a power-based threshold to truncate traditional sets, cluster sets may not be as superior as many practitioners may have originally thought but may only be superior to traditional sets when traditional sets are designed to induce large amounts of fatigue. Although our study provides valuable insight and indicates that velocity- or power-based thresholds level out the playing field when comparing traditional and cluster sets, future studies should carefully consider their research design to sufficiently address the challenges at hand. For example, the decision to require two repetitions to fall below 90% of MPmax before ending a set in the present study was made to be confident that fatigue had in fact accumulated and would continue to build. However, this decision theoretically could have allowed for a single “bad repetition” that may have been performed at 89% MPmax followed by another repetition at 90% and so on. In doing so, it is possible to inadvertently hover around 90% MPmax despite performing each concentric phase at maximum effort, resulting in an increasing number of repetitions below the threshold, but not consecutively. Using such thresholds draws a fine and very murky line between what can be considered as sound scientific methodology (whereby crossing a threshold can be seen as black and white) and what can be done in practice (whereby a repetition performed at 89.4% MPmax is essentially the same as a repetition performed at 89.5% or 90% MPmax, for example). Therefore, future researchers should strongly consider this as the strength and conditioning field continues with threshold-based research. Another limitation of this study is the large inter-subject variability in the number of repetitions performed in the CS sets. As with most sport science research, individual data can be presented and analyzed, but coaches should take the next step by applying these novel training principles on an athlete-by-athlete basis, including other athletes from other sport backgrounds.

As this study compared TS and CS both using a power-based threshold approach, the next step researchers may wish to take is to investigate a TS protocol using a true VBT approach to a CS protocol that does not use a VBT approach, but instead either redistributes the total rest time to include shorter but more frequent sets [23] or includes additional intra-set rest periods [11], both of which have been shown to maintain velocity and power output. Conducting such a study would further elucidate whether specialized equipment is needed to objectively monitor fatigue and reactively truncate each set, or if proactively adjusting rest periods would be sufficient for maintaining velocity and power output for a given training volume. Additionally, as this study is the first to utilize individualized loads based on MPmax during cluster sets, our findings should be validated using other exercises and before the results from this study become well-accepted and implemented across a variety of exercises.

Conclusions

This study indicates that when power-based thresholds are utilized, velocity and power output are equally maintained during cluster sets and traditional sets. However, cluster sets structures still allowed for a greater number of repetitions when using a 90% power-based threshold. Therefore, coaches and athletes can transfer these findings into practice by implementing cluster sets even during power- or velocity-based training when periods of greater training volumes are desired. However, when doing so, caution should be used as to not perform so many repetitions during cluster sets that they negatively affect the repetitions of subsequent sets.

Chapter 9

The data presented in Chapter 8 showed that, when using a power-based threshold, CS allowed for more effective repetitions performed above the threshold but required greater total training time. Considering this would greatly increase total training time, rest-redistribution would be a better real-life scenario. However, do date, the combination of rest-redistribution and velocity-based training had not been directly compared within the same study. Naturally, the fundamental difference between the two is that rest-redistribution is an ad-hoc prescription whereas velocity-based training is highly individualized and accounts for day-to-day variations in performance. Nevertheless, velocity-based training requires addition equipment and time, which some coaches cannot afford. Therefore, the purpose of the study in this chapter sought to determine whether rest-redistribution could function as an ad-hoc velocity-based training prescription. Please note that the formatting has been adjusted from the original manuscript that was accepted in the *Journal of Human Kinetics* in 2019 to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Rest redistribution functions as a free and ad-hoc equivalent to commonly used velocity-based training thresholds during clean pulls at different loads

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This study determined whether redistributing total rest time into shorter, but more frequent rest periods could maintain velocity and power output during 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest and during 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. The total number of repetitions performed above 10 and 20% velocity loss thresholds, mean and peak velocity maintenance (the average of all 18 repetitions relative to the best repetition; MVM, PVM), and decline (the worst repetition relative to the best repetition; MVD, PVD) were calculated. For MVM, PVM, MVD, and PVD, there were small-to-moderate effect sizes in favour of RR80 and RR100, but large effects favouring RR120, compared to their respective TS protocols. The number of repetitions within a 20% velocity loss threshold was 17.7 ± 0.6 during RR and 16.5 ± 2.4 during TS (effect size 0.69); and the number of repetitions within a 10% velocity loss threshold was about 13.1 ± 3.7 during RR and 10.7 ± 3.6 during TS (effect size 0.66). Therefore, RR generally allowed for a better overall maintenance of velocity and power, especially at heavy loads. Coaches who wish to implement velocity-based training, but who do not wish to purchase or use the associated equipment, may consider rest-redistribution to encourage similar training stimuli.

Introduction

Lower body power is considered to be essential for an athlete's overall performance in sports that require triple extension movements of the hip, knee, and ankle [173, 174]. Therefore, practitioners often implement triple extension movements like weightlifting movements and their derivatives during training. Typically, some training periods may involve high volumes of fatiguing resistance training (RT) in order to elicit greater training adaptations. However, performing multiple repetitions with maximal concentric effort (i.e. traditional sets) exacerbates fatigue [122], which causes acute decreases in movement velocity and power output. Therefore, some coaches now aim to objectively monitor movement velocity and power output during RT in order to adjust acute training loads or volume to match acute performance with their desired training goals.

Thanks to technological advancements, objective measurements of real-time velocity data have led to the emergence of velocity-based training (VBT). In science and in practice, the foundation of VBT lies in certain velocity thresholds that are implemented whereby exercise is truncated when velocity decreases to a certain degree [8, 120, 175, 176]. The theory behind this is that all repetitions performed are "quality" repetitions, and acute fatigue is mitigated. Generally, research has shown that implementing stricter velocity loss thresholds can result in similar or greater strength and power training adaptations as opposed to more permissive thresholds [176-178]. Despite such promising evidence supporting VBT, some coaches may not implement VBT due to its heavy reliance on expensive technology and the fact that technology can fail unexpectedly. Therefore, cheaper, ad-hoc approaches to preserve movement velocity during RT could be very beneficial.

Without decreasing training loads or training volume, likely the simplest and most effective way to mitigate acute fatigue is to adjust rest periods: specifically, adding intra-set rest. Although the addition of intra-set rest usually serves its purpose, these so-called “cluster sets” might not always be feasible from a practical perspective since they extend total time [11]. One alternative to such lengthy cluster set structures is to redistribute the total rest time of traditional set structures to include shorter and more frequent rest intervals [144]. This strategy, known as rest redistribution, can sufficiently maintain velocity and power output within individual sets compared to traditional sets [39, 58]. Moreover, one study [144] showed that 12-s inter-repetition rest periods allowed for 36 consecutive back squat repetitions to be performed with 75% 1RM without dropping below a 20% velocity-decrease threshold, which is a common threshold suggested by previous VBT researchers in order to elicit maximal power training adaptations [18, 178]. However, more recent research [179] has shed light on the idea that when using VBT, firm velocity-loss thresholds do not allow for leeway, meaning the training set or an exercise is terminated once athletes’ velocity drops below the predetermined velocity threshold.

Therefore, if an athlete has a single “bad repetition”, the VBT threshold informs the coach that the athlete should cease the set, whereas in reality, it is possible that the next repetition (or few repetitions) could still be performed above the threshold. This could be problematic as training volume would be incorrectly and inadvertently reduced beyond what is desired. This type of a real-life scenario introduces the idea that although the force-velocity relationship is linear, the “repetition-velocity” relationship might not always be linear in practice. Thus, the current VBT methodology may not be optimal, as VBT assumes that the best repetitions occur at the beginning of a set or a training session and successive repetitions decrease linearly.

With these points in mind, it would be advantageous if a free ad-hoc VBT alternative could treat the resistance training session holistically, rather than on a rep-by-rep basis. Therefore, the purpose of this study was to determine the ability of rest redistribution to maintain velocity and power output during the clean pull exercise, possibly allowing rest redistribution to serve as a free and ad-hoc alternative to VBT. Based on previous findings [144], we hypothesized that shorter, but more frequent rest periods would allow for greater preservation of movement velocity and power output, and a greater number of repetitions being performed above adopted thresholds when compared to traditional sets.

Methods

Participants

Fifteen strength-trained men participated in this study (age 28.8 ± 4.48, body mass 89.1 ± 8.7 kg), had at least 1 year of resistance training experience using the power clean and the clean pull exercises, and could power clean at least 90% of their body mass. Participants were excluded if they reported any recent musculoskeletal injuries or were not proficient with either exercise technique. Participants averaged a power clean 1-repetition maximum (1RM) of 99.8 ± 10.8 kg, resulting in a 1RM-to-body-mass ratio of 1.13 ± 0.14. All participants were members of a local gym where Olympic weightlifting movements were commonplace during training, which were always supervised by one of the gym's certified coaches. All procedures were carried out in accordance with the Declaration of Helsinki and all participants gave written informed consent prior to the beginning of the study.

Study Design

Participants reported to the lab for a 1RM power clean session and six experimental sessions, which occurred in counter-balanced, randomized order. These experimental sessions included the clean pull exercise for one of the following protocols: 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest (Figure 9.1). These six experimental sessions were each performed on different days, separated by 48 to 72 hours. For the duration of the study, participants were instructed to refrain from any type of fatiguing lower body activity for at least 48 hours before each session. All participants were allowed to use weightlifting chalk, but lifting belts and straps were forbidden. All participants successfully completed all 18 repetitions in every experimental session.

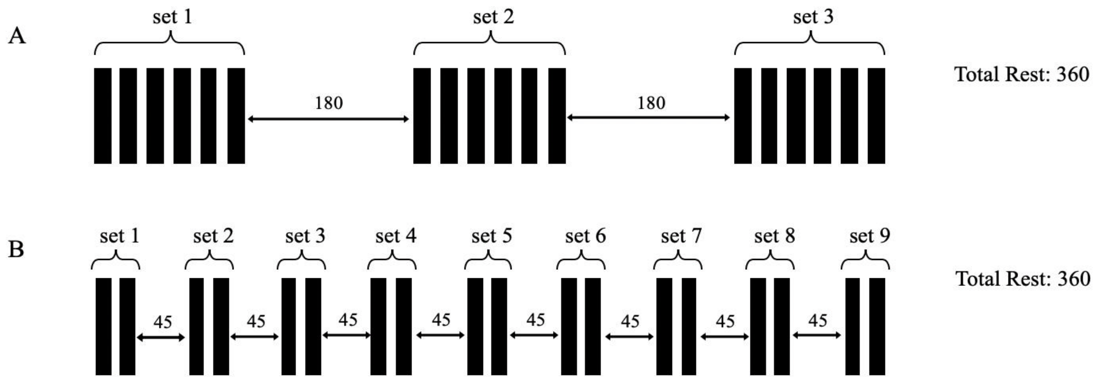

Figure 9.1 Set structure protocols. Traditional sets, 3 sets of 6 with 180 seconds of inter-set rest (panel A). Rest redistribution sets, 9 sets of 2 with 45 seconds of inter-set rest (panel B).

Repetition-Maximum Testing: Session 1

Participants refrained from strenuous exercise at least 72 hours before Session 1. During Session 1, participant's body height and mass were recorded, and they were familiarized with the protocols and the 0-10 OMNI-RES scale: a resistance training specific rating of perceived exertion (RPE) scale. After a dynamic warm-up with a special focus on the hips, shoulders, and wrists (8 to 10 min), participants performed 10 barbell front squats followed by 3 power clean repetitions at 50%, 2 power clean repetitions at 70%, and 1 power clean repetition at both 80% and 90% of their estimated power clean 1RM, respectively. Power clean 1RM was then assessed starting at 90% estimated 1RM with 2 to 3 min of rest between each successive attempt. The load was progressively increased until the 1RM was achieved. If the participant failed an attempt with an increased load, they were given the option to attempt it a second time. However, no decreases in the load were allowed and if the lift was missed on the second occasion, the load of the last successful attempt was recorded as the 1RM. All participants obtained their actual 1RM in up to 4 maximal trials. Proper technique of the power clean was assessed as discussed previously [180, 181] by the research personnel (certified weightlifting coaches).

Experimental Testing: Sessions 2-7

During these randomized sessions, the participants performed the clean pull exercise in both traditional and rest redistribution protocols with loads that were based upon their power clean 1RM. The warm-up consisted of the same dynamic warm-up as Session 1, after which the participants performed a set of 5, 4, 3, 2 and 1 repetition at 50, 60, 70, 80 and 90% of the actual load that they had to perform that day (i.e. 80, 100 or 120% of their 1RM power clean), respectively. Therefore, the loads during the warm-ups were not identical across sessions, but instead were standardized according to the load that was to be used during each respective session. A schematic view of the described set structures and their respective loads can be seen in Figure 9.1.

As all of the participants were well-versed in the clean pull exercise, no specific instructions were warranted for all participants other than standard verbal coaching cues. For example, when appropriate, participants were instructed to avoid initiating the first pull (of the floor) too forward on the balls of the feet and toes, and to maintain the angle of the torso to the floor. In the event that a lifter failed to keep the bar close to the body while transitioning the bar from the knee to the power position, the lifter was reminded to always pull “up and into the body” keeping the bar as close to the body as possible [182]. All participants were instructed to execute triple extension of the hips, knees, and ankles aggressively and as fast as possible, with strong verbal encouragement provided throughout all trials.

During the experimental sets, participants were required to avoid bouncing the loaded barbell off the floor when transitioning from one repetition to the next by implementing a 1-s pause with the barbell on the floor, starting each consecutive repetition with their original setup as determined by the investigators for a repetition to be considered successful. However, there were no repetitions that the investigators deemed unsuccessful, indicating that the experienced participants maintained their clean pull technique and the 1-s pause throughout the entire experiment. During all repetitions, the feet were required to maintain contact with the floor (i.e. no jumping) while allowing the trajectory phase of the lift to reach its maximal height at the conclusion of each repetition to ensure full extension of the ankle, knee and hip joint. The position of the toes and heels were based upon chalk drawings for each participant during all sessions and the distance was measured between the feet to ensure the identical starting stance each time. Ten minutes after completing each protocol, participants were asked to rate their session on a 0-10 RPE scale.

Data Acquisition and Preparation

For the purposes of the present study, a Gymaware (GymAware Power Tool, Kinetic Performance Technologies, Canberra, Australia) linear position transducer device was used to measure mean force (MF), peak force (PF), mean concentric velocity (MV), peak concentric velocity (PV), mean power output (MP), and peak power output (PP) during all repetitions throughout the sessions. The device consists of a power tool, made up of a steel cable that is wound on a cylindrical spool coupled to the shaft of an optical encoder. The power tool unit was placed on the right side of the barbell, between the hands and the loaded sleeves, according to the manufacturer's instructions. The end of the cable was vertically attached to the barbell using a Velcro strap. Gymaware measures vertical displacement of its cable in response to changes in the barbell position. Within the Gymaware software, the displacement data were time-stamped at 20 millisecond time points and down-sampled to 50 Hz for analysis. The sampled data were not filtered. Instantaneous velocity was determined as change in the barbell position with respect to time, which was also directly measured in the Gymaware software. Acceleration data were automatically calculated as change in barbell velocity over change in time for each consecutive data point. The device's software also determined instantaneous force by multiplying the system mass with acceleration, in which system mass was the barbell load plus the relative body mass of the participant [162, 183]. Power was then calculated as the product of force and velocity. Data obtained from the Gymaware were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.4.1 app, and to the Gymaware online cloud before being exported to Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and prepared for further analysis. The device did not require to be calibrated. Similar to previous research (Jukic and Tufano, 2019; Tufano et al., 2016), the effect of set structure on MV, PV, MP, and PP across each protocol was determined by a percent decline from the $\text{fastest}_{(\max)}$ to the $\text{slowest}_{(\min)}$ repetition using the following equation: Percent decline = $[(\text{repetition}_{\min} - \text{repetition}_{\max})/\text{repetition}_{\max}] \times 100$. Furthermore, to provide a more holistic view of MV, PV, MP, and PP during all repetitions within each set the overall maintenance was calculated by the following equation: $\text{Maintenance}_{\text{set}} = 100 - [(\text{mean}_{\text{set}} - \text{repetition}_{\max})/\text{repetition}_{\max}] \times 100$. As a result, the variables of MV and PV decline (MVD and PVD, respectively), MP and PP percent decline (MPD and PPD, respectively), MV and PV maintenance (MVM and PVM, respectively), and MP and PP maintenance (MPM and PPM, respectively) were calculated. Finally, the number of repetitions performed during each of the protocols above the 10 and 20% loss thresholds for mean velocity ($MV_{90\%}$ and $MV_{80\%}$), peak velocity ($PV_{90\%}$ and $PV_{80\%}$), mean power ($MP_{90\%}$ and $MP_{80\%}$), and peak power ($PP_{90\%}$ and $PP_{80\%}$) was measured to assess the number of "effective" repetitions being performed.

Statistical Analyses

Means and SDs were calculated for all variables. A two-way 2 × 3 (set structure × load) repeated-measures analysis of variance (ANOVA) was used to compare the mean values of MVD, PVD, MPD, PPD, MVM, PVM, MPM and MPM per protocol.

An individual 2 × 3 (set structure × load) repeated measures ANOVA was computed to compare session RPE scores of each load per protocol. In addition, individual 2 x 3 (set structure x load) repeated measures ANOVA was used to compare the number of repetitions performed within each protocol for $MV_{90\%}$, $MV_{80\%}$, $PV_{90\%}$, $PV_{80\%}$, $MP_{90\%}$, $MP_{80\%}$, $PP_{90\%}$ and $PP_{80\%}$.

When significant main effects or interactions were obtained, a Holm's Sequential Bonferroni follow-up test was performed to control for type I error and assess pairwise comparisons. Hedge's *g* effect sizes with 90% confidence intervals (90%CI) were used to determine practically relevant magnitude of difference, which can be interpreted as: $d < 0.2$ (trivial), $d = 0.2–0.5$ (small), $d = 0.5–0.8$ (moderate), and $d > 0.8$ (large). Hedge's *g* was chosen in preference of Cohen's *d* in order to account for the small sample sizes. To avoid an exasperating number of effect sizes, only moderate and large values were reported and discussed. An a priori level of significance was set at $p < .05$ for all tests. All statistical analyses were performed using SPSS version 23.0 (IBM, Armonk, NY, United States).

Results

When all repetitions during a single protocol were averaged together, there was no significant set structure*load interaction for MVD ($p = .270$), MVM ($p = .182$), PVD ($p = .180$), PVM ($p = .161$), MPD ($p = .258$), MPM ($p = .226$), PPD ($p = .544$), or PPM ($p = .644$). However, there were significant main effects of set structure for MVD ($p = .018$), MVM ($p = .006$), PVD ($p = .009$), PVM ($p < .001$), MPD ($p = .012$), MPM ($p = .004$), and PPD ($p = .021$), but not for PPM ($p = .191$) (Table 9.1).

When analysing the total number of repetitions performed above the adopted thresholds (i.e. 10 and 20% loss) during a single protocol that were averaged together, there was a significant set structure*load interaction for $PV_{80\%}$ ($p = .029$), but not for $MV_{90\%}$ ($p = .168$), $MV_{80\%}$ ($p = .248$), $PV_{90\%}$ (P$p = .165$), $MP_{90\%}$ ($p = 0.117$), $MP_{80\%}$ ($p = 0.233$), $PP_{90\%}$ ($p = .741$) and $PP_{80\%}$ ($p = .904$) (Table 9.2). However, there was a main effect of set structure for $MV_{90\%}$ ($p = .018$), $MV_{80\%}$ ($p = .010$), $PV_{90\%}$ ($p = .005$), $PV_{80\%}$ ($p = .004$), $MP_{90\%}$ ($p = .001$), $MP_{80\%}$ ($p = .035$), but not for $PP_{90\%}$ ($p = .741$) and $PP_{80\%}$ ($p = .355$) (Table 9.2).

When all session RPE scores during a single protocol were averaged together, there was a significant set structure*load interaction ($p = .014$), as well as main effect of set structure ($p < .001$) and load ($p < .001$) (Table 9.3).

Table 9.1 Means and standard deviations and results of analysis of variance between Rest Redistribution sets (RR) and Traditional sets (TS) in MVM, PVM, MPM, PPM, MVD, PVD, MPD and PPD across 80%, 100%, and 120% 1RM.

		RR		TS					
		M	*SD*	*M*	*SD*	*F*	*g*	*LCI*	*UCI*
MVM	80%	92.99	1.82	91.17	5.63	1.66	0.42	-0.18	1.03
	100%	92.58	2.42	91.34	2.14	1.89	0.50†	-0.12	1.09
	120%	92.71	3.24	88.35	4.99	12.86**	1.05††	0.41	1.69
PVM	80%	92.68	2.73	90.84	4.06	3.63	0.52†	-0.09	1.13
	100%	93.58	2.53	91.96	1.88	5.59	0.70†	0.09	1.32
	120%	91.57	2.44	87.79	3.42	17.70**	1.24††	0.58	1.89
MPM	80%	91.66	3.77	89.43	7.16	1.42	0.38	-0.23	0.99
	100%	92.64	3.25	91.13	2.14	2.03	0.53†	-0.08	1.15
	120%	92.56	2.54	87.68	4.78	16.22**	1.24††	0.58	1.90
PPM	80%	87.44	6.13	87.11	6.67	0.01	0.01	-0.63	0.58
	100%	88.03	4.35	86.80	3.64	0.56	0.30	-0.31	0.90
	120%	85.55	4.02	82.79	8.67	1.43	0.40	-0.21	1.00
MVD	80%	16.20	6.47	18.62	9.51	0.66	-0.29	-0.89	0.31
	100%	16.83	7.38	20.27	6.50	1.76	-0.48	-1.09	0.13
	120%	15.86	6.23	24.13	8.75	8.51*	-1.06††	-1.70	-0.42
PVD	80%	14.57	3.69	17.78	7.05	4.10	-0.56†	-0.96	0.25
	100%	15.28	7.42	17.32	2.50	0.85	-0.36	-0.96	0.25
	120%	17.52	3.79	24.44	7.13	9.45*	-1.18††	-1.83	-0.53
MPD	80%	17.91	7.14	20.63	10.53	0.75	-0.29	-0.90	0.31
	100%	17.09	7.50	20.52	6.47	1.64	-0.48	-1.08	0.13
	120%	16.00	6.04	24.80	8.39	10.29*	-1.17††	-1.82	-0.52
PPD	80%	23.32	7.37	24.37	8.89	0.15	-0.13	-0.73	0.48
	100%	23.61	8.33	26.21	5.49	0.76	-0.36	-0.96	0.25
	120%	26.53	5.11	32.25	9.60	5.41*	-0.72†	-1.34	-0.10

Note. MVM – Mean velocity maintenance; PVM – Peak velocity maintenance; MPM – Mean power maintenance; PPM – Peak power maintenance; MVD – Mean velocity decline; PVD – Peak velocity decline; MPD – Mean power decline; PPD – Peak power decline; g – Hedges' g; *LCI* – lower confidence interval; *UCI* – upper confidence interval; **(p < 0.05); ** (p < 0.01); † (g = 0.5-0.79); †† (g > 0.8).*

Table 9.2 Means and standard deviations and results of analysis of variance between Rest Redistribution sets (RR) and Traditional sets (TS) in MV80%, MV90%, PV80%, PV90%, MP80%, MP90%, PP80% and PP90% across 80%, 100%, and 120% 1RM.

		RR		TS					
		M	*SD*	*M*	*SD*	*F*	*g*	*LCI*	*UCI*
$MV_{80\%}$	80%	17.80	0.41	16.67	3.85	1.24	0.40	-0.20	1.01
	100%	17.60	0.63	17.20	1.15	1.75	0.42	-0.19	1.03
	120%	17.60	0.91	15.13	3.38	6.40	0.97†	0.34	1.61
$PV_{80\%}$	80%	17.87	0.52	17.07	2.84	1.76	0.38	-0.22	0.99
	100%	17.8	0.56	17.93	0.26	0.65	-0.30	-0.90	0.31
	120%	17.53	0.83	15.27	3.20	8.92*	0.94††	0.31	1.58
$MP_{80\%}$	80%	17.13	2.56	16.2	4.09	0.52	0.27	-0.34	0.87
	100%	17.53	0.74	17.07	1.22	1.78	0.45	-0.16	1.06
	120%	17.67	0.82	14.93	3.75	6.98	0.98††	0.34	1.62
$PP_{80\%}$	80%	14.93	4.61	14.73	4.35	0.02	0.04	-0.56	0.64
	100%	15.00	3.70	14.40	3.07	0.19	0.17	-0.43	0.77
	120%	13.07	4.52	11.93	4.56	0.68	0.24	-0.36	0.85
$MV_{90\%}$	80%	13.60	2.87	12.67	4.39	0.63	0.24	-0.36	0.85
	100%	13.27	4.37	11.27	2.91	2.31	0.52†	-0.09	1.13
	120%	13.20	3.67	8.93	4.77	7.69*	0.98††	0.34	1.61
$PV_{90\%}$	80%	12.80	4.35	11.67	4.45	0.69	0.25	-0.35	0.85
	100%	14.40	3.85	12.13	2.82	6.03	0.65†	0.04	1.27
	120%	11.87	3.96	7.67	3.33	11.63**	1.12††	0.47	1.76
$MP_{90\%}$	80%	12.47	4.69	10.80	4.78	1.71	0.34	-0.26	0.95
	100%	13.40	4.48	10.87	2.85	3.05	0.66†	0.04	1.27
	120%	13.13	3.80	7.53	4.75	15.62**	1.27††	0.61	1.93
$PP_{90\%}$	80%	7.40	4.55	8.33	5.50	0.34	-0.18	-0.78	0.42
	100%	8.13	4.42	6.47	3.31	1.15	0.41	-0.19	1.02
	120%	5.53	2.90	5.47	2.72	0.01	0.02	-0.58	0.62

Note. $MV_{80\%}$ *– Mean velocity 80% threshold;* $PV_{80\%}$ *– Peak velocity 80% threshold;* $MP_{80\%}$ *– Mean power 80% threshold;* $PP_{80\%}$ *– Peak power 80% threshold;* $MV_{90\%}$ *– Mean velocity 90% threshold;* $PV_{90\%}$ *– Peak velocity 90% threshold;* $MP_{90\%}$ *– Mean power 90% threshold;* $PP_{90\%}$ *– Peak power 90% threshold; g – Hedges' g; LCI – lower confidence interval; UCI – upper confidence interval; *(*$p < 0.05$*); ** (*$p < 0.01$*); † (g = 0.5-0.79); †† (g > 0.8).*

Table 9.3 Means and standard deviations, and results of analysis of variance between Rest Redistribution sets (RR) and Traditional sets (TS) in session RPE scores across 80%, 100%, and 120% 1RM.

	RR		TS					
	M	*SD*	*M*	*SD*	*F*	*g*	*LCI*	*UCI*
80%	2.63	0.90	3.37	0.74	9.88**	-0.87††	-1.50	-0.24
100%	3.80	1.00	5.37	1.22	21.54**	-1.37††	-2.04	-0.70
120%	5.97	1.33	7.77	1.15	65.42**	-1.41††	-2.08	-0.74

Note. g – Hedges' g; LCI – lower confidence interval; UCI – upper confidence interval; *($p < 0.05$); ** ($p < 0.01$); † ($g = 0.5\text{-}0.79$); †† ($g > 0.8$).

Discussion

This study was designed to investigate the effectiveness of rest redistribution for maintaining velocity and power output during clean pulls at different loading magnitudes with the aim of functioning as a free ad-hoc alternative to VBT. The major findings from the present study were that RR allowed participants to perform more repetitions above 90 and 80% velocity- and power-loss thresholds for all variables, except $PP_{90\%}$ and $PP_{80\%}$, compared to their respective TS protocols. In addition, the shorter, but more frequent inter-set rest periods during RR generally allowed for greater MVM, MPM, PVM and PPM than TS while also resulting in less MVD, MPD, PVD, PPD and RPE, whereby differences were more prominent as the loading magnitude increased. Therefore, when the long inter-set rest periods of TS were redistributed to create shorter, but more frequent sets, velocity and power were better maintained.

To our knowledge, only two other studies have taken a similar approach to assess the ability of RR to maintain velocity and power output above certain thresholds [144, 179], but those studies used cluster sets inclusive of extra rest periods, did not have a traditional set protocol, and either analysed the effects of a single load over multiple sets or assessed an undetermined number of repetitions per set. The unique approach of this study allowed to assess the ability of RR to potentially serve as an ad-hoc alternative to different velocity- and power-based thresholds (i.e. 90 and 80% loss) using the same number of repetitions and total rest time, over multiple sets and loading magnitudes. In doing so, our data show that participants were able to perform more repetitions during RR above the 90 and 80% thresholds, even more so at higher intensities (Figures 9.2 and 9.3). These findings are somewhat in agreement with a previous study that showed that redistributing total rest to create 36 sets of 1 repetition with 12 s of inter-set rest allowed participants to perform all 36 repetitions of back squat exercise above the 80% velocity-based threshold, but the same did not happen when rest was redistributed to make 9 sets of 4 with 52.5 s of inter-set rest [144]. Although the exercises and loads were different between that study and the present one, it may be possible that rest-redistribution is particularly effective when exaggerating a shorter, but more frequent set concept, yet future studies should be conducted to substantiate such a claim. Additionally, the results of the present study expand on previous findings demonstrating that the differences between RR and TS were more profound when the velocity and power thresholds were stricter (i.e. 90%) and when the external load was greater (i.e. 120% > 100% > 80%).

On a methodological note, when describing how fatiguing certain RT set structures can be, many researchers use the decline of velocity or power to substantiate their claims. These decline variables are often calculated as the absolute or percentage difference between the first and the final repetition [11]. In this manner, decrements in movement velocity and power have been shown to range between 20 and 37% during traditional sets, depending on the exercise and the number of repetitions being performed [11, 12, 30, 31, 58]. However, using only decline calculations that include solely two repetitions, the remaining repetitions between the first repetition and the last are not accounted for, thus possibly resulting in misleading conclusions about how fatiguing an exercise session is. In that regard, it may be more appropriate to use maintenance calculations whereby all repetitions are expressed relative to the best repetition, and then the average decline of all repetitions is taken into consideration. For example, one study reported a decline in velocity and power of 23% during high volume back squats, but when all repetitions were taken into account (i.e. maintenance was calculated), the authors reported a maintenance of 92%, resulting in an average decline of only 8% [11]. Similar findings have been observed in the present study where TS resulted in an MVD and PVD of between 14 and 17% each depending on the intensity, but MVM and MPM were between 92 and 88% each. These differences, especially in decline variables, between the findings could likely be explained by the different exercise and multiple loading magnitudes being used in the present study. Given the large discrepancy between decline and maintenance variables, one should address both, as they may each tell a different story.

On a practical note, the general practice of VBT, the calculation of decline variables, and the calculation of maintenance variables generally assume that that the best repetitions occur at the beginning of a set or a training session. However, this might not always be the case, as can be seen in the present study (Figures 9.2 and 9.3). Although we did not analyse the differences between when participants performed their fastest or most powerful repetition, it generally occurred between the first and third repetitions while some of them had their fifth repetition as their best. This means that although the force-velocity relationship is linear, the repetition-velocity relationship might not always be linear in practice. Therefore, coaches who use VBT should be aware of this, since participants of the present study were trained lifters and rarely had their best repetition as their first. Considering these points, we would like to highlight the importance of not basing fatigue on the first repetition of a training set, but actually identifying the best and the worst repetition, using those and all of the other repetitions within a training session to provide a more holistic objective view on velocity and power output.

Lastly, considering the fact that RR allowed for a better maintenance and lower decline of movement velocity and power output than TS, it was expected that the RPE scores would be lower during RR. As the loading magnitude increased, the present study showed a linear increase of the difference in RPE scores between RR and TS (Table 9.1). Since the RPE has been shown to simultaneously increase as movement velocity decreases when lifting the same load with maximal intent [22, 84], the results of the present study further highlight the relationship between velocity loss during RT and the degree of fatigue. This is not the first study that showed lower perceptual responses while implementing more frequent rest periods as opposed to TS during RT. For example, in one study [22], participants performed three traditional sets of six power cleans using 80% RM with 3 min of inter set rest resulting in RPE scores of 6, 7.5 and 9 after each set. However, RPE scores decreased to 4, 5 and 6 when more frequent rest periods (i.e. after every repetition) were adopted [22]. In the current study, RPE scores progressively increased from T80 (3.37 ± 0.74), T100 (5.37 ± 1.22) to TS120 (7.77± 1.15), and were also decreased when more frequent rest periods were allowed (RR80 (2.63 ± 0.9), RR100 (3.80 ± 1.0) and RR120 (5.97 ± 1.33)). In both studies, the RPE served as an accurate measure of perceived exertion, evidenced by progressive decrements in movement velocity and power as the number of sets or loading magnitude increased. Since the RPE reflected changes in movement velocity and power output, it has been proven again to be a valid tool to determine a degree of fatigue, which is quick and easy to use.

Finally, based on the findings of the present study, the RR protocols seem to allow for a better overall maintenance of velocity than TS at all loads, especially at heavier loads while also ensuring lower perceptual responses of participants. Additionally, although the average number of repetitions performed within the 10 and 20% velocity loss thresholds were greater during RR, individual differences were not compared in this study, and it is possible that certain athletes may fatigue more than others. Nevertheless, this is the first study to show the potential of RR protocols to serve as an ad-hoc alternative to common VBT thresholds. Future research should seek to determine whether different set and repetition schemes, during different exercises and using multiple loading magnitudes, could be associated with different velocity- and/or power-based thresholds in order to provide practitioners, who may not use VBT devices, with benefits of VBT in a more practical way.

The present study shows the ability of RR to maintain movement velocity and power output to a greater extent when compared to TS while performing clean pulls at different loads, especially at higher loads (100 and 120% 1RM). However, RR might not be that beneficial when the protocol is not extremely fatiguing (i.e. 80% 1RM). Furthermore, coaches should be aware that although the force-velocity relationship is linear, the repetition-velocity relationship might not always be in practice. Therefore, caution should be taken while using VBT percentage-based thresholds and other variables which assume the linearity of the repetition-velocity relationship (i.e. 1st repetition is always the best). Lastly, strength and conditioning professionals who wish to implement VBT principles during training, but who do not wish to purchase or use VBT equipment, can likely encourage similar training stimuli by redistributing traditional long inter-set rest periods to create shorter, but more frequent sets.

Chapter 10

The data shown in Chapter 9 showed that RR could function as an ad-hoc equivalent to velocity-based training thresholds that are commonly used in practice, especially at higher loads (100 and 120% 1RM). However, RR might not be that beneficial when the protocol is not extremely fatiguing (i.e. 80% 1RM), which is in line with previous findings whereby rest-redistribution may not be very advantageous compared to traditional sets that were performed further from failure. However, the absolute velocity and power variables were not assessed. Considering the popularity of absolute velocity and power output in research and in training, a manuscript presenting the absolute values would increase the likelihood of adopting this strategy in real-life. Therefore, the purpose of the study in this chapter sought to determine absolute velocity and power output in response to rest-redistribution during clean pulls at different loads. Please note that the formatting has been adjusted from the original manuscript that was accepted in the *Journal of Strength and Conditioning Research* in 2020 to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Traditional three-to-five-minute inter-set rest periods may not be necessary when performing fewer repetitions per set, using cleans pulls as an example

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This study investigated the effects of rest redistribution over multiple repetitions and sets of clean pulls with different loads. Fifteen strength-trained men performed a 1RM power clean and six experimental sessions: 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. All repetitions were recorded using a GymAware linear position transducer, from which peak velocity (PV), peak power (PP), mean velocity (MV), and mean power (MP) were gathered. When all 18 repetitions were averaged together, PV was greater during RR than TS at all loads (80%: 1.74 vs 1.68m/s; 100%: 1.47 vs 1.41m/s; 120%: 1.21 vs 1.16m/s; $p<0.05$), PP was greater at RR100 (1874.6 vs 1732.3W; $p<0.05$) and RR120 (1777.8 vs 1650.4W; $p<0.05$) than TS100 and TS120 respectively, and MP was greater during RR80 (774.2 vs 740.5W; $p<0.05$) and RR100 (806.5 vs 771.5W; $p<0.05$) than TS80 and TS100 respectively. Overall, RR allowed for greater MV, MP, PV and PP than TS within individual sets, with a gradual increase in these differences as the number of sets increased. Therefore, RR generally allowed for greater velocities and power outputs compared to TS, while these differences increased as the number of sets and repetitions increase, especially at greater loads.

Introduction

Rapid force production and muscle power are considered to be two of the determining factors that differentiate the performance between athletes in a variety of sports [140, 184, 185]. Like many sport-related movements, weightlifting movements (i.e. snatch, clean, and jerk) and their derivatives (i.e. clean pull, snatch pull, mid-thigh pull) can be characterized as powerful movements that require rapid force production of the lower limbs. Because of that, it is not surprising that previous research has indicated strong relationships between weightlifting movements and sprinting [186], vertical jump [186, 187], and change of direction ability [186], which is partly why strength and conditioning professionals often prescribe weightlifting movements for their athletes. However, recent literature now suggests that coaches may consider omitting the catch phase and only performing clean and snatch pulling derivatives [174] because: (i) the catch phase has been associated with greater injury rates [174, 188]; (ii) pulling derivatives excluding the catch phase can provide a similar training stimulus [189, 190]; and (iii) athletes may prematurely drop under and try to catch the barbell before fully extending their hips, knees, and ankles during the second pull [174]. With these points in mind and because weightlifting movements have been shown to produce high rates of force development [191, 192], it may be rational for practitioners to emphasize safer alternatives to full weightlifting movements in order to facilitate the greatest transfer to sport performance.

As athletes are often exposed to a continuum of loads during competition, it is suggested to develop the ability to maximize power output across a variety of loads [139]. Thus, it seems logical that pulling derivatives also be performed with various loads to cover a wider range of the force-velocity profile of an athlete [173, 193]. For example, one of the exercises that could be easily incorporated to enhance different portions of the heavy end of the force-velocity curve is the clean pull exercise [182], as athletes produce large ground reaction forces during the first and the second pull of the clean [99, 194], with the greatest forces occurring during the second pull [99]. Furthermore, the finishing position of a clean pull includes full extension at the hip, knee and ankle joints, which may not occur in inexperienced athletes who attempt to catch a clean and do not complete the 2nd pull by prematurely dropping under the bar for the catch. Therefore, the clean pull could be a useful exercise not only for experienced weightlifters, but also for other athletes who do not specialize in weightlifting movements but wish to utilize movement-specific training adaptations that could translate into improved sport performance.

To increase sport performance, a recent trend in the strength and conditioning literature is to limit fatigue during resistance training sessions, which can be objectively assessed by measuring movement velocity. When limiting acute neuromuscular fatigue (i.e. maintaining movement velocity at a given load), greater training adaptations may arise compared to more fatiguing exercises with large decreases in training velocity [176, 178]. Therefore, it would be beneficial to prescribe the clean pull exercise in a way that would maximize and maintain movement velocity throughout an entire exercise session without the need to decrease the barbell load. One strategy to better maintain acute movement velocity is to implement cluster sets where intra-set rest periods are added within a training set alongside standard inter-set rest periods. It has been repeatedly shown that these extra intra-set rest periods ameliorate potential velocity and power decrements often experienced during traditional set structures [11, 195], but as a result, total training time is extended, which might not be always feasible from a practical perspective [11]. In this regard, researchers have investigated other possible alternatives to lengthy cluster sets such as redistributing the total rest time of traditional set structures by abbreviating the inter-set rest and shifting it to include shorter and more frequent rest intervals [122]. This strategy, known as rest redistribution, has been shown to be effective in numerous studies [39, 58, 144] that collectively show that when total rest time is the same, shorter but more frequent rest periods are the most effective for maintaining movement velocity, power output, and acute resistance training performance.

Interestingly, a recent study showed that rest-redistribution may only be advantageous compared to traditional sets that are highly fatiguing [179], meaning that clean pulls performed with different loads may respond differently to rest-redistribution. To our knowledge, only a few studies to date investigated the influence of different set structures on weightlifting movements [12, 13] both of which used cluster set structures that extend total training time allocated for training. For example, Hardee et al. [12] showed greater velocity and power outputs during 3 sets of 6 repetitions of power cleans with a catch during cluster sets structures with 80% of 1 repetition maximum (1RM). On the other hand, Haff et al. [13] demonstrated greater peak velocities during cluster sets in clean pull exercise without the catch performed at 90% and 120% of 1RM, but only within a single set. Therefore, as the effect of set structure using multiple loads over multiple repetitions and sets of weightlifting movements remains unexplored within the same study, the purpose of this study was to investigate the effects of rest redistribution on kinetics and kinematics over multiple repetitions and multiple sets during the clean pull exercise using different loads in strength-trained men. Based on previous studies using weightlifting movements [12, 13], it was hypothesized that the protocol containing shorter but more frequent rest periods would result in a greater movement velocity and power output than traditional sets, especially when lifting heavier loads.

Methods

Subjects

Fifteen strength-trained men participated in this study (age 28.8 ± 4.48, body mass 89.1 ± 8.7 kg), had at least 1 year of resistance training experience using the power clean and the clean pull exercises, and could power clean at least 90% of their body mass. Participants were excluded if they reported any recent musculoskeletal injuries or were not proficient with either exercise technique. Participants averaged a power clean 1-repetition maximum (1RM) of 99.8 ± 10.8 kg, resulting in a 1RM-to-body-mass ratio of 1.13 ± 0.14. All participants were members of a local gym where Olympic weightlifting movements were commonplace during training, which were always supervised by one of the gym's certified coaches. All procedures were carried out in accordance with the Declaration of Helsinki and all participants gave written informed consent prior to participating.

Experimental approach to the problem

Participants reported to the laboratory for a 1RM power clean session and six experimental sessions, which occurred in a counter-balanced, quasi-randomized order. These experimental sessions included the clean pull exercise for one of the following protocols: 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest (Figure 10.1). Therefore, the protocol designs in this study allowed for the investigation of the effect of different set structures using multiple loads on kinetics and kinematics over multiple repetitions and sets of the clean pull exercise. All experimental sessions were each performed on different days, separated by 48 to 72 hours. For the duration of the study, subjects were instructed to refrain from any type of fatiguing lower body activity for at least 48 hours before each session. All participants were allowed to use weightlifting chalk, but lifting belts and straps were forbidden. All participants successfully completed all 18 repetitions in both protocols during all loading schemes.

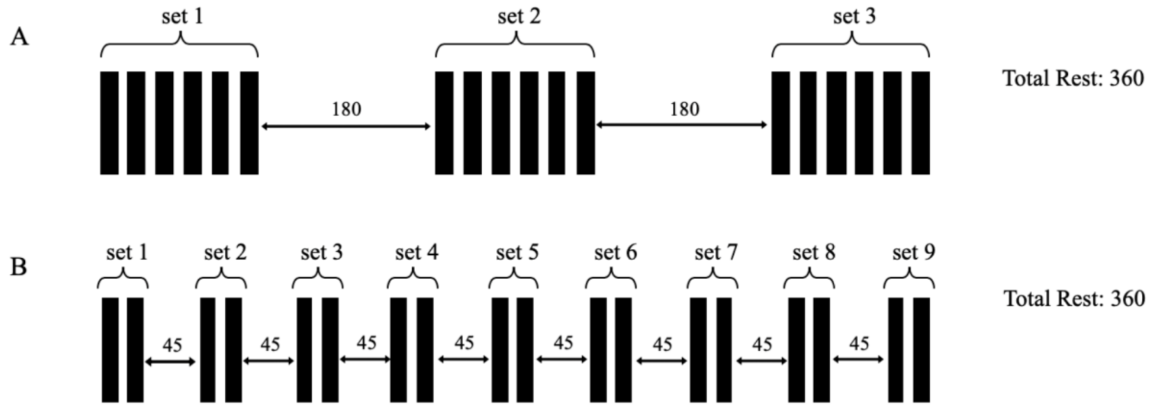

Figure 10.1 Set structure protocols. Traditional sets, 3 sets of 6 with 180 seconds of inter-set rest (panel A). Rest redistribution sets, 9 sets of 2 with 45 seconds of inter-set rest (panel B).

Procedures

Repetition-Maximum Testing: Session 1

Participants refrained from strenuous exercise at least 72 hours before Session 1. During Session 1, participant height and weight were recorded, and they were familiarized with the testing procedures. After a dynamic warmup with a special focus on the hips, shoulders, and wrists (8 to 10 minutes), participants performed 10 barbell front squats followed by 3 power clean repetitions at 50%, 2 power clean repetitions at 70%, and 1 power clean repetition at both 80% and 90% of their estimated power clean 1RM, respectively. Power clean 1RM was then assessed starting at 90% estimated 1RM with 2 to 3 minutes of rest between each successive attempt. The load was progressively increased (2.5 to 10 kg increments) until the 1RM was achieved. If the participant failed an attempt with an increased load, they were given the option to attempt it a second time. However, due to time constraints and to avoid a large number of attempts with decreasing load, no decreases in load were allowed, and if the lift was missed on the second occasion, the load of the last successful attempt was recorded as the 1RM. All participants obtained their actual 1RM in up to 4 maximal trials. Proper technique of the power clean was assessed as discussed previously [180, 181] by the research personnel (certified weightlifting coach). The position of the toes and heels were based upon chalk drawings for each participant's self-selected stance width, and this position was measured to ensure identical starting stances for each repetition during all sessions.

Experimental Testing: Sessions 2-7

During these sessions, the participants performed the clean pull exercise for that session's respective protocol with loads that were based upon their power clean 1RM. The warm-up consisted of the same dynamic warm-up as Session 1, after which the participants performed a set of 5, 4, 3, 2 and 1 repetition at 50, 60, 70, 80 and 90% of the actual load that they had to perform that day (i.e. 80, 100 or 120% of their 1RM power clean), respectively. Therefore, the loads during the warm-ups were not identical across sessions, but instead were standardized according to the load that was to be used during each respective session. A schematic view of the described set structures and their respective loads can be seen in Figure 10.1.

As all of the participants were well-versed in the clean pull exercise, no specific instructions were warranted for the subjects other than standard verbal coaching cues. For example, when appropriate, participants were instructed to avoid initiating the first pull (from the floor) too forward on the balls of the feet and toes, and to maintain the angle of the torso to the floor. In the event that a lifter failed to keep the bar close to the body while transitioning the bar from the knee to the power position, the lifter was reminded to always pull “up and into the body” keeping the bar as close to the body as possible [182]. All participants were instructed to execute triple extension of the hips, knees, and ankle aggressively and as fast as possible, with strong verbal encouragement provided throughout all trials. However, participants did not receive any verbal or visual feedback regarding the velocity of each repetition during the sessions.

During the experimental sets, participants were required to avoid bouncing the loaded barbell off of the floor when transitioning from one repetition to the next by implementing a 1-second pause with the barbell on the floor, starting each consecutive repetition with their original setup as determined by the investigators for a repetition to be considered successful. However, there were no repetitions that the investigators deemed unsuccessful, indicating that the experienced participants maintained their clean pull technique and the 1-second pause throughout the entire experiment. During all repetitions, the feet were required to maintain contact with the floor (i.e. no jumping) while allowing the barbell to reach its maximal height at the conclusion of each repetition to ensure full extension of the ankle, knee and hip joint.

Data Acquisition and Preparation

A Gymaware (GymAware Power Tool, Kinetic Performance Technologies, Canberra, Australia) linear position transducer device was used to measure mean concentric velocity (MV), peak concentric velocity (PV), mean power output (MP), and peak power output (PP) during all repetitions throughout the sessions. The device consists of a power tool, made up of a steel cable that is wound on a cylindrical spool coupled to the shaft of an optical encoder. The power tool unit was placed on the right side of the barbell, between the hands and the loaded sleeves, according to the manufacturer's instructions, and the end of the cable was attached to the barbell using a Velcro strap. Gymaware measures the total displacement of its cable in response to changes in the barbell position and incorporates an angle sensor that enables motion in the horizontal plane to be accounted for in vertical displacement measurements. The Gymaware software later accounts for the total distance and angle, and using basic trigonometry, provides a resultant vertical displacement [196]. Within the Gymaware software, the displacement data were time-stamped at 20 millisecond time points and down-sampled to 50Hz for analysis [183]. The sampled data were not filtered. Instantaneous velocity was determined as the change in barbell position with respect to time, which is also directly measured in the Gymaware software. Acceleration data were automatically calculated as the change in barbell velocity over the change in time for each consecutive data point. The device's software also determined instantaneous force by multiplying the barbell mass with acceleration. Power was then calculated as the product of force and velocity. Data obtained from the Gymaware were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the Gymaware v2.4.1 app, and to the Gymaware online cloud before being exported to Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and prepared for further analysis. The device does not require to be externally calibrated, as it automatically calibrates upon powering on the device and zeroing its position.

Although the number of repetitions was the same during RR and TS, the number of repetitions per set differed between RR (2 repetitions per set) and TS (6 repetitions per set) structures (Figure 10.1). Therefore, an ad-hoc decision was made for RR sets 1 to 3, 4 to 6, and 7 to 9 to be grouped together to create "three chronological sets of six repetitions" for the sake of comparing 3 RR sets (although technically 9 sets total) to 3 TS sets. Another ad-hoc decision was also made to not analyse all 18 repetitions within each protocol independently, but to collapse repetitions similar to previous research using a very similar design [12]. For example, repetitions 1, 7, and 13 were collapsed together; repetitions 2, 8, and 14 were collapsed together; and this process continued until "one collapsed set of six repetitions" was created. By collapsing data into thee chronological sets and one collapsed set of six repetitions, it is possible to determine what is happening over time (sets) and on a repetition-by-repetition basis within each set without the need for a 2 x 18 repeated measures ANOVA, which could possibly wash out any potential differences between the protocols.

Statistical Analyses

All data were normally distributed as determined by the Shapiro-Wilk test of normality. Means and SDs were calculated for all mechanical variables. As the purpose of this study was to compare the effect of set structure on force, velocity, and power at different loads, the three loads used were not compared against each other, but can instead be viewed as three separate experiments. Therefore, for each variable, a repeated-measures analysis of variance (ANOVA) was used to compare the mean values of all 18 repetitions per protocol. To compare each mechanical variable across the "three chronological sets of six repetitions", individual 2 × 3 (set structure × set) repeated measures ANOVA were carried out for each load. To compare each variable across individual repetitions in the "one collapsed set of six repetitions" a 2 × 6 (set structure x repetition) repeated measures ANOVA was carried out for each load.

When significant main effects or interactions were obtained, a Holm's Sequential Bonferroni follow-up test was performed to control for type I error and assess pairwise comparisons. Furthermore, partial eta-squared η_p^2 was reported as a measure of effect size for the ANOVAs whereas Hedge's g effect sizes with 95% confidence intervals (95%CI) were used to determine a practically relevant magnitude of difference of the pairwise comparisons of main effects. Hedge's g was used in preference of Cohen's d in order to account for the small sample size ($n < 20$). The magnitude of difference was determined with the criteria: small (0.2 – 0.49), moderate (0.5 – 0.79) and large (> 0.8) respectively [197]. To avoid an unnecessarily large number of effect sizes, only moderate and large effects are reported and discussed. An a priori level of significance was set at $p < 0.05$ for all tests. All statistical analyses were performed using SPSS version 23.0 (IBM, Armonk, NY, United States).

Results

Mean ± SDs for MV, MP, PV and PP are presented in Table 10.1. When all repetitions during a single protocol were averaged together, RR80 allowed for greater MV ($p = 0.023$), MP ($p = 0.023$), PV ($p = 0.045$) but not PP ($p = 0.289$) than TS80. In addition, MP ($p = 0.016$), PV ($p = 0.013$) and PP ($p = 0.016$) were greater during RR100 than TS100, but no differences were observed for MV ($p = 0.160$). While the differences in MV ($p = 0.063$) and MP ($p = 0.071$) were not present between RR120 and TS120, greater PV ($p = 0.011$) and PP ($p = 0.009$) were observed during RR120.

When analyzed across the three chronological sets of six repetitions, there was no set structure × set interaction for MV ($p = 0.244$; $\eta_p^2 = 0.097$), PV ($p = 0.359$; $\eta_p^2 = 0.071$), MP ($p = 0.425$; $\eta_p^2 = 0.051$), or PP ($p = 0.373$; $\eta_p^2 = 0.068$) at 80% 1RM. However, there was a main effect of set structure with RR80 resulting in greater MV ($p = 0.023$; $\eta_p^2 = 0.318$), PV ($p = 0.045$; $\eta_p^2 = 0.256$), and MP ($p = 0.023$; $\eta_p^2 = 0.318$) than TS80, but PP was not different between TS80 and RR80 ($p = 0.289$; $\eta_p^2 = 0.80$) (Table 10.2). At 100% 1RM, there was no set structure × set interaction for MV ($p = 0.676$; $\eta_p^2 = 0.028$), PV ($p = 0.719$; $\eta_p^2 = 0.023$), MP ($p = 0.740$; $\eta_p^2 = 0.021$), or PP ($p = 0.975$; $\eta_p^2 = 0.002$). However, there was a main effect for set structure with RR100 resulting in greater PV ($P = 0.013$; $\eta_p^2 = 0.368$), MP ($p = 0.016$; $\eta_p^2 = 0.348$), and PP ($p < 0.001$; $\eta_p^2 = 0.645$), but MV was not different between TS100 and RR100 ($p = 0.160$; $\eta_p^2 = 0.136$) (Table 10.2). At 120% 1RM, there was a set structure × set interaction with RR120 allowing for greater MV ($p = 0.009$; $\eta_p^2 = 0.285$), PV ($p = 0.017$; $\eta_p^2 = 0.252$), MP ($p = 0.004$; $\eta_p^2 = 0.323$), and PP ($p < 0.0001$; $\eta_p^2 = 0.181$) than TS120. There was also a main effect of set structure with RR120 allowing for greater PV ($p = 0.011$; $\eta_p^2 = 0.379$) and PP ($p = 0.009$; $\eta_p^2 = 0.395$) than TS120, but MV ($p = 0.063$; $\eta_p^2 = 0.226$) and MP ($p = 0.071$; $\eta_p^2 = 0.214$) were not different between TS120 and RR120 (Table 10.2).

When analyzing across the one collapsed set of six repetitions, there was a set structure × repetition interaction at 80% 1RM for MV ($p < 0.001$; $\eta_p^2 = 0.366$), PV ($p < 0.001$; $\eta_p^2 = 0.351$), MP ($p < 0.001$; $\eta_p^2 = 0.307$), and PP ($p = 0.002$; $\eta_p^2 = 0.232$), all in favour of RR80 over TS80 (Table 10.3; Table 10.4). There was also a main effect of set structure with greater MV ($p = 0.023$; $\eta_p^2 = 0.318$), PV ($p = 0.045$; $\eta_p^2 = 0.256$), and MP ($p = 0.023$; $\eta_p^2 = 0.318$) being observed during RR80, but PP was not different between TS80 and RR80 ($p = 0.289$; $\eta_p^2 = 0.080$) (Table 10.3; Table 10.4). At 100% 1RM, there was a set structure × repetition interaction for MV ($p < 0.001$; $\eta_p^2 = 0.421$), PV ($p < 0.001$; $\eta_p^2 = 0.404$), MP ($p < 0.001$; $\eta_p^2 = 0.427$), and PP ($p < 0.001$; $\eta_p^2 = .386$), all in favour of RR100 over TS100 (Table 10.3; Table 10.4). There was also a main effect of set structure with greater PV ($p = 0.013$; $\eta_p^2 = 0.368$), MP ($p = 0.016$; $\eta_p^2 = 0.348$), and PP ($p < 0.001$; $\eta_p^2 = 0.645$) during RR100, but MV was not different between TS100 and RR100 ($p = 0.160$; $\eta_p^2 = 0.136$) (Table 10.3; Table 10.4). Similarly, at 120% 1RM, there was a set structure × repetition interaction for MV ($p < 0.001$; $\eta_p^2 = 0.581$), PV ($p < 0.001$; $\eta_p^2 = 0.620$), MP ($p < 0.001$; $\eta_p^2 = 0.578$), and PP ($p < 0.001$; $\eta_p^2 = 0.405$) in favour of RR (Table 10.3; Table 10.4). There were no significant main effects of set structure for MV ($p = .063$; $\eta_p^2 = 0.226$)

or MP ($p = 0.071$; $\eta_p^2 = 0.214$), but greater PV ($p = 0.011$; $\eta_p^2 = 0.379$) and PP ($p = 0.009$; $\eta_p^2 = 0.395$) were observed during RR120 compared to TS120 (Table 10.3; Table 10.4).

Table 10.1 Means ± SDs for Velocity and Power for all 18 repetitions averaged within each protocol, P (Effect Size (95%CI)).

	Load (%1RM)	**RR**	**TS**	***P* (*Hedge's g* (95%CI))**
MV (m/s)	80%	0.97 ± 0.08*†	0.93 ± 0.08	0.023 (0.50 (-0.23, 1.22))
	100%	0.81 ± 0.09	0.79 ± 0.07	0.160 (0.31 (-0.41, 1.03))
	120%	0.67 ± 0.08	0.61 ± 0.10	0.063 (0.28 (-0.44, 1.00))
MP (W)	80%	774.2 ± 107.2*	740.5 ± 102.3	0.023 (0.31 (-0.41, 1.03))
	100%	806.5 ± 100.2*	771.5 ± 82.8	0.016 (0.37 (-0.35, 1.09))
	120%	782.7 ± 89.0	751.1 ± 103.4	0.071 (0.32 (-0.40, 1.04))
PV (m/s)	80%	1.74 ± 0.16*	1.68 ± 0.15	0.045 (0.40 (-0.29, 1.16))
	100%	1.47 ± 0.15*	1.41 ± 0.12	0.013 (0.44 (-0.29, 1.16))
	120%	1.21 ± 0.13*	1.16 ± 0.15	0.011 (0.35 (-0.37, 1.07))
PP (W)	80%	1814.9 ± 357.1	1754.2 ± 201.8	0.289 (0.20 (-0.51, 0.92))
	100%	1874.6 ± 267.5**†	1732.3 ± 250.4	0.0001 (0.54 (-0.19, 1.26))
	120%	1777.8 ± 226.1*†	1650.4 ± 249.1	0.009 (0.52 (-0.21, 1.25))

Abbreviations: RR, rest redistribution protocol; TS, traditional set; MV, mean velocity; PV, peak velocity; MP, mean power; PP, peak power; 95%CI, 95% confidence intervals.

*(P < .05); significantly greater than traditional set

**(P < .001); significantly greater than traditional set

†(g = 0.5-0.79); moderate effect size (differences)

Table 10.2 Means ± SDs and effect sizes (95%CI) for Velocity and Power for all 3 sets within each protocol.

	Load (% 1RM)	**Set 1** **RR – TS; *Hedge's g* (95% CI)**	**Set 2** **RR – TS; *Hedge's g* (95% CI)**	**Set 3** **RR – TS; *Hedge's g* (95% CI)**
MV (m/s)	80	0.96±0.09 – 0.93±0.10; 0.29 (-0.43, 1.01)	0.98±0.09* – 0.93±0.08; 0.59 (-0.15, 1.32)†	0.98±0.09 – 0.92±0.09; 0.58 (-0.15, 1.31)†
	100	0.81±0.09 – 0.79±0.06; 0.25 (-0.47, 0.97)	0.81±0.08 – 0.78±0.08; 0.37 (-0.36, 1.09)	0.82±0.10 – 0.79±0.08; 0.28 (-0.44, 1.00)
	120	0.67±0.07 – 0.65±0.09; 0.16 (-0.58, 0.88)	0.66±0.08 – 0.64±0.10; 0.24 (-0.48, 0.96)	0.67±0.09* – 0.63±0.11; 0.40 (-0.32, 1.12)
PV (m/s)	80	770.9±112.6 – 746.7±112.5; 0.29 (-0.43, 1.01)	775.6±102.3 – 738.0±96.0; 0.46 (-0.27, 1.18)	776.8±110.8 – 736.7±108.4; 0.41 (-0.31, 1.14)
	100	801.5±103.9 – 771.0±74.7; 0.46 (-0.27, 1.18)	804.7±95.4 – 765.0±84.8; 0.47 (-0.26, 1.19)	813.2±106.9 – 778.4±94.7; 0.36 (-0.36, 1.08)
	120	781.4±85.9 – 766.3±105.2; 0.17 (-0.55, 0.88)	779.2±92.5 – 750.3±105.8; 0.33 (-0.39, 1.05)	787.5±92.9 – 736.6±108.6; 0.48 (-0.25, 1.20)
MP (W)	80	1.74±0.15 – 1.69±0.14; 0.20 (-0.51, 0.92)	1.74±0.16 – 1.67±0.15; 0.37 (-0.35, 1.09)	1.75±0.17 – 1.68±0.15; 0.36 (-0.37, 1.08)
	100	1.46±0.15 – 1.39±0.12; 0.33 (-0.39, 1.05)	1.47±0.14 – 1.40±0.12; 0.43 (-0.30, 1.15)	1.48±0.16 – 1.42±0.12; 0.34 (-0.38, 1.06)
	120	1.20±0.12 – 1.18±0.14; 0.15 (-0.56, 0.87)	1.20±0.13 – 1.16±0.14; 0.28 (-0.44, 1.00)	1.23±0.14* – 1.15±0.17; 0.49 (-0.24, 1.22)
PP (W)	80	1806.7±333.7 – 1773.0±206.2; 0.12 (-0.60, 0.83)	1804.8±380.2 – 1745.4±209.7; 0.19 (-0.53, 0.91)	1833.3±369.7 – 1744.3±209.1; 0.29 (-0.43, 1.01)
	100	1842.4±255.8* – 1696.3±264.8; 0.55 (-0.18, 1.27)†	1876.9±278.0* – 1733.6±257.6; 0.52 (-0.21, 1.25)†	1904.5±282.7* – 1766.8±250.9; 0.50 (-0.23, 1.23)†
	120	1776.8±243.2 – 1681.0±288.8; 0.31 (-0.41, 1.03)	1757.8±235.8 – 1650.8±243.3; 0.43 (-0.29, 1.16)	1808.9±245.0** – 1619.5±259.5; 0.73 (-0.01, 1.47)†

Abbreviations: RR, rest redistribution protocol; TS, traditional set; MV, mean velocity; PV, peak velocity; MP, mean power; PP, peak power; 95%CI, 95% confidence intervals.

*(P < .05); significantly greater than traditional set

**(P < .001); significantly greater than traditional set

†(d = 0.5-0.79); moderate effect size (differences)

Table 10.3 Means ± SDs and effect sizes (95%CI) for mean velocity (MV) and mean power (MP) after collapsing repetitions across sets.

		80% 1RM	**100% 1RM**	**120% 1RM**
	Repetitions	**RR – TS; *Hedge's g* (95% CI)**	**RR – TS; *Hedge's g* (95% CI)**	**RR – TS; *Hedge's g* (95% CI)**
MV (m/s)	1	0.96±0.11 – 0.94±0.10; 0.17 (-0.55, 0.89)	0.82±0.08 – 0.81±0.07; 0.03 (-0.68, 0.75)	0.67±0.07 – 0.68±0.07; -0.20 (-0.91, 0.52)
	2	0.97±0.08 – 0.95±0.10; 0.21 (-0.50, 0.93)	0.80±0.10 – 0.82±0.08; -0.18 (-0.89, 0.54)	0.66±0.08 – 0.67±0.10; -0.10 (-0.82, 0.62)
	3	0.96±0.09 – 0.94±0.10; 0.23 (-0.49, 0.94)	0.81±0.09 – 0.79±0.07; 0.27 (-0.45, 0.99)	0.68±0.08 – 0.66±0.10; 0.19 (-0.53, 0.91)
	4	0.98±0.08* – 0.93±0.08; 0.65 (-0.08, 1.38)†	0.81±0.09 – 0.78±0.07; 0.39 (-0.33, 1.11)	0.66±0.09 – 0.63±0.11; 0.30 (-0.42, 1.02)
	5	0.97±0.09 – 0.91±0.09; 0.69 (-0.04, 1.43)†	0.82±0.09 – 0.77±0.08; 0.55 (-0.18, 1.27)†	0.67±0.08* – 0.61±0.12; 0.58 (-0.15, 1.31)†
	6	0.98±0.08** – 0.90±0.09; 1.05 (0.28, 1.81)††	0.81±0.09 – 0.75±0.08; 0.71 (-0.03, 1.45)†	0.66±0.08* – 0.59±0.11; 0.70 (-0.04, 1.43)†
MP (W)	1	767.3±116.4 – 753.3±112.9; 0.12 (-0.60, 0.83)	813.4±101.6 – 801.1±91.8; 0.12 (-0.59, 0.84)	786.1±91.3 – 803.5±82.2; -0.19 (-0.91, 0.52)
	2	777.3±107.2 – 762.3±112.3; 0.13 (-0.58, 0.85)	797.9±100.0 – 804.8±95.9; -0.07 (-0.78, 0.65)	778.8±89.8 – 789.7±104.2; -0.11 (-0.83, 0.61)
	3	760.7±104.9 – 751.2±117.6; 0.08 (-0.63, 0.80)	803.7±105.6 – 773.0±84.9; 0.31 (-0.41, 1.03)	793.4±90.9 – 769.8±98.5; 0.24 (-0.48, 0.96)
	4	784.7±108.1* – 739.8±103.3; 0.41 (-0.31, 1.14)	807.0±101.4* – 764.0±91.6; 0.43 (-0.29, 1.16)	775.0±102.7 – 740.2±114.1; 0.31 (-0.41, 1.03)
	5	773.4±116.3 – 722.5±100.2; 0.46 (-0.27, 1.18)	812.8±105.8* – 754.0±79.2; 0.61 (-0.12, 1.34)†	786.8±96.0* – 711.3±124.7; 0.66 (-0.07, 1.40)†
	6	781.7±105.0* – 713.6±90.0; 0.68 (-0.06, 1.41)†	804.2±104.2* – 732.0±74.9; 0.77 (0.03, 1.52)†	776.2±81.6* – 692.0±114.4; 0.82 (0.08, 1.57)††

Abbreviations: RR, rest redistribution protocol; TS, traditional set; MV, mean velocity; MP, mean power; 95%CI, 95% confidence intervals.

*(P < .05); significantly greater than traditional set

**(P < .001); significantly greater than traditional set

†(g = 0.5-0.79); moderate effect size (differences)

††(g > 0.8); large effect size (differences)

Table 10.4 Means ± SDs and effect sizes (95%CI) for peak velocity (PV) and peak power (PP) after collapsing repetitions across sets.

		80% 1RM	**100% 1RM**	**120% 1RM**
	Repetitions	**RR – TS; *Hedge's g* (95% CI)**	**RR – TS; *Hedge's g* (95% CI)**	**RR – TS; *Hedge's g* (95% CI)**
PV (m/s)	1	1.72±0.19 – 1.70±0.18; 0.12 (-0.60, 0.84)	1.47±0.16 – 1.45±0.12; 0.14 (-0.58, 0.86)	1.22±0.11 – 1.24±0.12; -0.18 (-0.90, 0.54)
	2	1.77±0.14 – 1.72±0.17; 0.27 (-0.45, 0.99)	1.47±0.14 – 1.46±0.13; 0.08 (-0.63, 0.80)	1.21±0.12 – 1.22±0.14; -0.05 (-0.76, 0.67)
	3	1.71±0.14 – 1.70±0.15; 0.05 (-0.66, 0.77)	1.46±0.16 – 1.43±0.12; 0.22 (-0.50, 0.94)	1.23±0.14 – 1.19±0.14; 0.28 (-0.44, 1.00)
	4	1.77±0.16* – 1.67±0.15; 0.62 (-0.11, 1.35)†	1.46±0.15 – 1.40±0.12; 0.44 (-0.29, 1.16)	1.20±0.14* – 1.15±0.15; 0.35 (-0.37, 1.07)
	5	1.73±0.17 – 1.66±0.14; 0.40 (-0.32, 1.12)	1.48±0.17** – 1.37±0.13; 0.68 (-0.06, 1.42)†	1.21±0.14** – 1.10±0.17; 0.71 (-0.03, 1.45)†
	6	1.78±0.16* – 1.64±0.14; 0.87 (0.12, 1.62)††	1.48±0.15** – 1.35±0.13; 0.92 (0.16, 1.67)††	1.20±0.13** – 1.08±0.17; 0.72 (-0.01, 1.46)†
PP (W)	1	1767.4±380.4 – 1733.0±263.7; 0.10 (-0.61, 0.82)	1869.7±317.5 – 1802.0±286.6; 0.22 (-0.50, 0.94)	1804.6±269.7 – 1773.5±256.4; 0.11 (-0.60, 0.83)
	2	1824.7±311.5 – 1802.3±234.2; 0.08 (-0.64, 0.80)	1862.2±263.5 – 1812.5±287.3; 0.18 (-0.54, 0.89)	1768.4±224.7 – 1738.1±234.8; 0.13 (-0.59, 0.84)
	3	1751.1±308.5 – 1779.8±226.8; -0.10 (-0.82, 0.61)	1861.8±279.3 – 1773.8±269.8; 0.31 (-0.41, 1.03)	1829.6±259.1 – 1699.0±244.1; 0.50 (-0.22, 1.23)†
	4	1881.4±391.7 – 1730.3±219.3; 0.46 (-0.26, 1.19)	1842.2±258.9** – 1692.0±214.0; 0.62 (-0.12, 1.35)†	1748.7±213.1 – 1656.0±327.1; 0.33 (-0.39, 1.05)
	5	1818.4±431.5 – 1751.7±196.9; 0.19 (-0.52, 0.91)	1905.8±281.2** – 1670.4±248.7; 0.86 (0.11, 1.61)††	1780.6±264.3** – 1520.4±257.2; 0.97 (0.21, 1.73)††
	6	1846.8±368.3 – 1728.3±170.2; 0.40 (-0.32, 1.12)	1905.9±260.1** – 1642.9±267.4; 0.97 (0.21, 1.73)††	1735.0±216.7** – 1515.5±281.0; 0.85 (0.10, 1.60)††

Abbreviations: RR, rest redistribution protocol; TS, traditional set; PV, peak velocity; PP, peak power; 95%CI, 95% confidence intervals.

*($P < .05$); significantly greater than traditional set

**($P < .001$); significantly greater than traditional set

†($d = 0.5$-0.79); moderate effect size (differences)

††($d > 0.8$); large effect size (differences)

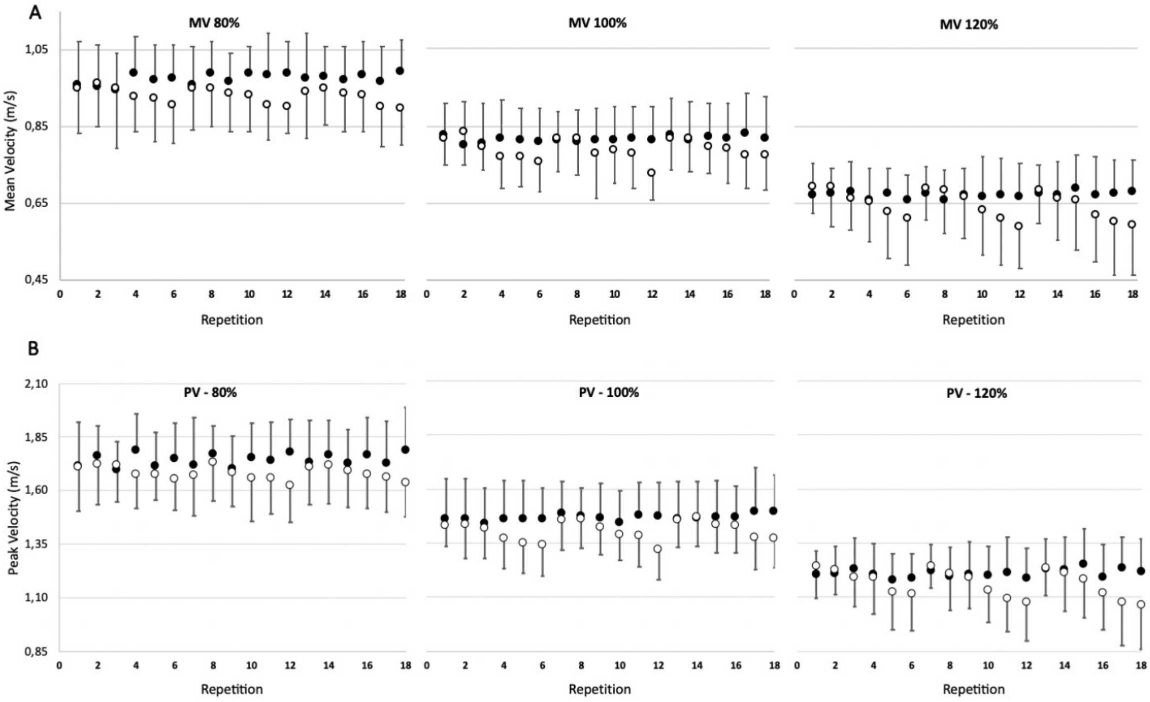

Figure 10.2 Means and standard deviations during rest redistribution sets at 80%, 100% and 120% intensity (RR80, RR100, RR120), and traditional sets at 80%, 100% and 120% intensity (TS80, TS100, TS120) across 18 repetitions for: mean velocity output (panel A) and peak velocity output (panel B). Open circles indicate velocity data for TS while closed circles represent velocity data for RR protocols. For the sake of simplicity, power data is not shown, as it followed the exact same pattern as velocity.

Discussion

The purpose of this study was to determine the effects of rest redistribution on kinetic and kinematic variables over multiple repetitions within multiple sets during a clean pull exercise. The main findings of the present study were that RR generally resulted in greater velocities and power outputs when: (i) analysing all sets and repetitions together (Table 10.1); (ii) analysing collapsed sets and repetitions (Table 10.2); and (iii) observing all repetitions in isolation (Table 10.3; Table 10.4). These differences were generally more pronounced at 100% and 120% 1RM, indicating that rest-redistribution may be more important when using heavier loads or when training may be more fatiguing.

Contrary to much of the cluster set and rest-redistribution literature, our study showed that rest-redistribution may not be as effective at maintaining performance as many believe, especially when compared to less-fatiguing traditional sets. In agreement with our study, a recent study [179] showed that when TS protocols are not extremely fatiguing (i.e. not performed to or near failure), like during TS80 and RR80 in the present study, rest-redistribution may not be as advantageous as it is compared to highly fatiguing traditional set structures that require a greater total effort. Compared to TS80, RR80 only allowed for greater MV during the second and the third set of the clean pull exercise while MP, PV and PP remained similar between the protocols. Although differences in MV, PV and MP were observed in favour of RR when averaging all 18 repetitions during both protocols, PP was similar between RR and TS. Since the clean pull is a ballistic power-based movement which consists of an acceleration and a phase where the barbell still travels up despite the legs being fully extended (i.e. after the shrug, especially if the elbows bend), MV and MP might not be the best variables to assess performance since the bar can continue to travel upwards even after triple extension. Therefore, following the second pull and shrug, there is a period where the barbell travels upwards during which the muscles do not play a large role in generating force near the barbell’s apex, before it begins to descend toward the ground. In addition, the first pulling phase of a clean or clean pull exercise is considerably slower than the second pull phase where the peak velocity occurs [198], thus possibly skewing the MV and MP data, especially at lower intensities (i.e. 80% 1RM) which allow for greater PV to occur. Therefore, although MV and MP may not be ideal for describing clean pull performance at 80% 1RM, these mean variables might be appropriate during heavier clean pulls (i.e. 100 and 120% 1RM) that have less of a ballistic phase and slower movement velocities, mimicking more of a heavy deadlift [198] than a lighter jump shrug. Therefore, it is important to keep in mind that PV and PP should be the main variables of interest when comparing protocols at lighter loads, which can later be complemented with MV and MP when the external load is increased and the ballistic phase of the lift is reduced or eliminated.

Generally, participants in the present study exhibited greater MV, MP, PV and PP within individual sets during the RR protocols (Table 10.2). Although significant set structure x set interactions were not present for any of the mechanical variables during 80 and 100% 1RM, the magnitude of difference was still in favour of RR over TS structures during 80% (MV: $\eta p^2 = 0.318$; MP: $\eta p^2 = 0.256$ and PP: $\eta p^2 = 0.318$) and 100% (PV: $\eta p^2 = 0.318$; MP: $\eta p^2 = 0.256$ and PP: $\eta p^2 = 0.318$). In addition, these differences tended to be greater as the protocol continued: a finding that is unique to this study, as previous studies did not investigate different set structures over multiple sets with multiple loads [12, 13]. These findings are somewhat supported by Hardee et al. [12] who showed a significantly greater MV and PV during a protocol with more frequent rest periods over each of the three sets of power cleans. Perhaps, differences in the present study between the protocols were not as profound since Hardee et al. [12] implemented both intra-set and inter-set rest periods, thus allowing for greater recovery which led to greater velocity and power outputs. As the number of sets increased, their data also showed a gradual increase in the difference in velocity and power measures between protocols with more frequent rest periods and TS, which was also the case in the present study. Nevertheless, it must be noted that Hardee et al. [12] used only one loading condition (i.e. power clean with 80% 1RM), hence limiting their findings only to that intensity whereas the results of the present study expand on their findings, showing more exaggerated differences at greater intensities (Table 10.2).

This is not the first study to show the individual repetition data during multiple repetitions of the weightlifting movements [12, 13]. For instance, Haff et al. [13] showed significant differences between cluster sets and traditional sets only during the first repetition performing clean pull at 90% of power clean 1RM, whereas the remaining four repetitions within a set remained similar. This is in contrast with the findings of the present study where differences between RR and TS were observed starting with the 4th repetition (Table 10.3; Table 10.4) suggesting that as the number of repetitions increases within a set, velocity and power measures decrease at a greater magnitude. Another study [12] partially supports this contention showing that weightlifters performing power cleans at 80% 1RM experienced PV decrement already at the second repetition, but PV continued to drop in a linear fashion until the end of the set of all 6 repetitions. The earlier onset of fatigue experienced in the study by Hardee et al. [12] may be due to the performance of the power clean exercise as opposed to the less complex clean pull exercise [173] that was performed in the present study. Specifically, participants could overload triple-extension without experiencing the additional stress and complexity of catching the load during every repetition as fatigue develops. Moreover, comparing the effects of different set structures on kinetic and kinematic variables across different exercises and loading magnitudes can be rather difficult. For example, Izquiredo et al. [33] found that velocity starts to significantly decrease after 3, 4, 5, and 7 repetitions (75, 70, 65, and 60% of 1RM, respectively) in the bench press and after 5, 9, 11, and 15 repetitions (75, 70, 65, and 60% of 1RM, respectively) in the back squat when performing a traditional set to failure. Thus, it may be that the onset of velocity and power decrement experienced during various TS protocols is exercise specific, and that during a clean pull exercise, both velocity and power starts to significantly decrease as from the 4th repetition during a set, especially when using heavier loads (Table 10.3; Table 10.4). Therefore, when the planning to perform multiple sets with more than 3 repetitions within a single set, RR should be implemented if the goal of the session and a training phase is to keep the velocity and power outputs as high as possible.

Although not measured in the current study, it can be hypothesized that RR may have enabled enhanced clearance of metabolic by-products and replenishment of phosphagen energy substrates in our study. A series of studies by Gorostiaga et al. [29-31] support this by showing that when the frequency of rest intervals increased, lactate levels were lower and participants maintained power, ATP stores, and PCr stores throughout the exercise session. In addition, as other authors have hypothesized the same while studying other exercises [58, 144] we believe that the increased frequency of rest periods during RR allowed for superior replenishment of ATP and PCr throughout the entire session, resulting in greater movement velocity during latter repetitions of each set compared with TS (Figure 10.2; Table 10.3; Table 10.4), but this idea was not examined during our study. Another thing to consider is that although the total rest time was redistributed to be equal in the present study, we cannot guarantee that all things were equal, as a decrease in velocity would theoretically result in a greater concentric repetition duration, which increases the total work-to-rest ratio. However, given the practical nature of this study, we do not view this as a limitation, but more as a consideration, as the total time of the protocols were similar between subjects and between loads (approximately 8 minutes).

Practical Applications

Weightlifting pulling derivatives, such as the clean pull exercise, are now often implemented in various training phases of an athlete since they allow for similar or greater training adaptations, are less complex and more time efficient with regard to teaching and learning when compared to full weightlifting movements. However, in order to elicit maximal training adaptations, maintaining acute velocity during such exercises is crucial. The current body of evidence supports the redistribution of long inter-set rest periods into shorter but more frequent rest periods when velocity and power maintenance are desired but, no studies have investigated this in weightlifting movements. Based on the results of the present study, RR tends to allow for a greater velocities and power outputs to be achieved within each individual set as opposed to TS, while the more profound differences could be expected as the number of sets and repetitions increase, even more so at higher loading magnitudes. Therefore, if athletes or coaches aim to maintain acute movement velocity and power output over multiple sets of clean pulls, shorter but more frequent rests would be recommended, especially with heavier loads or more fatiguing protocols.

Chapter 11

The data shown in Chapter 10 showed that RR could maintain movement absolute velocity and power output to a greater extent when compared to TS while performing clean pulls at different loads, especially at higher loads (100 and 120% 1RM). However, RR might not be that beneficial when the protocol is not extremely fatiguing (i.e. 80% 1RM), which is in line with previous findings whereby rest-redistribution may not be very advantageous compared to traditional sets that were performed further from failure. However, the clean pull is a technical lift whereby the displacement of the barbell is important. If a lifter could maintain maximal displacement of the barbell while also moving at greater velocities, rest-redistribution would further prove to be beneficial when training weightlifting movements. Therefore, the purpose of the study in this chapter sought to determine the mechanical and perceptual responses to rest-redistribution during clean pulls at different loads. Please note that the formatting has been adjusted from the original manuscript that was published in *Sports Biomechanics* in 2020 to allow for continuity throughout the entire thesis document. The body of the text, the information in the tables and figures, and the references have not been altered in any way.

Acute effects of shorter but more frequent rest periods on mechanical and perceptual fatigue during a weightlifting derivative at different loads in strength-trained men.

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This study investigated the effects of rest redistribution on peak vertical barbell displacement (DISP), concentric repetition duration (CRDI), peak velocity decline (PVD), and perceptual exertion (RPE) over multiple repetitions, sets, and loads during a clean pull exercise. Fifteen strength-trained men performed a one repetition maximum (1RM) power clean session and six experimental sessions that included: 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100), and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. When all 18 repetitions were averaged together, DISP was greater during RR100 ($p = 0.008$; ES = 0.39) and RR120 ($p < 0.001$; ES = 0.56) compared to TS100 and TS120, respectively. In addition, PVD was lower during RR120 than TS120 ($p = 0.008$; ES = 1.18), while CRDI was greater during TS100 ($p = 0.010$; ES = 0.98) and TS120 ($p = 0.003$; ES = 0.89) when compared to RR100 and RR120, respectively. Rest redistribution protocols resulted in lower RPE across the sets at all loads ($p < 0.001$; ES = 1.11-1.24). Rest redistribution generally resulted in lower perceptual as well as mechanical measures of fatigue as evidenced by lower RPE, PVD, CRDI and greater DISP than traditional set structures. These results were accentuated with the increment of the load and the number of sets.

Introduction

It is generally accepted that the expression of muscular power, quantified by measures of force and velocity, is critical in most sports [139]. As a result, practitioners often implement ballistic exercises, weightlifting movements, and weightlifting derivatives, which are often performed with a variety of loads, aiming to increase performance throughout the whole force-velocity spectrum [173, 174, 199]. During various training phases, clean pulls are commonly used as they still focus on rapid force development of the lower limbs but do not include the catch phase, allowing for external training loads greater than the athlete's full clean one repetition maximum (1RM) [173]. Regardless of the external load, performing multiple repetitions consecutively (i.e. traditional sets) with maximal concentric effort is fatiguing, and it leads to decreases in movement velocity, power output, and ultimately vertical barbell displacement [12, 13, 200], all of which are likely unwarranted when the aim is to elicit power training adaptations.

To combat acute fatigue during resistance training with traditional sets that do not include intra-set rest intervals, cluster sets that include short intra-set rest intervals have been shown to be effective in maintaining power, velocity, and vertical displacement of the barbell during weightlifting movements [13, 55]. Although these studies, and others, demonstrate the superiority of cluster sets over traditional sets for maintaining acute performance, the addition of intra-set rest during cluster sets might not always be feasible from a practical perspective since they extend the total training time [11]. Thus, redistributing total rest time to create shorter but more frequent sets has become an interesting strategy for strength and conditioning professionals to offset fatigue during resistance training [201]. However, Torrejón et al. [202] have recently brought this method into question while showing no differences in movement velocity in comparison to a traditional set during strength-oriented resistance training sessions conducted with the bench press exercise. Therefore, it is important to elucidate whether the positive effects on mechanical variables previously reported for cluster set configurations during weightlifting movements could also be observed when the rest redistribution approach is used.

Another important practical tool to gauge the degree of fatigue during resistance training is the self-reported rating of perceived exertion (RPE). The modified OMNI scale for resistance training [203] has been shown to be reliable and representative of training intensity and the degree of fatigue [22, 203, 204], and also been shown to mimic changes in power output during weightlifting movements, making it a good indicator of acute fatigue [22]. Since lower RPE scores have been associated with greater power outputs, movement velocity and vertical barbell displacements [12, 22, 55] set structures that result in low RPE scores may be useful during training that involves weightlifting movements. Lastly, although some studies have already investigated the influence of different set structures on RPE, power outputs, velocity, and the displacement of the barbell during weightlifting movements, those studies used cluster sets inclusive of extra rest periods (i.e. increased total training time).

Although resistance training programs typically include different loads and multiple sets per exercise, the studies that have examined the effect of cluster set configurations on mechanical variables during weightlifting movements have only considered the effects of multiple loads within a single set [13] or a single load over multiple sets [12]. However, the effects of set structure using multiple loads over multiple repetitions and sets remains unexplored within the same study. Therefore, the purpose of this study was to investigate the effects of rest redistribution on changes in peak vertical barbell displacement, concentric repetition duration, peak velocity changes, and RPE over multiple repetitions and multiple sets of the clean pull exercise using different loads in strength-trained men. Based on previous studies [12, 13, 22], it was hypothesized that the protocols containing shorter but more frequent rest periods would result in a more stable peak velocity and greater vertical barbell displacements, while also resulting in lower RPE than traditional sets, especially when lifting heavier loads.

Methods

Experimental Approach to the Problem

Subjects reported to the laboratory for a 1RM power clean session and six experimental sessions, which occurred in a counter-balanced, quasi-randomized order, separated by approximately 48 to 72 hours. The experimental sessions consisted of the clean pull exercise that was performed following one of these protocols: 3 traditional sets of 6 repetitions using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 “rest redistribution” protocols of 9 sets of 2 repetitions using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. Subjects were instructed to avoid any type of fatiguing lower body activity for at least 48 hours before each session. All subjects successfully completed all 18 repetitions in every experimental session.

Subjects

Fifteen strength-trained men participated in this study (age 28.8 ± 4.48 y, body mass 89.1 ± 8.7 kg, power clean 1RM 99.8 ± 10.8 kg, 1RM-to-body-mass ratio 1.13 ± 0.14) and had at least 1 year of resistance training experience using the power clean and the clean pull. All subjects were members of a local gym where weightlifting movements were commonplace during training, which were always supervised by one of the gym’s certified weightlifting coaches. All procedures were carried out in accordance with the Declaration of Helsinki and all subjects gave written informed consent prior to participating.

Repetition-Maximum Testing: Session 1

During Session 1, subjects' height and body mass were recorded, and they were familiarized with the protocols and the 0-10 OMNI-RES scale: a resistance training specific RPE scale [146]. After anthropometric measures, subjects completed a 5-minute stationary cycle warm-up, pedalling at 60 revolutions per minute with 100W resistance. Subjects then performed a dynamic warmup with a special focus on the hips, shoulders, and wrists (8 to 10 minutes), followed by 10 barbell front squats followed and 3, 2, 1, and 1 power clean repetitions at 50%, 70%, 80%, and 90% of their estimated power clean 1RM, respectively. After the estimated 90% repetition, the load was progressively increased until the 1RM was achieved, with 2 to 3 minutes of rest between each successful attempt. The attempt was considered to be successful if the top of the thighs were parallel to the ground or above with the bar properly racked on the shoulders without excessive thoracic flexion. This was visually inspected by one of the investigators examining the performance of the lift from the perpendicular position to the subject. All subjects obtained their actual 1RM in up to 4 maximal trials. Proper technique of the power clean was assessed, as discussed previously [180, 181], by the research personnel (certified weightlifting coach). During this visit, each subject’s foot placement was recorded using chalk outlines and was then maintained for the experimental sessions.

Experimental Testing: Sessions 2-7

The first experimental session took place 48 hours after the 1RM testing. During all experimental sessions, the subjects performed the clean pull exercise with loads corresponding to their power clean 1RM. The warm-up consisted of the same dynamic warm-up as Session 1, after which the subjects performed a set of 5, 4, 3, 2 and 1 repetition at 50, 60, 70, 80 and 90% of the actual load that they had to perform that day (i.e. 80, 100 or 120% of their 1RM power clean). Therefore, the loads during the warm-ups were not identical across sessions, but instead were standardized according to the load lifted during each respective session.

As all of the subjects were well-versed in the clean pull exercise, no specific instructions were warranted for the subjects other than standard verbal coaching cues. For example, when appropriate, subjects were instructed to avoid initiating the first pull (from the floor) too forward on the balls of the feet and toes, and to maintain the angle of the torso to the floor. In the event that a lifter failed to keep the bar close to the body while transitioning the bar from the knee to the power position, the lifter was reminded to always pull "up and into the body" keeping the bar as close to the body as possible [182]. Subjects were instructed to perform the second pull and shrug of the clean pulls aggressively and as fast as possible, with strong verbal encouragement provided throughout all trials. Subjects were required to avoid bouncing the loaded barbell off the floor when transitioning from one repetition to the next by implementing a 1-second pause with the barbell on the floor, starting each consecutive repetition with their original starting position. During all repetitions, the feet were required to maintain contact with the floor (i.e. no jumping), but subjects were instructed to achieve triple extension of the hips, knees, and ankles.

Data Acquisition and Preparation

A linear position transducer (LPT) (GymAware Power Tool, Kinetic Performance Technologies, Canberra, Australia) was used to measure concentric repetition duration (CRD), peak velocity (PV), and peak vertical displacement of the barbell (DISP) during all repetitions. The LPT, which has been previously validated [183], was attached to the right side of the barbell between the hands and the loaded barbell sleeves, according to the manufacturer's instructions. The LPT used in the present study measures the total displacement of its cable in response to changes in the barbell position and incorporates an angle sensor that enables motion in the horizontal plane to be accounted for in vertical displacement measurements. The LPT software later accounts for the total distance and angle, and using basic trigonometry, provides a resultant vertical displacement [196]. Instantaneous velocity was determined as the change in barbell position with respect to time, which is also directly measured in the LPT software. Acceleration data were automatically calculated as the change in barbell velocity over the change in time for each consecutive data point. The device’s software also determined instantaneous force by multiplying the barbell mass with acceleration. Power was then calculated as the product of force and velocity [183]. Data obtained from the LPT were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.4.1 app, and to the online cloud before being exported to Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and prepared for further analysis.

For each protocol, the absolute DISP and CRD were each combined and averaged across all 18 repetitions, allowing the respective RR and TS protocols to be compared on a global level at each load. In addition to these protocol averages, the PV, DISP, and CRD of individual repetitions were each compared relative to each protocol’s best repetition, resulting in 18 data points for each variable. From these relative values, the greatest percent change (a decrease for PV and DISP (PVD and DISPD) and an increase for CRD (CRDI)) was calculated, similar to previous research [12, 201] using the following equation: $[(\text{repetition}_{\text{min}} - \text{repetition}_{\text{max}})/\text{repetition}_{\text{max}}] \times 100$, where $_{\text{min}}$ and $_{\text{max}}$ represent the repetitions where the minimum and maximum value occurred, respectively, for PV, DISP, and CRD. This was done rather than comparing the first and last repetitions, as the first repetition is not always the best and the last repetition is not always the worst.

To simplify the statistical analyses, the 1st, 7th, and 13th repetition were collapsed together, and this process was repeated for the 2nd, 8th, and 14th repetition and so-on, ultimately creating a single set of six collapsed repetitions [12, 58]. By collapsing data into thee chronological sets and one collapsed set of six repetitions, it is possible to determine what is happening over time (sets) and on a repetition-by-repetition basis within each set without the need for a 2 x 18 repeated measures ANOVA, which could possibly wash out any potential differences between the protocols. Lastly, as the number of repetitions per set differed between RR (2 repetitions per set) and TS (6 repetitions per set), RR sets 1 to 3, 4 to 6, and 7 to 9 were grouped together to create “three sets” for the sake comparing 3 RR sets (although technically 9 sets total) to 3 TS sets.

Rating of Perceived Exertion

Familiarization of the RPE scale took place during Session 1 using low and high anchoring procedures as previously described [203]. During sessions 2–7, RPE (0 = no effort, 10 = maximal effort) was obtained after the 6th, 12th, and 18th repetitions. Like previous research using weightlifting movements, these three RPE scores were also averaged together to create an average RPE for each protocol [22].

Statistical Analyses

All data were normally distributed as determined by the Shapiro-Wilk test of normality. For each load, differences between the entire RR and TS protocols were examined using separate repeated-measures analysis of variance (ANOVA) for CRD, DISP, PVD, CRDI, DISPD, and RPE. For each load, differences between RR and TS within the three sets were examined using separate 2 x 3 (set structure x set) repeated measures

ANOVA for PVD and RPE. For each load, differences between RR and TS within the collapsed repetitions were then examined using separate 2 × 6 (set structure x repetition) repeated measures ANOVA for PVD, CRDI, and DISPD.

When significant main effects or interactions were obtained, a Holm's Sequential Bonferroni follow-up test was performed. Furthermore, Hedge's g effect sizes with 90% confidence intervals (90%CI) were used and were interpreted as small (0.2 – 0.49), moderate (0.5 – 0.79), and large (> 0.8) [197]. To avoid an unnecessarily large number of effect sizes, only moderate and large effects are reported and discussed. An a-priori level of significance was set at $p < 0.05$ for all tests. All statistical analyses were performed using SPSS version 25.0 (IBM, Armonk, NY, United States).

Results

Significant interactions and main effects are described in the text, whereas particular p values and effect sizes are shown in Table 11.1. At 80% 1RM, RPE was less during RR80 than TS80, but no differences were present for CRD, DISP, PVD, CRDI, or DISPD (Table 11.1). At 100% 1RM, DISP was greater during RR100, and CRDI and RPE were less during RR100 than TS100 (Table 11.1). At 120% 1RM, DISP was greater during RR120, and CRDI and RPE were less during RR120 than TS120 (Table 11.1). Absolute rep-by-rep data presented in Figure 11.1.

Table 11.1 Means ± SDs for Peak Displacement, Concentric Repetition Duration, Peak Velocity Decline, Peak Displacement Decline, Concentric Repetition Duration Increment, and RPE for all 18 repetitions averaged within each protocol, P (Effect Size (95%CI)).

	Load (%1RM)	**RR**	**TS**	***P* (Hedge's *g* (90%CI))**
DISP (m)	80%	0.91 ± 0.09	0.88 ± 0.07	0.094 (0.30 (-0.31, 0.90))
	100%	0.86 ± 0.07[a]	0.83 ± 0.06	0.008 (0.39 (-0.22, 0.99))
	120%	0.79 ± 0.06[b]†	0.76 ± 0.06	0.0001 (0.56 (-0.05, 1.17))
CRD (s)	80%	0.94 ± 0.07	0.96 ± 0.08	0.169 (-0.32 (-0.93, 0.28))
	100%	1.05 ± 0.09	1.07 ± 0.09	0.195 (-0.23 (-0.84, 0.37))
	120%	1.20 ± 0.15	1.22 ± 0.18	0.449 (-0.10 (-0.70, 0.50))
PVD (m/s)	80%	14.57 ± 3.69†	17.78 ± 7.05	0.062 (-0.56 (-1.17, 0.06))
	100%	14.10 ± 5.23†	17.32 ± 2.50	0.060 (-0.77 (-1.39, -0.14))
	120%	17.52 ± 3.79*††	24.44 ± 7.13	0.008 (-1.18 (-1.83, -0.53))
DISPD (m)	80%	10.35 ± 3.77	9.63 ± 3.33	0.478 (0.20 (-0.41, 0.80))
	100%	9.03 ± 5.06	8.77 ± 2.95	0.835 (0.06 (-0.44, 0.76))
	120%	8.49 ± 4.73	10.84 ± 5.34	0.247 (-0.47 (-1.07, 0.15))
CRDI (s)	80%	15.38 ± 8.33	18.05 ± 8.56	0.364 (-0.31 (-0.91, 0.30))
	100%	13.44 ± 4.60*††	19.94 ± 7.84	0.010 (-0.98 (-1.51, -0.25))
	120%	13.92 ± 6.59*††	20.24 ± 7.28	0.003 (-0.89 (-1.56, - 0.26))
RPE	80%	2.61 ± 0.80*††	3.58 ± 0.84	0.001 (-1.15 (-1.80, -0.50))
	100%	4.29 ± 1.02**††	5.64 ± 1.32	0.0001 (-1.11 (-1.76, -0.47))
	120%	6.50 ± 1.25**††	8.04 ± 1.16	0.0001 (-1.24 (-1.90, -0.59))

Abbreviations: RR, rest redistribution protocol; TS, traditional set; PD, peak displacement; CRD, concentric repetition duration; PVD, peak velocity decline; PDD, peak displacement decline; CRDI, concentric repetition duration increment; RPE, average rate of perceived exertion from three sets.

*(P < .05); significantly lower than traditional set

**(P < .001); significantly lower than traditional set

a(P < .05); significantly greater than traditional set

b(P < .001); significantly greater than traditional set

†(g = 0.5-0.79); moderate effect size (differences)

††(g > 0.8); large effect size (differences)

Set-by-set comparisons

At 80% 1RM, there were no set structure x set interactions for PVD (*p* = .081), DISPD (*p* = .529), CRDI (*p* = .301) or RPE (*p* = .194), but there were significant main effects of set structure with RR80 resulting in less PVD (*p* = .044) and a lower RPE (*p* < .001) than TS80, but similar CRDI (*p* = .299) and DISPD (*p* = .188) (Figure 11.2; Figure 11.3). At 100% 1RM, there were no set structure x set interactions for PVD (*p* = .137), DISPD (*p* = .245), CRDI (*p* = .376) or RPE (*p* = .848), but there were significant main effects of set structure with RR100 resulting in less PVD (*p* = 0.019), CRDI (*p* = .023) and lower RPE (*p* < .001) than TS100 whereas DISPD remained similar (*p* = .483) (Figure 11.2; Figure 11.3). At 120% 1RM, there were no set structure x set interactions for PVD (*p* = .938), DISPD (p = .428), CRDI (*p* = .135) or RPE (*p* = .331), but there were main effects of set structure with RR120 resulting in less PVD (*p* < .001), CRDI (*p* = .135), DISPD (*p* = .010) and lower RPE (*p* < .001) than TS120 (Figure 11.2; Figure 11.3).

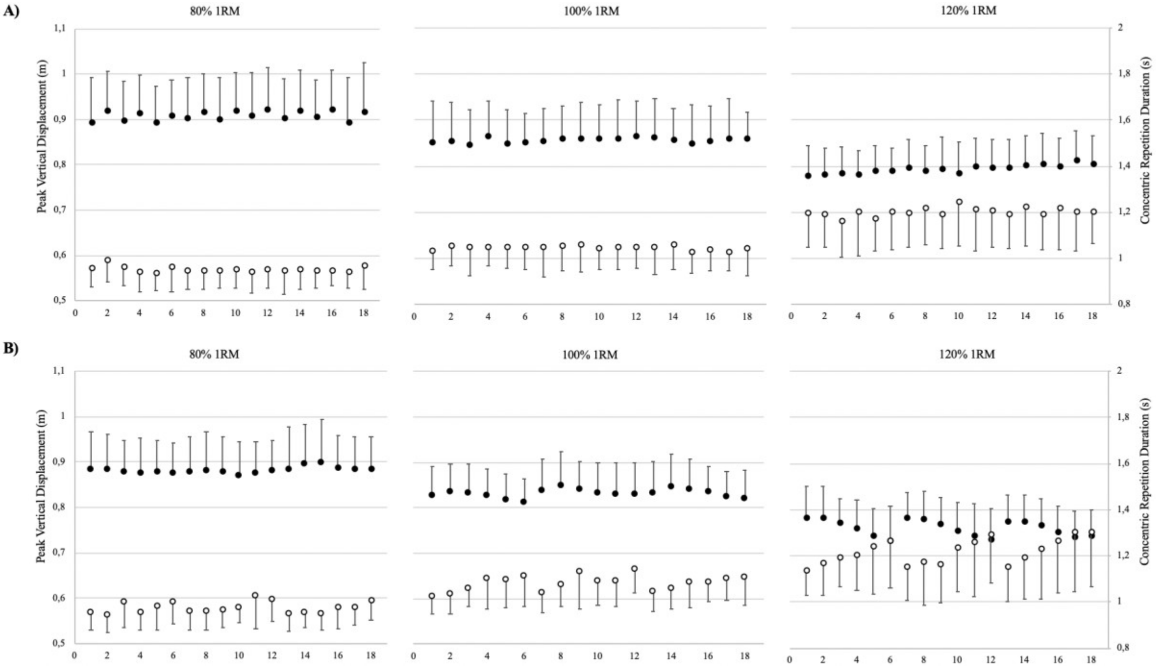

Figure 11.1: Means and standard deviations across 18 repetitions for concentric repetition duration (open circles) and peak vertical displacement (closed circles) data during: rest redistribution sets (panel A) at 80%, 100% and 120% intensity (RR80, RR100, RR120), and traditional sets (panel B) at 80%, 100% and 120% intensity (TS80, TS100, TS120).

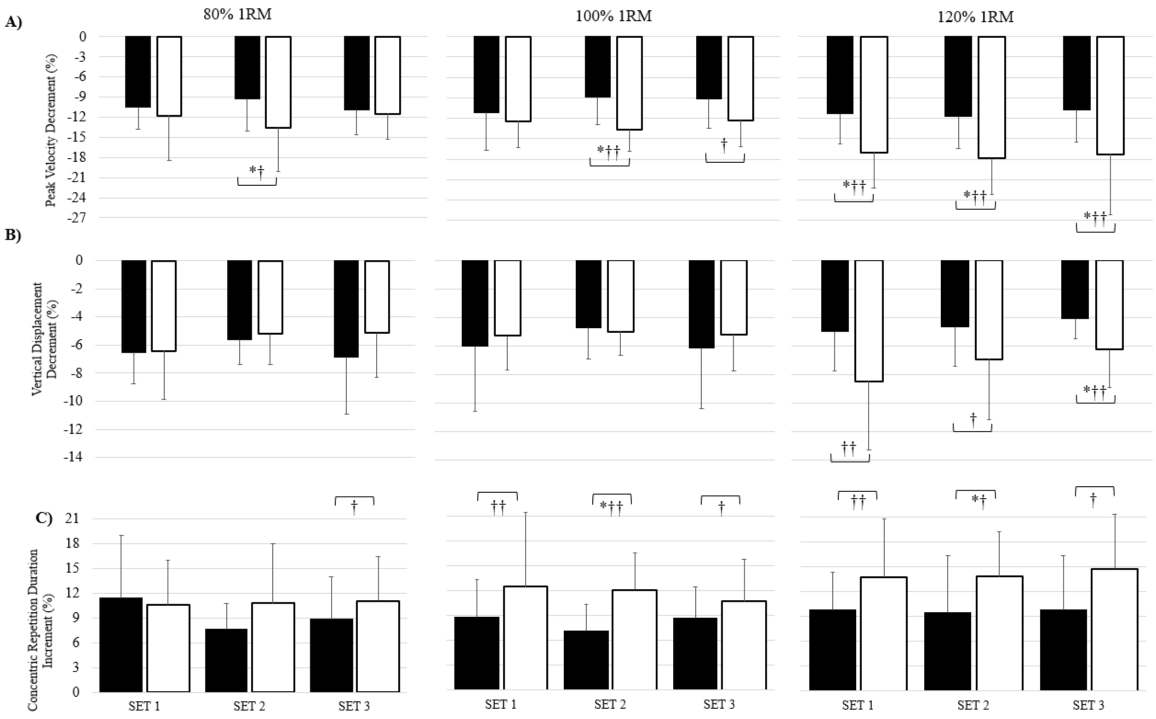

*Figure 11.2: Means and standard deviations across 3 sets for peak velocity decrement (panel A), peak vertical displacement decrement (panel B), and concentric repetition duration increment (panel C) data during: rest redistribution sets (closed rectangles) at 80%, 100% and 120% intensity (RR80, RR100, RR120), and traditional sets (open rectangles) at 80%, 100% and 120% intensity (TS80, TS100, TS120). * significantly less than TS (P < .05); † moderate effect size (g = 0.5 -0.79); †† large effect size (g > 0.8).*

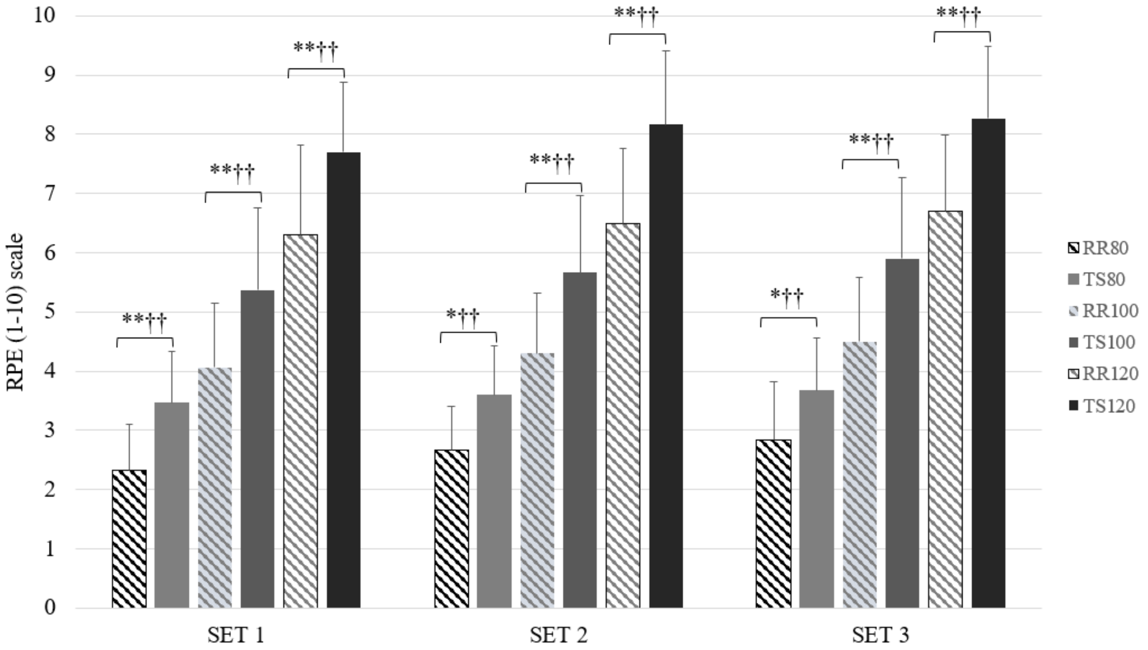

*Figure 11.3: Means and standard deviations across 3 sets for rating of perceived exertion (RPE) during: rest redistribution sets (rectangles with diagonal stripes) at 80%, 100% and 120% intensity (RR80, RR100, RR120), and traditional sets (closed rectangles) at 80%, 100% and 120% intensity (TS80, TS100, TS120). * significantly less than TS (P < .05); ** significantly less than TS (P < .001); † moderate effect size (g = 0.5 -0.79); †† large effect size (g > 0.8).*

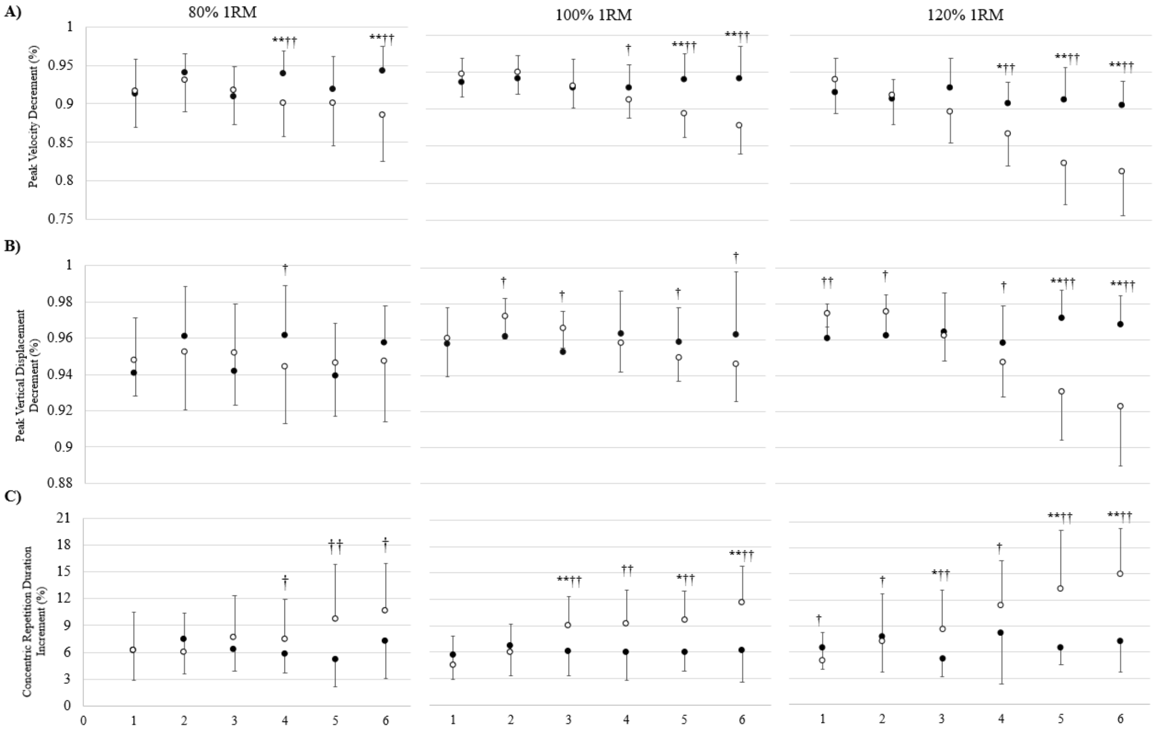

Figure 11.4: Means and standard deviations for 6 collapsed repetitions (i.e. the 1st, 7th, and 13th repetition etc) for peak velocity decrement (panel A), peak vertical displacement (panel B), and

*concentric repetition duration increment (panel C) data during: rest redistribution sets (closed circles) at 80%, 100% and 120% intensity (RR80, RR100, RR120), and traditional sets (open circles) at 80%, 100% and 120% intensity (TS80, TS100, TS120). * significantly less than TS (P < .05); ** significantly less than TS (P < .001); † moderate effect size (g = 0.5 -0.79); †† large effect size (g > 0.8).*

Repetition-by-repetition comparisons

At 80% 1RM, there were set structure x repetition interactions for PVD (*p* < .001), DISPD (*p* = .010), and CRDI (*p* < .001), all in favour of RR80 over TS80 (Figure 11.4). However, main effects of set structure were not observed for PVD (*p* = .078), DISPD (*p* = .798), or CRDI (*p* = .136). At 100% 1RM, there were set structure x repetition interactions for PVD (*p* < .001), DISPD (*p* < 0.001), and CRDI (*p* < .0001) all in favour of RR100 over TS100 (Figure 11.4). Main effects of set structure were not observed for DISPD (*p* = .962), but main effects of set structure were observed for PVD (*p* = .016) and CRDI (*p* =.009) with lower values during RR100. At 120% 1RM, significant set structure x repetition interactions were observed for PVD, CRDI, and DISPD (*p* < .001) in favour of RR120 over TS120 (Figure 11.4). Main effects of set structure were not observed for DISPD (*p* = .070), but main effects for set structure were observed for PVD (*p* < .001) and CRDI (*p* = .002) with lower values during RR120.

Discussion

This study investigated the effects of rest redistribution on mechanical and perceptual measures of fatigue during clean pulls at different loads. Although there were no interactions present in this study, the pattern of fatigue was different between TS and RR. The results demonstrate the effectiveness of shorter but more frequent rest periods on fatigue management during latter repetitions, supported by lower PVD, CRDI, and RPE during clean pulls at different loads, where these differences between RR and TS were even more prominent as the external load increased. In addition, although DISPD was similar between RR and TS, RR allowed for greater DISP and lower CRD of the barbell at all loads, which supports the notion of performing fewer repetitions per set in order to maintain acute resistance training performance.

Considering the performance aspects of weightlifting movements, maintaining mechanical outputs is important for inducing the proper training stimulus which ultimately leads to improved performance. [13, 55, 99]. We observed an interesting inverse relationship between CRD and DISP during TS where CRD progressively increased from repetition to repetition and DISP progressively decreased, especially at heavier loads (Figure 11.1B). As CRD and DISP remained fairly stable across sets at all loads during RR (Figure 11.1B), the data indicate that performing two repetitions at a time maintains mechanical performance better than performing six repetitions at a time, even when the total rest time is equal and the inter-set rest periods are shorter. Previous research has shown that adding extra intra-set rest periods plays a role in maintaining technique and decreasing fatigue during power cleans [55] and maintaining mechanical outputs during clean pulls [13]. However, the former study included 20 and 40 seconds of extra inter-repetition rest periods and the latter study did not control total rest time but stated that subjects had an extra 15 to 30 seconds of inter-repetition rest. In either case, it is important to note that cluster set structures (add extra rest periods) would drastically increase total training time if performed throughout an entire session, which may not always be warranted or possible [11]. Therefore, our study is the first to show that the performance during weightlifting movements can be enhanced using shorter and more frequent rest periods without increasing total training time: a finding that was accentuated as the number of repetitions increased at heavier loads (Figure 11.2; Figure 11.4).

Over the last decade, researchers have begun to use volume load (repetitions x load) in conjunction with DISP to estimate the amount of external work in resistance training studies [205-207]. Considering the fact that subjects in the present study were achieving higher DISP during RR protocols while using the same load as during TS, it would be logical to state that subjects may have performed slightly more work during RR than during TS protocols. This is interesting, since we also observed an inverse relationship between DISP and RPE whereby RR allowed for greater DISP and lower RPE (i.e. a greater DISP with the same external load) [112, 205]. A similar finding of increased displacement but lower RPE was also reported by Hardee et al [22, 55] but those researchers did not equate total rest time, which suggests that lower perceptual fatigue in their studies could be attributed to the additional rest period provided. Therefore, our data show that although total rest time was equal, subjects perceived RR sets as easier than TS despite the fact that more work was performed during RR. This finding, coupled with less PVD during RR at all loads (especially at heavier loads; Figure 11.2; Figure 11.4), shows that maintaining movement velocity is possible while RPE is decreased when the number of repetitions performed in a row is minimized. Other studies have also shown that set configurations with fewer repetitions per set result in lower RPE during resistance training [84, 201, 208], indicating that the number of repetitions performed in sequence is an important factor to consider when aiming to reduce an athlete's perceived exertion [84]. This might be explained by a higher phospho-creatine (PCr) depletion which might have occurred during TS structures, since it is thought that PCr depletion may increase RPE [137] and also decrease force production capabilities during high-intensity exercise [25]. In addition, previous studies reported RPE to be associated with an increase in blood lactate [204, 209, 210] which can further lead to a reliance on anaerobic glycolysis [211]. Therefore, it may be speculated that increased perception of effort during the clean pull exercise could be associated with an increased reliance on anaerobic glycolysis and the inability of the system to buffer hydrogen ions [22, 212, 213], which ultimately led to an acute decrease in performance. However, these variables were not measured in the present study and should be addressed in future research.

Although there is no consensus on whether RPE better represents fatigue or intensity, results of the present study show that it might be influenced by both. For example, significantly higher RPE was observed during TS80 than RR80 although differences in DISPD, PVD and CRDI were not as profound as during higher loading magnitudes (i.e. 100 and 120% 1RM). This questions the ability of RPE to represent changes in mechanical performance at lower (farther from failure) intensities, possibly making it intensity-dependent, and further supports the influence of set structure and number of repetitions performed within a set on RPE [84, 201]. Despite all the above, RPE was still able to represent differences in acute performance during higher loads in the present study, suggesting that RPE can serve as an accurate measure of acute fatigue, which is quick and easy to use.

The results of the present study have implications for various training phases such as strength-endurance, maximal strength, strength-speed, and speed-strength phases [173, 174]. For example, a strength-endurance phase often requires many repetitions to be performed to increase overall work capacity and stimulate increases in muscle cross-sectional area. However, performing a high volume of repetitions during this phase may lead to deterioration in technique due to acute fatigue. Although lifting form was not objectively addressed in this study, a higher DISP and lower PVD, CRDI, and RPE experienced during RR (Table 11.1; Figure 11.2; Figure 11.3; Figure 11.4) suggests the potential benefit of RR for maintaining acute performance. Furthermore, during a maximal strength phase, practitioners often shift their training focus to exercises that emphasize force production. While full weightlifting movements are often performed at 80-90% of 1RM, clean pulls can allow for loads greater than the athlete's 1RM (e.g. 120% in the present study) due to a decreased displacement of the load and elimination of the catch phase [173], thus, training the high-force end of the force-velocity spectrum. Lastly, both strength-speed and speed-strength phases aim to increase rate of force development while lifting relatively heavy loads as quickly as possible. Rest redistribution can encourage greater velocity, power outputs, and vertical displacement, since fatigue can quickly manifest itself when repeatedly performing explosive movements under externally loaded conditions using TS training structures [122] which can result in sub-maximal training adaptations [176, 214].

Although not measured in the current study, it can be hypothesized that shorter but more frequent rest periods may have enabled enhanced clearance of metabolic by-products and replenishment of phosphagen energy substrates in our study. This notion is in line with previous studies that collectively suggested that when the frequency of rest intervals increased, lactate levels and RPE were lower and subjects better maintained power, ATP stores, and PCr stores throughout the exercise session [29-31, 215]. In addition, as other authors have hypothesized the same while studying other exercises [58, 144], we believe that the increased frequency of rest periods during RR allowed for superior replenishment of ATP and PCr throughout the entire session, resulting in lower perceptual as well as mechanical measures of fatigue as evidenced by lower RPE, decrement in movement velocity and greater barbell displacement than TS.

Practical Applications

This study is the first to show that extra intra-set rest intervals (i.e. basic cluster sets) might not always be needed to maintain performance during weightlifting movements since simply redistributing long inter-set rest intervals into shorter but more frequent inter-set rest intervals can also maintain performance through lower levels of perceptual and mechanical fatigue. Compared to other compound movements such as back squats and the bench press where the range of motion and technique are fairly constant regardless of the load, weightlifting movements are highly technical, and traditional sets, due to a greater accumulation of fatigue, should be avoided if maximal barbell displacement is desired. Lastly, the data in this study show that RPE mimics the changes in mechanical performance, especially with heavier loads. Therefore, RPE could be used to monitor acute fatigue during weightlifting movements. However, caution should be taken with lower (farther from failure) intensities, as RPE does not seem to be sensitive enough to detect changes in performance.

Chapter 12: General Summary and Conclusions

General Summary

The overall purpose of this work was to examine the effect of various CS and RR loading schemes on the mechanical, hormonal, perceptive, and technical responses to various free-weight exercises (namely back squats and clean pulls) in trained men. Previous researchers had investigated the effects of CS on mechanical and hormonal responses to resistance-training, but the majority of research had focused on maintaining velocity and power output during acute training sessions [122]. Therefore, the early studies in this work were designed specifically to address the lack of research focusing on high-volume protocols and to question the belief set forth in the original review of CS literature [16] that CS should not be used when aiming to increase skeletal muscle hypertrophy or strength. Furthermore, athletes and coaches may value the ability of protocols to stimulate muscle growth or strength without sacrificing acute exercise performance. Hence, not only were the studies of this work designed to investigate the effects of CS on acute hypertrophy-related variables, but they included combinations of loads and rest periods that would allow for similar relative maintenance of velocity and external power output while using heavier loads than those which are typically recommended for high-volume training.

Specifically, Chapter 3 showed that CS with additional intra-set rest intervals (CS2) maintained acute movement velocity and power output greater than a protocol containing half of the intra-set rest (CS4), and both CS protocols maintained velocity and power output compared to TS. Such findings were expected, but the entirety of the back squat CS literature to date had provided limited data and used only RR protocols, highlighting the need for a comprehensive analysis of kinetics and kinematics using basic CS protocols. The additional rest periods during CS2 most likely allowed for the continual replenishment of immediate energy stores, resulting in a consistent performance, whereas CS4 followed suit but to a lesser extent. Nevertheless, the study was designed in this manner to provide baseline data for creating the protocols used in the second study.

Chapter 4 was the first study, to the authors' knowledge, to show that CS could be used to complete the same number of repetitions with a greater load, thereby increasing TW and TUT. According to the force-velocity spectrum, the maximal attainable concentric velocity decreases as load increases. Therefore, fatigue (i.e. decreases in movement velocity) had to be standardized by using the same relative training load for each protocol. Theoretically, similar decreases in movement velocity suggested that energy consumption and restoration occurred at similar rates between the protocols, and that all of the protocols were equally fatiguing. The results from this study are possibly the most influential for the strength and conditioning field, as CS are traditionally thought of as "energy sparing" protocols that allow a lifter to perform exercises at greater velocities and power outputs compares to TS. As the purpose of this work was to determine how CS could be systematically manipulated to account for multiple training goals simultaneously, the ability of CS to allow for greater loads for a given number of repetitions across the loading spectrum opened the door for future research investigating strength- or hypertrophy-oriented CS loading.

Chapters 5 and 6 compared a basic CS that had inter-set and intra-set rest to two different RR protocols: one with inter-repetition rest (RR1) and the other with inter-set rest periods after every four repetitions (RR4). Previous studies had shown that RR protocols maintain performance as basic CS do, but no studies had compared a basic CS protocol to RR protocols, making this study the first to compare these different CS sub-categories. The results of this study showed that CS and RR protocols result in similar decreases in velocity and power output, similar increases in La during exercise, similar RPE, and similar shifts in hormonal concentrations after exercise. The main difference between the protocols was that MVL was less during RR1 compared to CS4 and RR4 during the first third of the exercise session. Additionally, MV never dropped below 80% of the fastest repetition of the RR1 protocol; RR4 and CS4 resulted in 22% (8 out of 36) and 11% (4 out of 36) of repetitions falling below 80% of maximal attainable velocity, respectively. Therefore, although the results of this study support the idea that RR and CS protocols have equal kinetic and kinematic effects, the RR1 protocol may be more appropriate when approximately 12 repetitions are performed, or when a minimum velocity threshold must be maintained over 36 repetitions.

Chapters 7 and 8 then observed that CS and RR are likely most useful compared to TS that are extremely fatiguing. Nevertheless, even during less-fatiguing protocols, CS and RR could still serve a purpose, as the pattern of fatigue was different between CS/RR and TS, especially as the number of repetitions increased. Additionally, it seems as though regardless of the total number of repetitions performed, CS and RR decrease RPE, which may be indicative of other physiological responses, but further research should continue to investigate this.

Chapters 9, 10, and 11 continued to investigate the effects of RR, but instead of during high-volume exercises, in weightlifting movements across different loads. The data collectively indicate that RR becomes increasingly more important as total work increases (greater loads for the same number of repetitions). Specifically, RR maintained barbell displacement, velocity, and power output all while decreasing RPE. Perhaps most importantly, RR was shown to induce similar velocity responses to the increasingly popular velocity-based training phenomenon whereby performance is maintained during exercise up to a certain threshold.

Collectively, these studies showed that CS could in fact be designed in a way that could increase TW and TUT compared to TS while maintaining relative velocity and power output similar to TS. Additionally, the use of different sub-types of CS (i.e. RR and basic CS) can influence metabolic and hormonal responses in favor of muscle anabolism during and after resistance-training. Therefore, this work sheds light on the process of adjusting training loads and rest periods within a training session, showing that CS and RR are extremely malleable and can be designed to target a variety of training goals.

Limitations

Together, the information presented in this work indicates that CS can be designed to result in different acute responses to resistance-training, possibly eliciting different chronic adaptations. Although efforts were made to create scientifically sound methods while maintaining the practical nature of the research, limitations are present. For example, all of the studies within this thesis included force, velocity, and power output measures. Specifically, power output was calculated using barbell velocity and ground reaction forces. Although this method is valid and is commonly used to describe the external power output of various exercises [110], it can be argued that measuring barbell velocity instead of the velocity of the center of mass may overestimate the velocity of the entire body-barbell system, resulting in inflated power outputs. However, to determine the center of mass, advanced 3-dimensional motion capture systems must be synchronized with high-speed cameras and other technology, also requiring advanced computational skills. Although measuring velocity using the center of mass of the system may have provided a more accurate velocity, and in turn power, measurements, the changing trends of velocity and power output remain the same as changes in power output and velocity are quite parallel (as seen in Figures 3.2 and 3.3). Additionally, the use of commercially available velocity measuring devices like the position transducers used in the present studies increases the external validity and direct application of science in the strength and conditioning field, where practitioners can purchase displacement-time technology to monitor barbell velocity instantaneously during training.

Additionally, the protocols used in in the first study were created to investigate the effects of the number of intra-set rest periods provided within a training session. Although scientifically sound, the length of the CS2 protocol may be concerning to some, as three sets of a single exercise took over 15 minutes to complete. Ultimately, training restrictions, such as time constraints, play a large role when designing a training program; but if a professional setting allows for a practically unlimited training time, such protocols may be implemented without having to reduce the time needed for other commitments outside of training.

A limitation of the second study was the fact that the loads and rest periods were different between the protocols, meaning that there were technically two independent variables. Although multiple independent variables can be viewed as a scientific flaw, the nature of the research question (how can CS be manipulated to allow a greater load for the same number of repetitions) required different rest periods in order for greater loads to be used while resulting in similar relative decreases in movement velocity. Therefore, the alteration of rest periods and loads go hand-in-hand, and the practical applications of the second study outweigh such a slight limitation within an otherwise scientifically sound and groundbreaking examination of CS. Also, as the greater loads resulted in greater TW and TUT, it can be argued that such increases in mechanical stress may result in subsequent fatigue and increased muscle soreness. Although those variables were not of interest of the second study, the practical implications of these possibilities should be taken into consideration by the strength and conditioning professional. It is likely that an athlete’s training history, nutritional status, and recovery regime play a large role in the management of fatigue and soreness. Therefore, individuals may respond differently to increased mechanical stress, making it even more important for the strength and conditioning professional to be actively involved throughout the training process.

Within the third study, two main limitations were present: a small sample size of eight subjects and a lack of a TS protocol. Unfortunately, a lack of funding was responsible for the decision to limit the sample size and the number of visits (protocols) within the study. Additionally, as stated within Chapter 6, the importance of acute hormonal concentrations for skeletal muscle hypertrophy has become a subject of debate. Traditionally, researchers believed that acute increases in hormones such as growth hormone (GH) and testosterone (TT) were precursors for anabolism, and that a chronic training-induced elevation in these hormones would result in a greater and longer anabolic response. However, recent evidence has shunned this idea and researchers have stated that the hormonal response to training is not a driving force for hypertrophy. Nonetheless, the data that came out of this study should not be undervalued, as this study was the first to compare a basic CS to RR protocols and was only the third study to compare the acute effects of CS on hormonal responses.

In addition to these acute limitations within each study, the main limitation of the work as a whole is the lack of a study to determine the effects of such protocols on the development of maximal strength, muscle endurance, power output, and hypertrophy. Although this work did not contain a training study, the cross-sectional analyses present are valuable and have built up a base of knowledge that future research can be built upon. However, it is important to understand that the results from such acute studies cannot directly determine the effectiveness of protocols in a training environment. Although a training study would have been able to determine the effectiveness of CS to develop multiple training goals simultaneously, the purpose of this work was to provide a comprehensive cross-sectional data set that would allow for other protocols to be created and implemented in future research: a goal that was accomplished.

Directions for Further Research

Although many researchers have begun to investigate the effect of CS, the seemingly infinite combination of acute training variables require further investigation. The studies within this work primarily focused on the acute mechanical responses to CS and the final study touched on the metabolic, hormonal, and perceptual responses. However, the neuromuscular response to CS remains relatively unexplored within the literature and warrants investigation, as maximal strength relies heavily on neuromuscular adaptations. Additionally, evidence has shown that inter-repetition rest has different effects on different exercises [122] and the data of this work is no exception, as Chapter 5 showed that the RR1 protocol displayed different patterns of force, velocity, and power output than RR4 and CS4. Therefore, the effects of CS on different exercises warrants investigation since CS may actually impede certain aspects of performance of some exercises [57] while enhancing other aspects [122].

Specifically building from the data presented within this work, the original idea of finding a single “optimal” protocol seems unattainable. The principle of specificity and the force-velocity relationship ultimately dictate what should and can be accomplished during a resistance-training program. Additionally, the intent to move a load at a maximal velocity should never be overlooked during training [19, 50, 216], and a variety of training loads should be used to target neuromuscular and physiological adaptations across the loading spectrum. However, the CS4 protocol of Studies 2 and 3 which contained three sets of 12 repetitions using 75% 1RM with 30 s of intra-set rest after every four repetitions and 120 s of inter-set rest seems promising for developing skeletal muscle hypertrophy because it resulted in greater TW and TUT than TS without decreasing relative movement velocity and without drastically increasing the training duration like the CS2 protocol did in the second study with twice the amount of intra-set rest. Additionally, the CS4 protocol of the second and third studies resulted in significant increases in La and GH, indicating that not only did have a positive effect on mechanical stress, but also on metabolic stress and hormonal responses. Therefore, another recommendation for future research would be to experiment with protocols similar to the CS4 protocol of Studies 2 and 3 if aiming to increase hypertrophy while minimizing the amount of acute neuromuscular fatigue.

Depending on the external load used during training, a protocol similar to the RR1 protocol of the third study may be beneficial for acutely maintaining external power output for up to 12 repetitions, and possibly more repetitions. Eventually, the RR1 protocol experienced similar decreases in movement velocity as CS4 and RR4, but was able to maintain at least 80% of the fastest repetition's MV. Although the 80% threshold has been recommended by previous researchers [18, 120, 121], the effectiveness of a protocol with inter-repetition rest periods should be investigated. Additionally, the 12 s inter-repetition rest period during RR1 was used to equalize the total rest time between protocols, but future research should investigate the effects on inter-repetition rest using heavier and lighter loads.

Lastly, although some studies have investigated the chronic effects of training with various types of CS on the development of strength, hypertrophy, and power output, additional training studies should be conducted. Specifically, future research should determine if different types of CS result in different chronic responses, or if the responses are similar.

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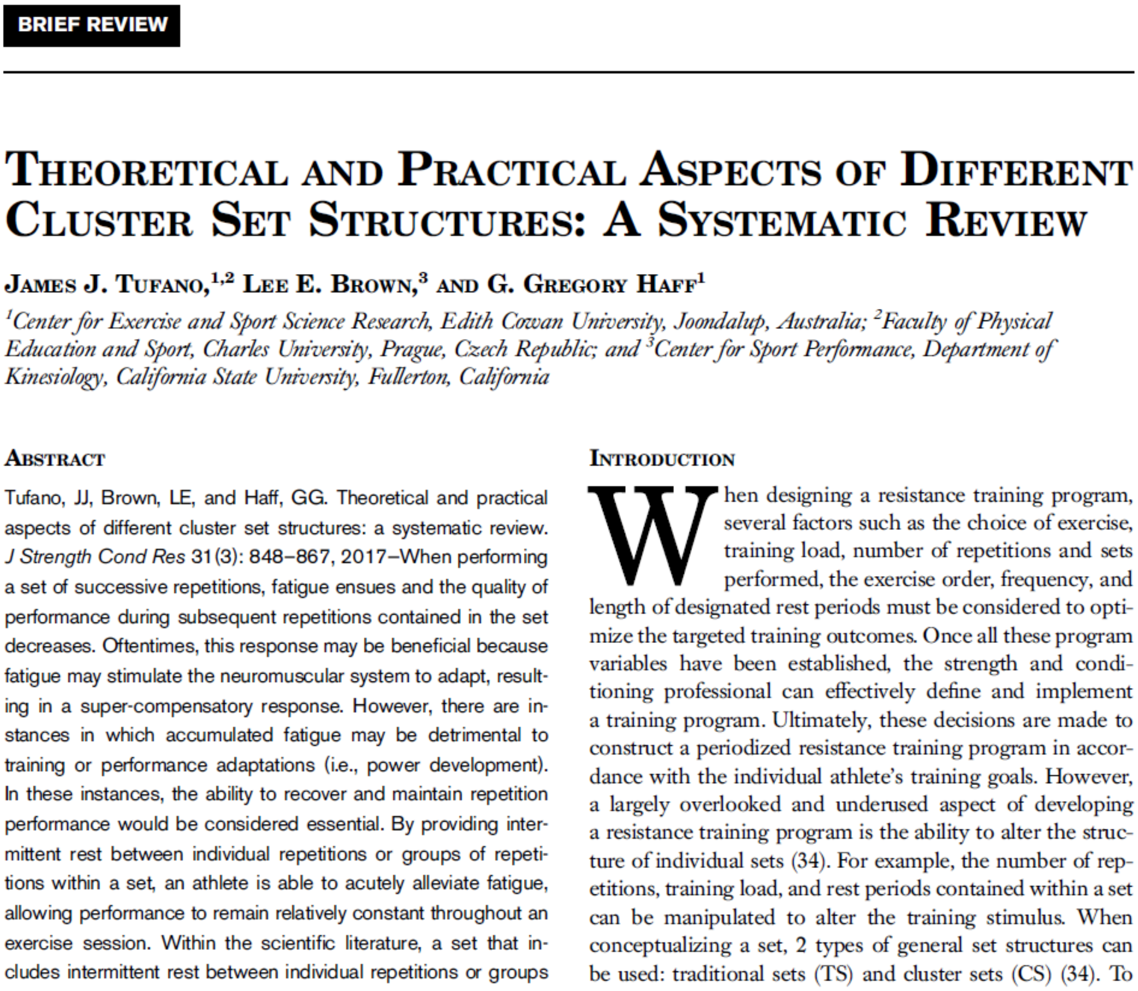
Appendix 1: List of peer-reviewed publications

Chapter 2



BRIEF REVIEW

THEORETICAL AND PRACTICAL ASPECTS OF DIFFERENT CLUSTER SET STRUCTURES: A SYSTEMATIC REVIEW

JAMES J. TUFANO,[1,2] LEE E. BROWN,[3] AND G. GREGORY HAFF[1]

[1]Center for Exercise and Sport Science Research, Edith Cowan University, Joondalup, Australia; [2]Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic; and [3]Center for Sport Performance, Department of Kinesiology, California State University, Fullerton, California

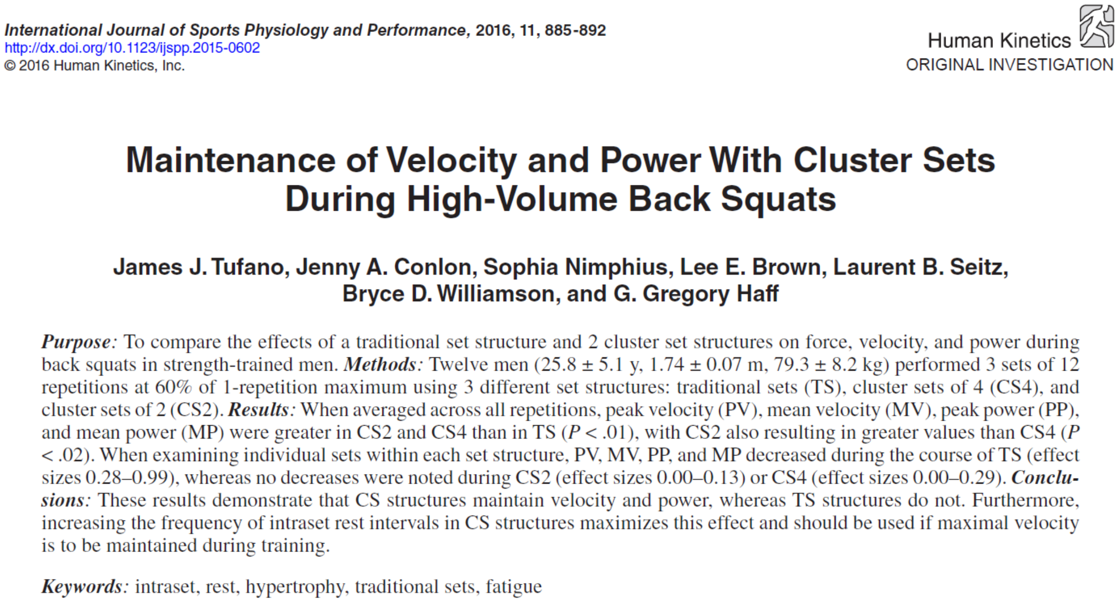
ABSTRACT

Tufano, JJ, Brown, LE, and Haff, GG. Theoretical and practical aspects of different cluster set structures: a systematic review. *J Strength Cond Res* 31(3): 848–867, 2017—When performing a set of successive repetitions, fatigue ensues and the quality of performance during subsequent repetitions contained in the set decreases. Oftentimes, this response may be beneficial because fatigue may stimulate the neuromuscular system to adapt, resulting in a super-compensatory response. However, there are instances in which accumulated fatigue may be detrimental to training or performance adaptations (i.e., power development). In these instances, the ability to recover and maintain repetition performance would be considered essential. By providing intermittent rest between individual repetitions or groups of repetitions within a set, an athlete is able to acutely alleviate fatigue, allowing performance to remain relatively constant throughout an exercise session. Within the scientific literature, a set that includes intermittent rest between individual repetitions or groups

INTRODUCTION

When designing a resistance training program, several factors such as the choice of exercise, training load, number of repetitions and sets performed, the exercise order, frequency, and length of designated rest periods must be considered to optimize the targeted training outcomes. Once all these program variables have been established, the strength and conditioning professional can effectively define and implement a training program. Ultimately, these decisions are made to construct a periodized resistance training program in accordance with the individual athlete's training goals. However, a largely overlooked and underused aspect of developing a resistance training program is the ability to alter the structure of individual sets (34). For example, the number of repetitions, training load, and rest periods contained within a set can be manipulated to alter the training stimulus. When conceptualizing a set, 2 types of general set structures can be used: traditional sets (TS) and cluster sets (CS) (34). To

Chapter 3



International Journal of Sports Physiology and Performance, 2016, 11, 885-892
http://dx.doi.org/10.1123/ijspp.2015-0602

Human Kinetics
ORIGINAL INVESTIGATION

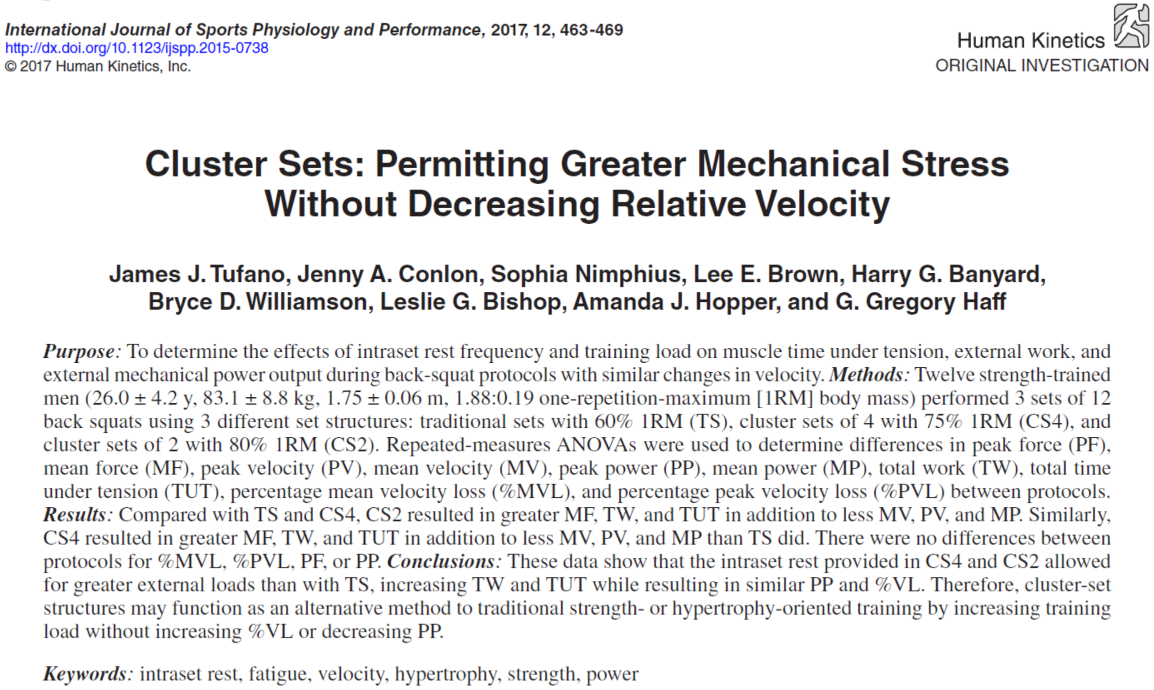
Maintenance of Velocity and Power With Cluster Sets During High-Volume Back Squats

James J. Tufano, Jenny A. Conlon, Sophia Nimphius, Lee E. Brown, Laurent B. Seitz, Bryce D. Williamson, and G. Gregory Haff

Purpose: To compare the effects of a traditional set structure and 2 cluster set structures on force, velocity, and power during back squats in strength-trained men. ***Methods:*** Twelve men (25.8 ± 5.1 y, 1.74 ± 0.07 m, 79.3 ± 8.2 kg) performed 3 sets of 12 repetitions at 60% of 1-repetition maximum using 3 different set structures: traditional sets (TS), cluster sets of 4 (CS4), and cluster sets of 2 (CS2). ***Results:*** When averaged across all repetitions, peak velocity (PV), mean velocity (MV), peak power (PP), and mean power (MP) were greater in CS2 and CS4 than in TS ($P < .01$), with CS2 also resulting in greater values than CS4 ($P < .02$). When examining individual sets within each set structure, PV, MV, PP, and MP decreased during the course of TS (effect sizes 0.28–0.99), whereas no decreases were noted during CS2 (effect sizes 0.00–0.13) or CS4 (effect sizes 0.00–0.29). ***Conclusions:*** These results demonstrate that CS structures maintain velocity and power, whereas TS structures do not. Furthermore, increasing the frequency of intraset rest intervals in CS structures maximizes this effect and should be used if maximal velocity is to be maintained during training.

Keywords: intraset, rest, hypertrophy, traditional sets, fatigue

Chapter 4



International Journal of Sports Physiology and Performance, 2017, 12, 463-469
http://dx.doi.org/10.1123/ijspp.2015-0738

Human Kinetics
ORIGINAL INVESTIGATION

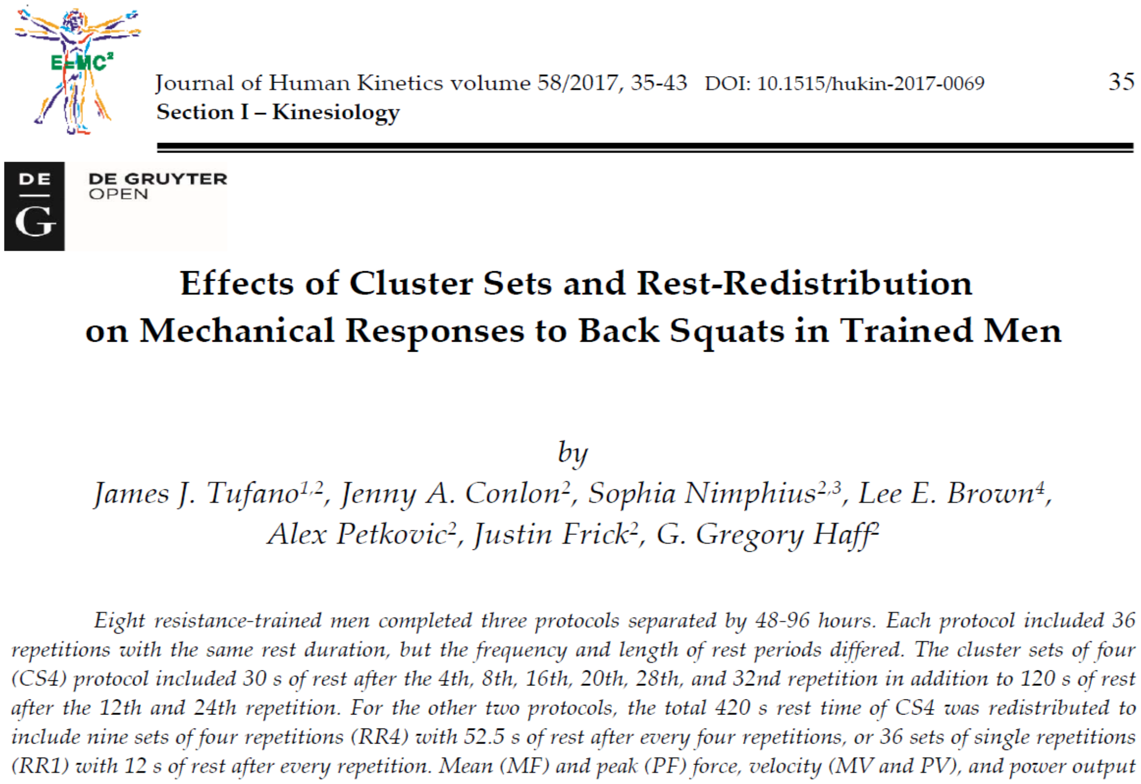
Cluster Sets: Permitting Greater Mechanical Stress Without Decreasing Relative Velocity

James J. Tufano, Jenny A. Conlon, Sophia Nimphius, Lee E. Brown, Harry G. Banyard, Bryce D. Williamson, Leslie G. Bishop, Amanda J. Hopper, and G. Gregory Haff

Purpose: To determine the effects of intraset rest frequency and training load on muscle time under tension, external work, and external mechanical power output during back-squat protocols with similar changes in velocity. ***Methods:*** Twelve strength-trained men (26.0 ± 4.2 y, 83.1 ± 8.8 kg, 1.75 ± 0.06 m, 1.88:0.19 one-repetition-maximum [1RM] body mass) performed 3 sets of 12 back squats using 3 different set structures: traditional sets with 60% 1RM (TS), cluster sets of 4 with 75% 1RM (CS4), and cluster sets of 2 with 80% 1RM (CS2). Repeated-measures ANOVAs were used to determine differences in peak force (PF), mean force (MF), peak velocity (PV), mean velocity (MV), peak power (PP), mean power (MP), total work (TW), total time under tension (TUT), percentage mean velocity loss (%MVL), and percentage peak velocity loss (%PVL) between protocols. ***Results:*** Compared with TS and CS4, CS2 resulted in greater MF, TW, and TUT in addition to less MV, PV, and MP. Similarly, CS4 resulted in greater MF, TW, and TUT in addition to less MV, PV, and MP than TS did. There were no differences between protocols for %MVL, %PVL, PF, or PP. ***Conclusions:*** These data show that the intraset rest provided in CS4 and CS2 allowed for greater external loads than with TS, increasing TW and TUT while resulting in similar PP and %VL. Therefore, cluster-set structures may function as an alternative method to traditional strength- or hypertrophy-oriented training by increasing training load without increasing %VL or decreasing PP.

Keywords: intraset rest, fatigue, velocity, hypertrophy, strength, power

Chapter 5



Journal of Human Kinetics volume 58/2017, 35-43 DOI: 10.1515/hukin-2017-0069 35
Section I – Kinesiology

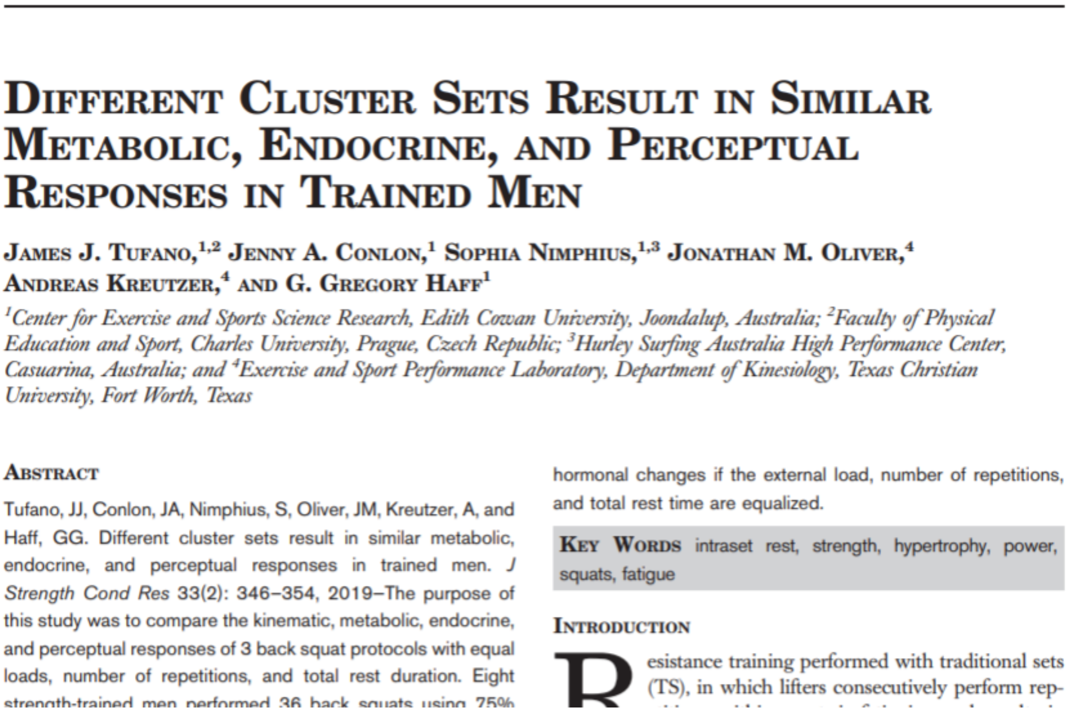
DE GRUYTER
OPEN

Effects of Cluster Sets and Rest-Redistribution on Mechanical Responses to Back Squats in Trained Men

by
James J. Tufano[1,2], *Jenny A. Conlon*[2], *Sophia Nimphius*[2,3], *Lee E. Brown*[4], *Alex Petkovic*[2], *Justin Frick*[2], *G. Gregory Haff*[2]

Eight resistance-trained men completed three protocols separated by 48-96 hours. Each protocol included 36 repetitions with the same rest duration, but the frequency and length of rest periods differed. The cluster sets of four (CS4) protocol included 30 s of rest after the 4th, 8th, 16th, 20th, 28th, and 32nd repetition in addition to 120 s of rest after the 12th and 24th repetition. For the other two protocols, the total 420 s rest time of CS4 was redistributed to include nine sets of four repetitions (RR4) with 52.5 s of rest after every four repetitions, or 36 sets of single repetitions (RR1) with 12 s of rest after every repetition. Mean (MF) and peak (PF) force, velocity (MV and PV), and power output

Chapter 6



DIFFERENT CLUSTER SETS RESULT IN SIMILAR METABOLIC, ENDOCRINE, AND PERCEPTUAL RESPONSES IN TRAINED MEN

JAMES J. TUFANO,[1,2] **JENNY A. CONLON,**[1] **SOPHIA NIMPHIUS,**[1,3] **JONATHAN M. OLIVER,**[4]
ANDREAS KREUTZER,[4] **AND G. GREGORY HAFF**[1]

[1]Center for Exercise and Sports Science Research, Edith Cowan University, Joondalup, Australia; [2]Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic; [3]Hurley Surfing Australia High Performance Center, Casuarina, Australia; and [4]Exercise and Sport Performance Laboratory, Department of Kinesiology, Texas Christian University, Fort Worth, Texas

ABSTRACT

Tufano, JJ, Conlon, JA, Nimphius, S, Oliver, JM, Kreutzer, A, and Haff, GG. Different cluster sets result in similar metabolic, endocrine, and perceptual responses in trained men. *J Strength Cond Res* 33(2): 346–354, 2019—The purpose of this study was to compare the kinematic, metabolic, endocrine, and perceptual responses of 3 back squat protocols with equal loads, number of repetitions, and total rest duration. Eight strength-trained men performed 36 back squats using 75%

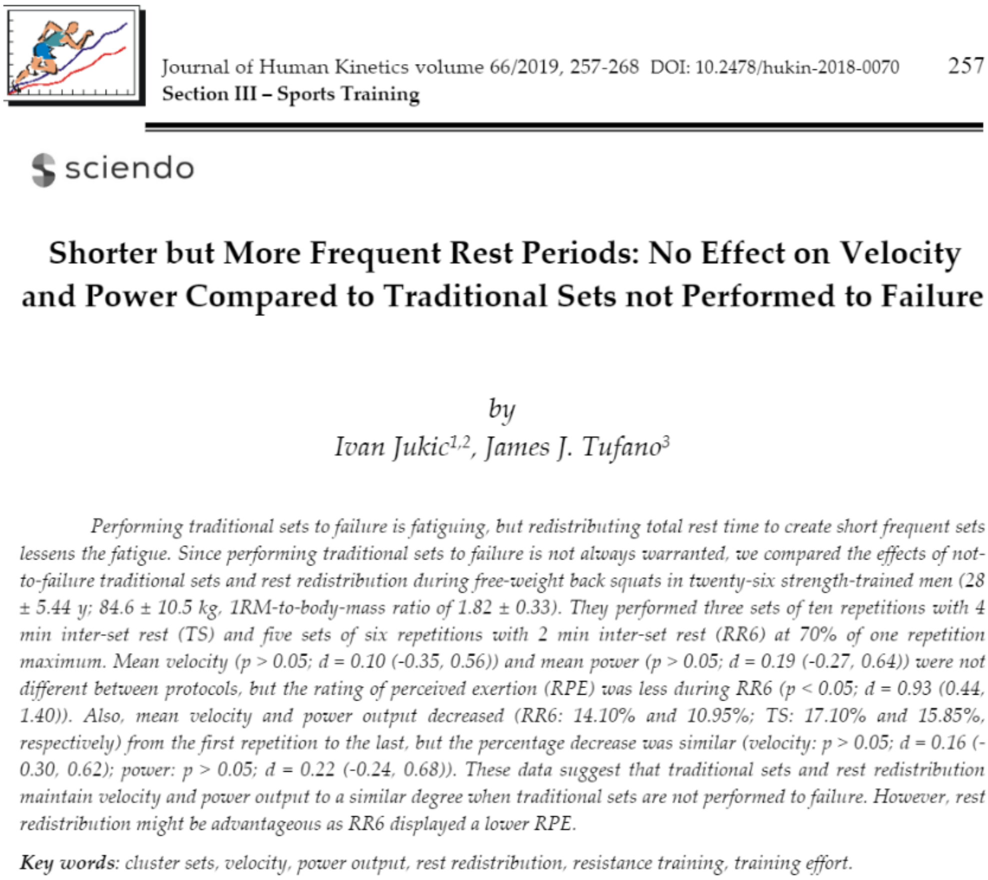
hormonal changes if the external load, number of repetitions, and total rest time are equalized.

KEY WORDS intraset rest, strength, hypertrophy, power, squats, fatigue

INTRODUCTION

Resistance training performed with traditional sets (TS), in which lifters consecutively perform rep-

Chapter 7



Journal of Human Kinetics volume 66/2019, 257-268 DOI: 10.2478/hukin-2018-0070 257
Section III – Sports Training

sciendo

Shorter but More Frequent Rest Periods: No Effect on Velocity and Power Compared to Traditional Sets not Performed to Failure

by
Ivan Jukic[1,2], *James J. Tufano*[3]

Performing traditional sets to failure is fatiguing, but redistributing total rest time to create short frequent sets lessens the fatigue. Since performing traditional sets to failure is not always warranted, we compared the effects of not-to-failure traditional sets and rest redistribution during free-weight back squats in twenty-six strength-trained men (28 ± 5.44 y; 84.6 ± 10.5 kg, 1RM-to-body-mass ratio of 1.82 ± 0.33). They performed three sets of ten repetitions with 4 min inter-set rest (TS) and five sets of six repetitions with 2 min inter-set rest (RR6) at 70% of one repetition maximum. Mean velocity ($p > 0.05$; $d = 0.10$ (-0.35, 0.56)) and mean power ($p > 0.05$; $d = 0.19$ (-0.27, 0.64)) were not different between protocols, but the rating of perceived exertion (RPE) was less during RR6 ($p < 0.05$; $d = 0.93$ (0.44, 1.40)). Also, mean velocity and power output decreased (RR6: 14.10% and 10.95%; TS: 17.10% and 15.85%, respectively) from the first repetition to the last, but the percentage decrease was similar (velocity: $p > 0.05$; $d = 0.16$ (-0.30, 0.62); power: $p > 0.05$; $d = 0.22$ (-0.24, 0.68)). These data suggest that traditional sets and rest redistribution maintain velocity and power output to a similar degree when traditional sets are not performed to failure. However, rest redistribution might be advantageous as RR6 displayed a lower RPE.

Key words: *cluster sets, velocity, power output, rest redistribution, resistance training, training effort.*

Chapter 8

PLOS | ONE

RESEARCH ARTICLE

Cluster sets vs. traditional sets: Levelling out the playing field using a power-based threshold

James J. Tufano[1]*, Matej Halaj[2], Tomas Kampmiller[2], Adrian Novosad[2], Gabriel Buzgo[3]

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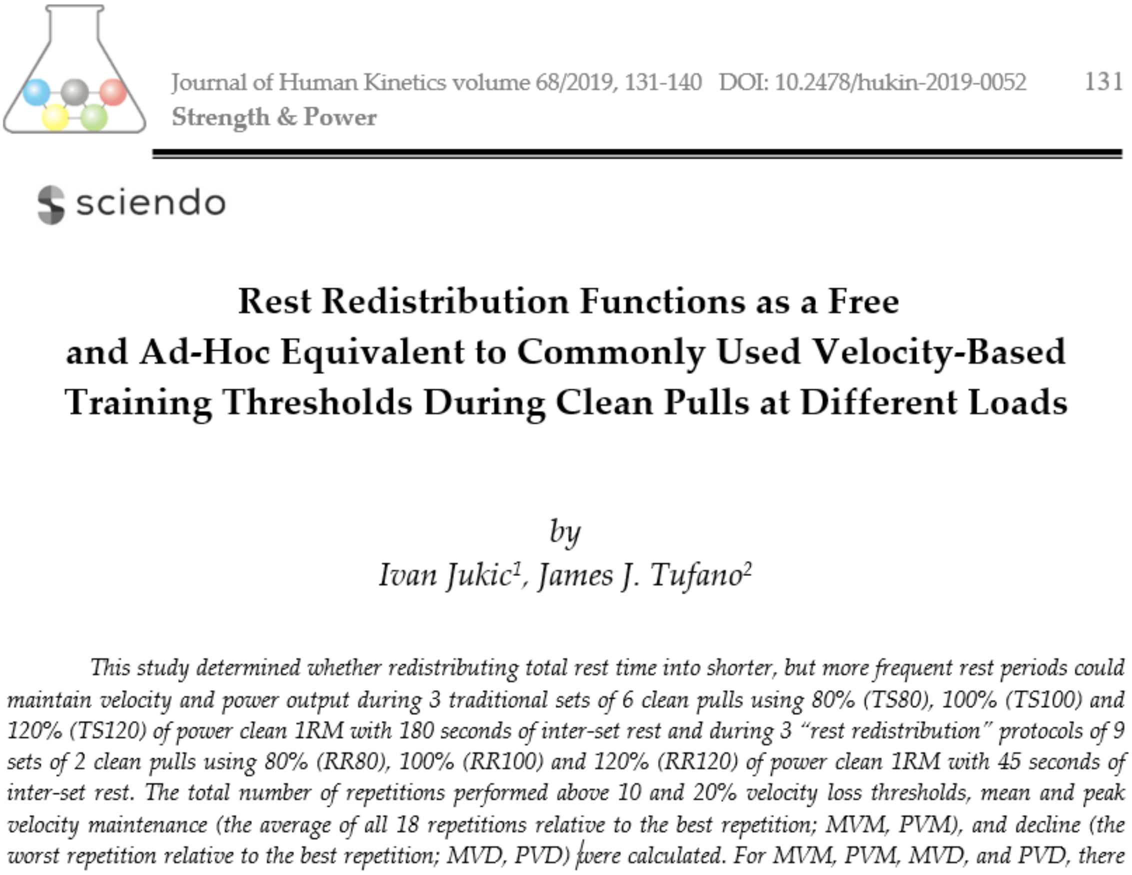
Abstract

Cluster sets allow for velocity and power output maintenance, but the literature routinely

Chapter 9



Journal of Human Kinetics volume 68/2019, 131-140 DOI: 10.2478/hukin-2019-0052 131
Strength & Power

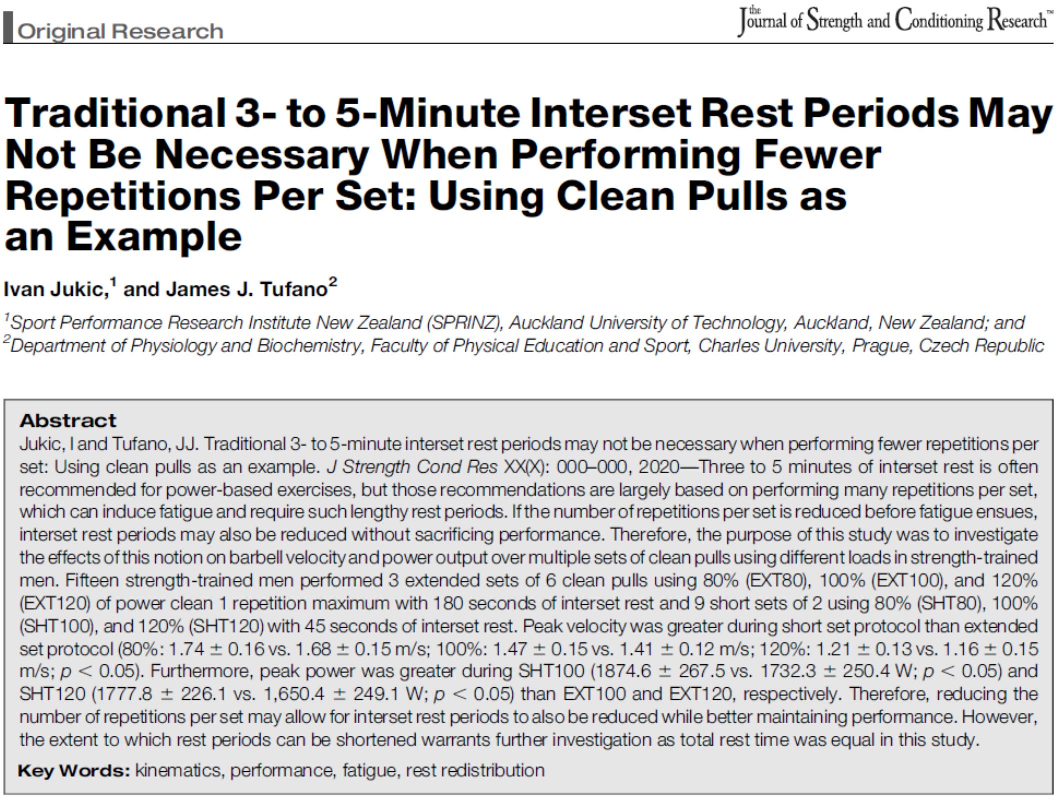
sciendo

Rest Redistribution Functions as a Free and Ad-Hoc Equivalent to Commonly Used Velocity-Based Training Thresholds During Clean Pulls at Different Loads

by
Ivan Jukic[1], James J. Tufano[2]

This study determined whether redistributing total rest time into shorter, but more frequent rest periods could maintain velocity and power output during 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest and during 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. The total number of repetitions performed above 10 and 20% velocity loss thresholds, mean and peak velocity maintenance (the average of all 18 repetitions relative to the best repetition; MVM, PVM), and decline (the worst repetition relative to the best repetition; MVD, PVD) were calculated. For MVM, PVM, MVD, and PVD, there

Chapter 10



Original Research

Journal of Strength and Conditioning Research™

Traditional 3- to 5-Minute Interset Rest Periods May Not Be Necessary When Performing Fewer Repetitions Per Set: Using Clean Pulls as an Example

Ivan Jukic,[1] and James J. Tufano[2]

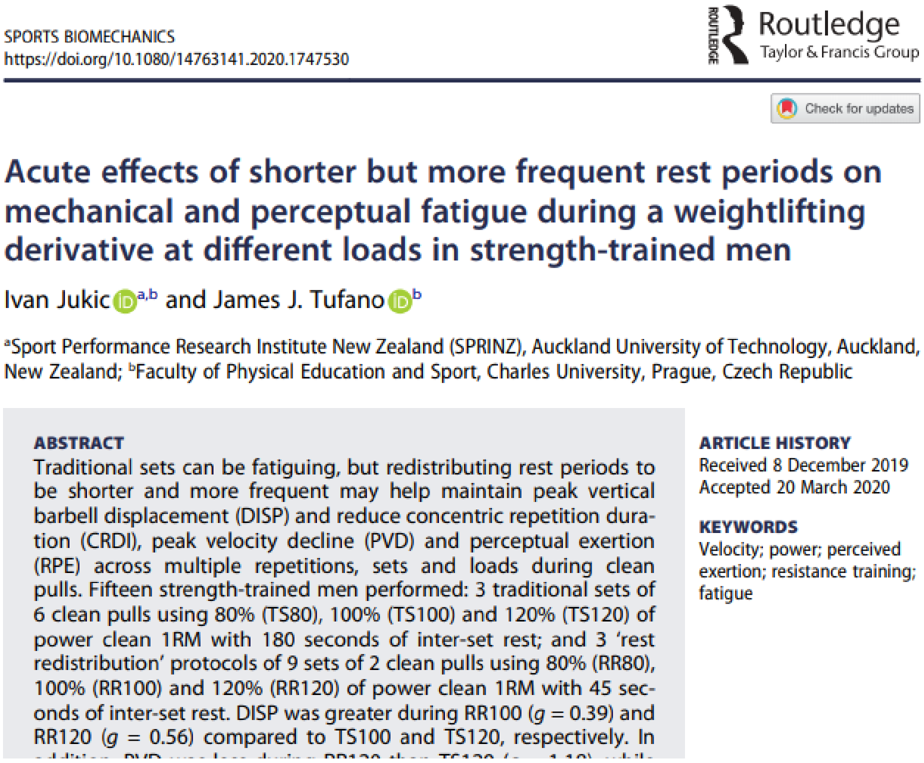
[1]Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand; and [2]Department of Physiology and Biochemistry, Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic

Abstract

Jukic, I and Tufano, JJ. Traditional 3- to 5-minute interset rest periods may not be necessary when performing fewer repetitions per set: Using clean pulls as an example. *J Strength Cond Res* XX(X): 000–000, 2020—Three to 5 minutes of interset rest is often recommended for power-based exercises, but those recommendations are largely based on performing many repetitions per set, which can induce fatigue and require such lengthy rest periods. If the number of repetitions per set is reduced before fatigue ensues, interset rest periods may also be reduced without sacrificing performance. Therefore, the purpose of this study was to investigate the effects of this notion on barbell velocity and power output over multiple sets of clean pulls using different loads in strength-trained men. Fifteen strength-trained men performed 3 extended sets of 6 clean pulls using 80% (EXT80), 100% (EXT100), and 120% (EXT120) of power clean 1 repetition maximum with 180 seconds of interset rest and 9 short sets of 2 using 80% (SHT80), 100% (SHT100), and 120% (SHT120) with 45 seconds of interset rest. Peak velocity was greater during short set protocol than extended set protocol (80%: 1.74 ± 0.16 vs. 1.68 ± 0.15 m/s; 100%: 1.47 ± 0.15 vs. 1.41 ± 0.12 m/s; 120%: 1.21 ± 0.13 vs. 1.16 ± 0.15 m/s; $p < 0.05$). Furthermore, peak power was greater during SHT100 (1874.6 ± 267.5 vs. 1732.3 ± 250.4 W; $p < 0.05$) and SHT120 (1777.8 ± 226.1 vs. 1,650.4 ± 249.1 W; $p < 0.05$) than EXT100 and EXT120, respectively. Therefore, reducing the number of repetitions per set may allow for interset rest periods to also be reduced while better maintaining performance. However, the extent to which rest periods can be shortened warrants further investigation as total rest time was equal in this study.

Key Words: kinematics, performance, fatigue, rest redistribution

Chapter 11



SPORTS BIOMECHANICS
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Acute effects of shorter but more frequent rest periods on mechanical and perceptual fatigue during a weightlifting derivative at different loads in strength-trained men

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[a]Sport Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand; [b]Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic

ABSTRACT

Traditional sets can be fatiguing, but redistributing rest periods to be shorter and more frequent may help maintain peak vertical barbell displacement (DISP) and reduce concentric repetition duration (CRDI), peak velocity decline (PVD) and perceptual exertion (RPE) across multiple repetitions, sets and loads during clean pulls. Fifteen strength-trained men performed: 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 'rest redistribution' protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. DISP was greater during RR100 ($g = 0.39$) and RR120 ($g = 0.56$) compared to TS100 and TS120, respectively. In

ARTICLE HISTORY
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KEYWORDS
Velocity; power; perceived exertion; resistance training; fatigue

Appendix 2: Conference Presentations

Chapter 3

Tufano JJ, Conlon JA, Seitz LB, Bishop LG, Williamson BD, Haff GG. Acute effects of hypertrophy-oriented cluster sets on work, power, and velocity. International Conference on Strength Training, Abano Terme, Italy, October 2014.

EJSS - Journal
Sport & Exercise Sciences
EJSS

Supplement to Volume 2 – October 2014
doi: 10.12863/ejssxs1x-2014

ACUTE EFFECTS OF HYPERTROPHY-ORIENTED CLUSTER SETS ON WORK, POWER, AND VELOCITY

James J. Tufano, Jenny A. Conlon, Laurent B. Seitz, Leslie G. Bishop, Bryce D. Williamson, and G. Gregory Haff

Centre for Exercise and Sport Science Research, Edith Cowan University, Joondalup, Western Australia

Saturday, 25th *Oral Presentation 2.4*

To investigate the effect of rest periods on fatigue, twelve resistance trained males (25.75±5.13 y; 79.27±8.17 kg; 1RM = 1.90±0.23 x body mass) performed 3 sets of 12 repetitions of back squats using 60% 1RM for two different set configurations: traditional sets (TS) where all repetitions within a set were performed in a row, and cluster sets (CS) where 30 seconds of rest was provided after the 2nd, 4th, 6th, 8th, and 10th repetition of each set.

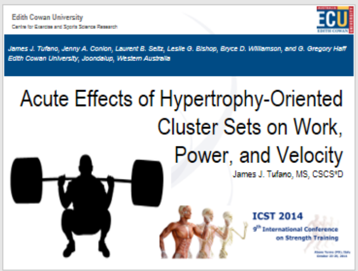
A minimum of 48 hours was required between TS and CS conditions. All repetitions were performed as explosively as possible and 2 minutes of rest were given between each set for both conditions. Force/time data were collected at 1,000 Hz. 2 x 3 (condition x set) repeated measures ANOVAs were performed to determine differences between sets for total work performed (TW), peak concentric velocity (PV), and peak concentric power (PP). There were no significant differences between conditions for TW.

A significant difference between conditions ($p \leq 0.001$) and a condition * set interaction ($p \leq 0.05$) were present for PV. A significant difference between conditions ($p \leq 0.002$) and a condition*set interaction ($p \leq 0.01$) were present for PP. Results indicate that subjects performed similar amounts of TW for each set across all conditions, but the CS condition resulted in a greater PV and PP than the TS condition.

With an increase in PV and PP, but no difference in TW, the maintenance of velocity and power experienced in the CS condition may be attributed to possible recovery experienced during the intra-set rest intervals.

These data show that 30 seconds of intra-set rest after every 2 repetitions within a set can offset the fatigue-induced decreases in power and velocity observed in TS training in a high-volume resistance training protocol, while not effecting TW.

Tufano et al. ICST 2014, Italy



James J. Tufano, Jenny A. Conlon, Laurent B. Seitz, Leslie G. Bishop, Bryce D. Williamson, and G. Gregory Haff
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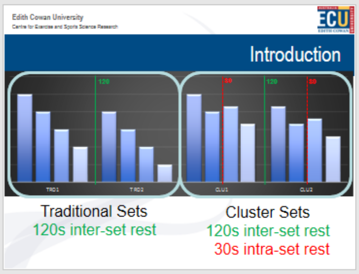
Acute Effects of Hypertrophy-Oriented Cluster Sets on Work, Power, and Velocity

James J. Tufano, MS, CSCS*D

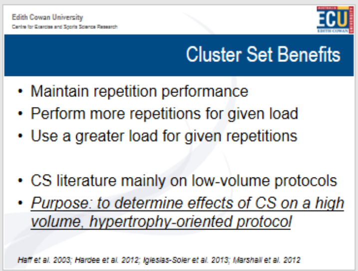
ICST 2014
9th International Conference on Strength Training



Introduction

Traditional Sets
120s inter-set rest

Cluster Sets
120s inter-set rest
30s intra-set rest

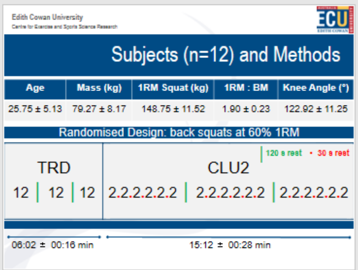


Cluster Set Benefits

- Maintain repetition performance
- Perform more repetitions for given load
- Use a greater load for given repetitions

- CS literature mainly on low-volume protocols
- *Purpose: to determine effects of CS on a high volume, hypertrophy-oriented protocol*

Haff et al. 2003; Hardee et al. 2012; Iglesias-Soler et al. 2013; Marshall et al. 2012



Subjects (n=12) and Methods

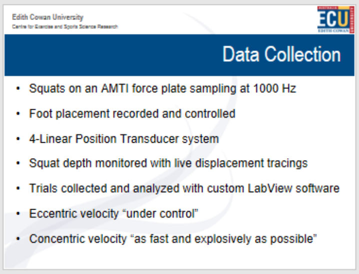
Age	Mass (kg)	1RM Squat (kg)	1RM : BM	Knee Angle (°)
25.75 ± 5.13	79.27 ± 8.17	148.75 ± 11.52	1.90 ± 0.23	122.92 ± 11.25

Randomised Design: back squats at 60% 1RM

120 s rest • 30 s rest

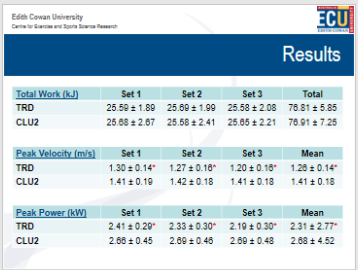
TRD
12 | 12 | 12
06:02 ± 00:16 min

CLU2
2.2.2.2.2.2 | 2.2.2.2.2.2 | 2.2.2.2.2.2
15:12 ± 00:28 min



Data Collection

- Squats on an AMTI force plate sampling at 1000 Hz
- Foot placement recorded and controlled
- 4-Linear Position Transducer system
- Squat depth monitored with live displacement tracings
- Trials collected and analyzed with custom LabView software
- Eccentric velocity "under control"
- Concentric velocity "as fast and explosively as possible"

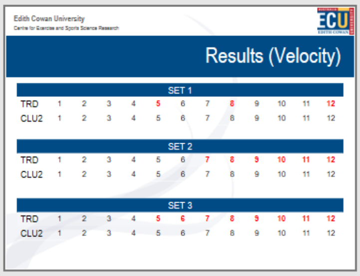


Results

Total Work (kJ)	Set 1	Set 2	Set 3	Total
TRD	25.59 ± 1.89	25.69 ± 1.99	25.58 ± 2.08	76.81 ± 5.85
CLU2	25.68 ± 2.67	25.58 ± 2.41	25.65 ± 2.21	76.91 ± 7.25

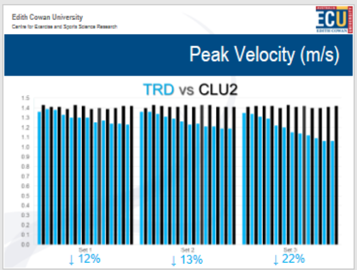
Peak Velocity (m/s)	Set 1	Set 2	Set 3	Mean
TRD	1.30 ± 0.14*	1.27 ± 0.16*	1.20 ± 0.16*	1.26 ± 0.14*
CLU2	1.41 ± 0.19	1.42 ± 0.18	1.41 ± 0.18	1.41 ± 0.18

Peak Power (kW)	Set 1	Set 2	Set 3	Mean
TRD	2.41 ± 0.29*	2.33 ± 0.30*	2.19 ± 0.30*	2.31 ± 2.77*
CLU2	2.66 ± 0.45	2.69 ± 0.46	2.69 ± 0.48	2.68 ± 4.52



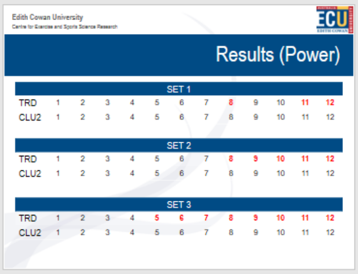
Results (Velocity)

SET 1												
TRD	1	2	3	4	5	6	7	8	9	10	11	12
CLU2	1	2	3	4	5	6	7	8	9	10	11	12
SET 2												
TRD	1	2	3	4	5	6	7	8	9	10	11	12
CLU2	1	2	3	4	5	6	7	8	9	10	11	12
SET 3												
TRD	1	2	3	4	5	6	7	8	9	10	11	12
CLU2	1	2	3	4	5	6	7	8	9	10	11	12



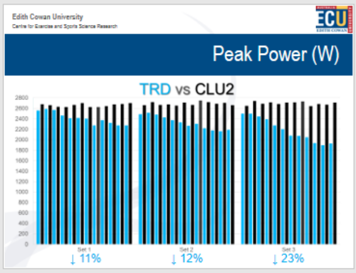
Peak Velocity (m/s)

TRD vs CLU2



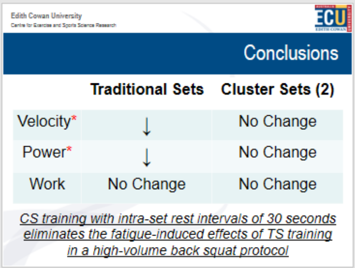
Results (Power)

SET 1												
TRD	1	2	3	4	5	6	7	8	9	10	11	12
CLU2	1	2	3	4	5	6	7	8	9	10	11	12
SET 2												
TRD	1	2	3	4	5	6	7	8	9	10	11	12
CLU2	1	2	3	4	5	6	7	8	9	10	11	12
SET 3												
TRD	1	2	3	4	5	6	7	8	9	10	11	12
CLU2	1	2	3	4	5	6	7	8	9	10	11	12



Peak Power (W)

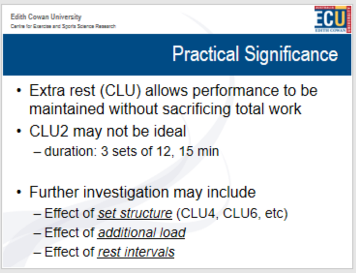
TRD vs CLU2



Conclusions

	Traditional Sets	Cluster Sets (2)
Velocity*	↓	No Change
Power*	↓	No Change
Work	No Change	No Change

CS training with intra-set rest intervals of 30 seconds eliminates the fatigue-induced effects of TS training in a high-volume back squat protocol



Practical Significance

- Extra rest (CLU) allows performance to be maintained without sacrificing total work
- CLU2 may not be ideal
  - duration: 3 sets of 12, 15 min

- Further investigation may include
  - Effect of *set structure* (CLU4, CLU6, etc)
  - Effect of *additional load*
  - Effect of *rest intervals*

Grazie mille!

Chapter 4

Tufano JJ, Conlon JA, Bishop LG, Williamson BD, Hopper AJ, Seitz LB, Nimphius S, and Haff GG. Effects of cluster sets on acute hypertrophic variables and fatigue during a high-volume squat session. National Strength and Conditioning Association Annual Conference, Orlando, FL, July 2015.

Journal of Strength and Conditioning Research | www.nsca.com

difference; $d = -1.05$, -0.92, and -0.83 over 5, 10 and 15 m respectively). The weaker TRAIN subjects displayed improved endurance paddling performance compared to the stronger subjects (92% likelihood of substantial true difference; $d = -0.62$). **Conclusions:** Short-term exposure to maximal strength training elicits improvements in paddling performance measures. However, the magnitude of performance increases appears dependent on initial strength levels with differential responses between strong and weaker athletes. **Practical Applications:** Although a longer maximal strength training period may have produced more significant paddling improvements in stronger subjects, the nature of professional surfing means that practitioners are unlikely to have any more than 5 weeks in an uninterrupted block with athletes. This study appears to reveal a "threshold" level of maximal strength (1.2 relative 1RM Pull Up) that if possessed, there seems to be little improvement in paddling performance with short-term maximal strength training. As such, thorough investigations into the point this maximal strength "threshold" is reached for individual sports would be important to determine for strength and conditioning practitioners.

EFFECTS OF CLUSTER SETS ON ACUTE HYPERTROPHIC VARIABLES AND FATIGUE DURING A HIGH-VOLUME SQUAT SESSION

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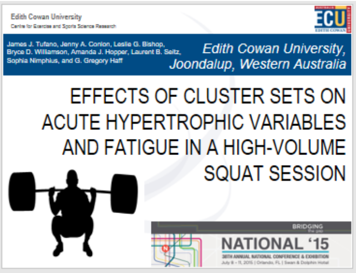
[1]*Centre for Exercise and Sport Science Research, Edith Cowan University; and* [2]*Edith Cowan University*

Performing multiple repetitions in sequence results in a decrease in velocity. Hence, power training does not normally coincide with high-volume training. However, it may be possible to maintain repetition velocity during high-volume protocols by adding extra rest periods. **Purpose:** The purpose of this study was to determine the effects of cluster sets (CS) on total work (TW), concentric time under tension (TUT), peak concentric velocity (PV), and PV maintenance (PV%), expressed as a percentage of the initial repetition's PV. **Methods:** Twelve resistance trained men (26.00 ± 4.2 years; 83.06 ± 8.8 kg; 153.44 ± 18.4 kg 1RM; 1RM:body mass = 1.88:1) performed 3 sets of 12 back squat repetitions using 3 different set configurations: traditional sets (TRD) with 60% 1RM where all repetitions within a set were performed successively; cluster sets of 4 (CLU4) with 75% 1RM, inclusive of 30 seconds rest after the fourth and eighth repetition of each set; and cluster sets of 2 (CLU2) with 80% 1RM, inclusive of 30 seconds rest after the second, fourth, sixth, eighth, and 10th repetition of each set. Subjects were instructed to perform full squats (mean peak knee flexion 120.75 ± 12.41°) and were verbally encouraged to perform the eccentric phase under control and concentric phase as explosively as possible. Two minutes of seated rest were given between each set in all 3 protocols. A minimum of 48 hours was required between protocols, which were performed in random order. Force-time data were collected at 1,000 Hz. **Results:** Repeated measures ANOVAs (3 protocol × 3 set) were used to find significant differences ($p \leq 0.05$). Main effects for protocol were found for TW and TUT with CLU2 > CLU4 > TRD, and for PV with CLU2 < CLU4 < TRD. Main effects for set were found for TUT with set 1 < set 2 < set 3, and for PV and PV% with set 1 > set 2 > set 3. No protocol × time interactions were present. Data are presented in Table 1. **Conclusions:** By utilizing cluster sets, subjects were able to use a greater load for a given number of repetitions without experiencing a greater decrease in velocity. Therefore, cluster sets allow for greater work to be performed while experiencing the same rate of velocity-assessed fatigue when compared to traditional sets using less load. Since hypertrophy is largely

	CLU2 Collapsed Sets Mean(*SD*) CLU2 Sets 1; 2; and 3 Mean(*SD*)	CLU4 Collapsed Sets Mean(*SD*) CLU4 Sets 1; 2; and 3 Mean(*SD*)	TRD Collapsed Sets Mean(*SD*) TRD Sets 1; 2; and 3 Mean(*SD*)
TW (kJ)	2.44(0.25) 2.44(0.26); 2.45(0.25); 2.45(0.25)	2.35(0.23) 2.34(0.23); 2.36(0.24); 2.34(0.24)	2.13(0.22) 2.12(0.21); 2.13(0.22); 2.14(0.22)
TUT (s)	1.34(0.19) 1.26(0.18); 1.33(0.19); 1.41(0.24)	1.20(0.15) 1.14(0.14); 1.19(0.14); 1.26(0.18)	0.97(0.10) 0.95(0.09); 0.96(0.09); 0.99(0.11)
PV ($m^{-1}s$)	0.99(0.15) 1.01(0.13); 0.99(0.16); 0.96(0.19)	1.04(0.17) 1.08(0.16); 1.05(.018); 1.00(0.18)	1.16(0.17) 1.17(0.19); 1.15(0.17); 1.14(0.16)
PV% (%)	93.0(9.29) 96.1(5.80); 92.9(10.9); 90.0(13.9)	94.0(7.21) 97.4(6.30); 94.5(8.83); 90.3(8.31)	93.0(8.21) 94.0(7.32); 92.9(9.24); 92.0(9.89)

Table 1. Cluster sets of 2 (CLU2), Cluster sets of 4 (CLU4), and Traditional sets (TRD). Total work (TW) in kilojoules, concentric time under tension (TUT) in seconds, peak velocity (PV) in meters per second, and peak velocity percentage (PV%) as the percentage of the initial repetition's peak velocity.



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James J. Tufano, Jenny A. Conlon, Leslie G. Bishop, Bryce D. Williamson, Amanda J. Hopper, Laurent B. Seitz, Sophia Nimphius, and G. Gregory Haff

Edith Cowan University, Joondalup, Western Australia

EFFECTS OF CLUSTER SETS ON ACUTE HYPERTROPHIC VARIABLES AND FATIGUE IN A HIGH-VOLUME SQUAT SESSION

BRIDGING the gap
NATIONAL '15
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July 8 - 11, 2015 | Orlando, FL | Swan & Dolphin Hotel

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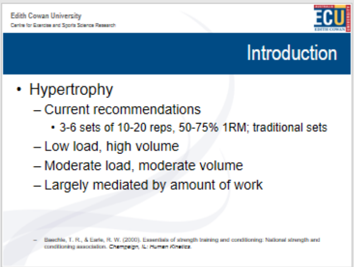

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Introduction

- Hypertrophy
  - Current recommendations
    - 3-6 sets of 10-20 reps, 50-75% 1RM; traditional sets
  - Low load, high volume
  - Moderate load, moderate volume
  - Largely mediated by amount of work

– Baechle, T. R., & Earle, R. W. (2000). Essentials of strength training and conditioning: National strength and conditioning association. Champaign, IL: Human Kinetics.

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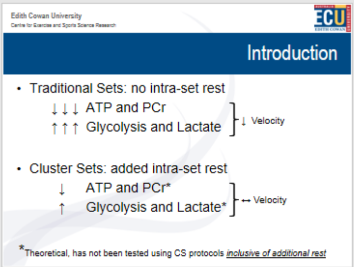

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Introduction

- Traditional Sets: no intra-set rest
  - ↓↓↓ ATP and PCr
  - ↑↑↑ Glycolysis and Lactate
  - } ↓ Velocity
- Cluster Sets: added intra-set rest
  - ↓ ATP and PCr*
  - ↑ Glycolysis and Lactate*
  - } ↔ Velocity

*Theoretical, has not been tested using CS protocols *inclusive of additional rest*

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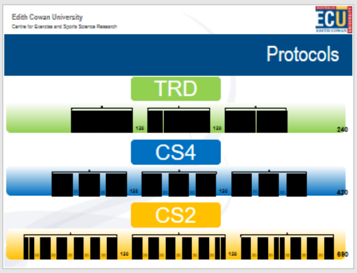

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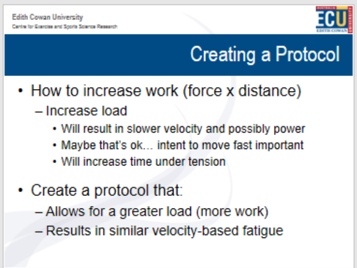
Protocols

4



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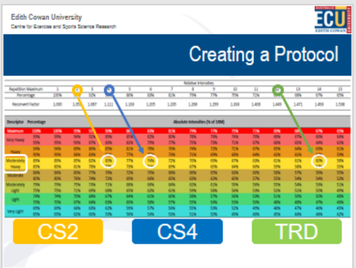
Creating a Protocol

- How to increase work (force x distance)
  - Increase load
    - Will result in slower velocity and possibly power
    - Maybe that's ok… intent to move fast important
    - Will increase time under tension
- Create a protocol that:
  - Allows for a greater load (more work)
  - Results in similar velocity-based fatigue

5



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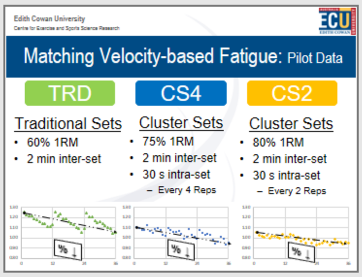
Creating a Protocol

6



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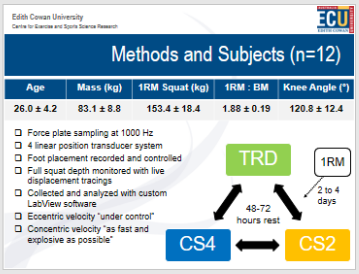
Matching Velocity-based Fatigue: Pilot Data

TRD	CS4	CS2
Traditional Sets	Cluster Sets	Cluster Sets
• 60% 1RM • 2 min inter-set	• 75% 1RM • 2 min inter-set • 30 s intra-set – Every 4 Reps	• 80% 1RM • 2 min inter-set • 30 s intra-set – Every 2 Reps

7



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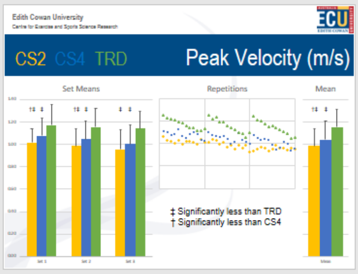
Methods and Subjects (n=12)

Age	Mass (kg)	1RM Squat (kg)	1RM : BM	Knee Angle (°)
26.0 ± 4.2	83.1 ± 8.8	153.4 ± 18.4	1.88 ± 0.19	120.8 ± 12.4

- ☐ Force plate sampling at 1000 Hz
- ☐ 4 linear position transducer system
- ☐ Foot placement recorded and controlled
- ☐ Full squat depth monitored with live displacement tracings
- ☐ Collected and analyzed with custom LabView software
- ☐ Eccentric velocity "under control"
- ☐ Concentric velocity "as fast and explosive as possible"

8 ★



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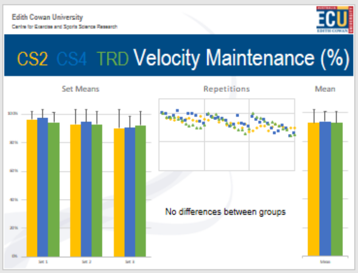
CS2 CS4 TRD Peak Velocity (m/s)

‡ Significantly less than TRD
† Significantly less than CS4

9 ★



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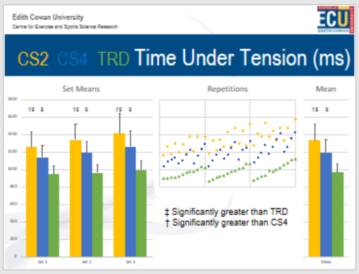
CS2 CS4 TRD Velocity Maintenance (%)

No differences between groups

10 ★



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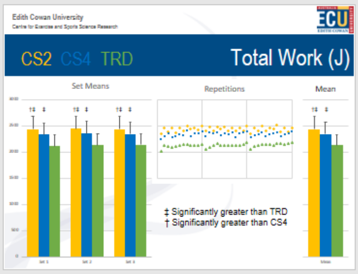
CS2 CS4 TRD Time Under Tension (ms)

‡ Significantly greater than TRD
† Significantly greater than CS4

11 ★



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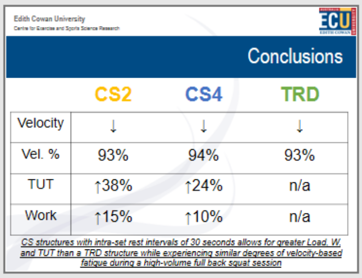
CS2 CS4 TRD Total Work (J)

‡ Significantly greater than TRD
† Significantly greater than CS4

12 ★



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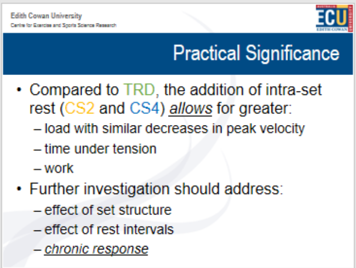
Conclusions

	CS2	CS4	TRD
Velocity	↓	↓	↓
Vel. %	93%	94%	93%
TUT	↑38%	↑24%	n/a
Work	↑15%	↑10%	n/a

CS structures with intra-set rest intervals of 30 seconds allows for greater Load, W, and TUT than a TRD structure while experiencing similar degrees of velocity-based fatigue during a high-volume full back squat session

13



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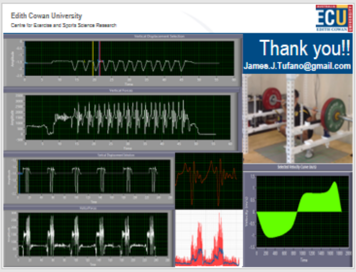
Practical Significance

- Compared to TRD, the addition of intra-set rest (CS2 and CS4) *allows* for greater:
  - load with similar decreases in peak velocity
  - time under tension
  - work
- Further investigation should address:
  - effect of set structure
  - effect of rest intervals
  - *chronic response*

14



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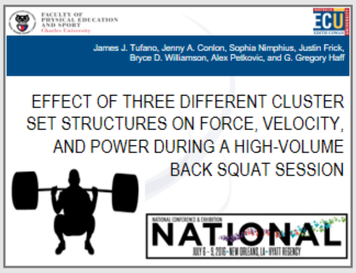
Thank you!!
James.J.Tufano@gmail.com

15

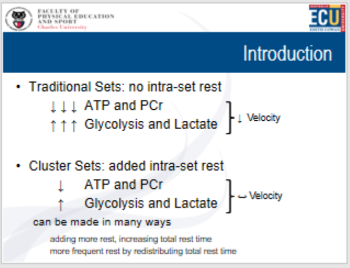
Chapter 5

Tufano JJ, Conlon JA, Nimphius S, Frick J, Williamson BD, Petkovic A, Haff GG. Effect of three different cluster set structures on force, velocity, and power during a high-volume back squat session. National Strength and Conditioning Association Annual Conference, New Orleans, LA, July 2016.



James J. Tufano, Jenny A. Conlon, Sophia Nimphius, Justin Frick, Bryce D. Williamson, Alex Petkovic, and G. Gregory Haff

EFFECT OF THREE DIFFERENT CLUSTER SET STRUCTURES ON FORCE, VELOCITY, AND POWER DURING A HIGH-VOLUME BACK SQUAT SESSION

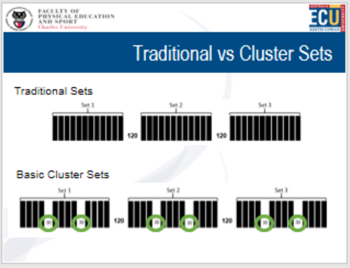


Introduction

- Traditional Sets: no intra-set rest
  ↓↓↓ ATP and PCr
  ↑↑↑ Glycolysis and Lactate } ↓ Velocity
- Cluster Sets: added intra-set rest
  ↓ ATP and PCr
  ↑ Glycolysis and Lactate } ↔ Velocity

can be made in many ways

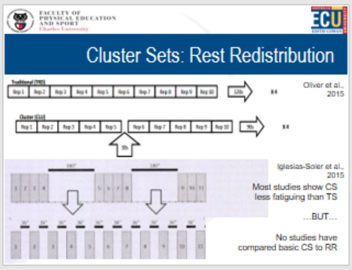
adding more rest, increasing total rest time
more frequent rest by redistributing total rest time



Traditional vs Cluster Sets

Traditional Sets

Basic Cluster Sets



Cluster Sets: Rest Redistribution

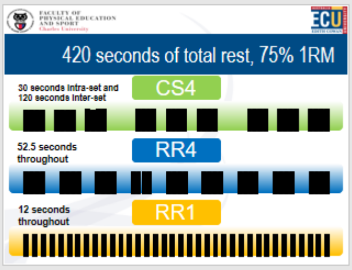
Oliver et al., 2015

Iglesias-Soler et al., 2015

Most studies show CS less fatiguing than TS

…BUT…

No studies have compared basic CS to RR

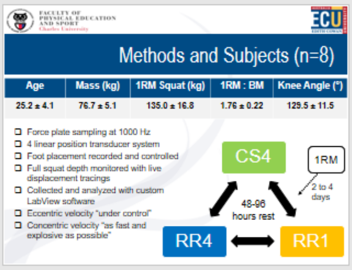


420 seconds of total rest, 75% 1RM

30 seconds intra-set and 120 seconds inter-set

52.5 seconds throughout

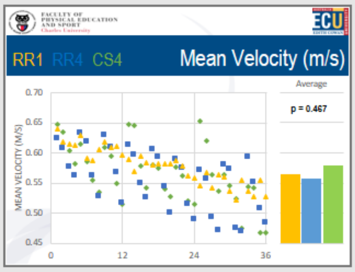
12 seconds throughout



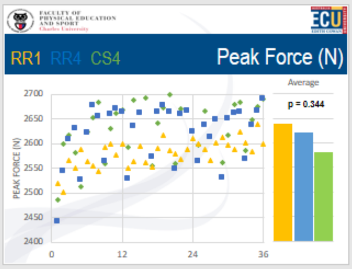
Methods and Subjects (n=8)

Age	Mass (kg)	1RM Squat (kg)	1RM : BM	Knee Angle (°)
25.2 ± 4.1	76.7 ± 5.1	135.0 ± 16.8	1.76 ± 0.22	129.5 ± 11.5

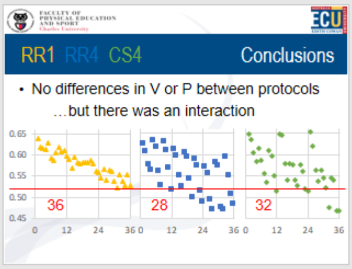
- ☐ Force plate sampling at 1000 Hz
- ☐ 4 linear position transducer system
- ☐ Foot placement recorded and controlled
- ☐ Full squat depth monitored with live displacement tracings
- ☐ Collected and analyzed with custom LabView software
- ☐ Eccentric velocity "under control"
- ☐ Concentric velocity "as fast and explosive as possible"



RR1 RR4 CS4 Mean Velocity (m/s)

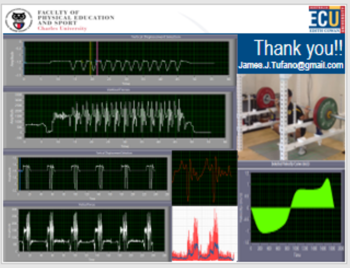


RR1 RR4 CS4 Peak Force (N)



RR1 RR4 CS4 Conclusions

- No differences in V or P between protocols
  …but there was an interaction



Thank you!!
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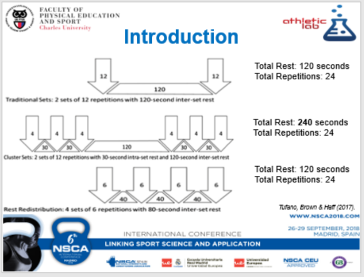
Chapter 7

Jukić I, Young M, **Tufano JJ**. Effects of different set structures on RPE, velocity and power decrement during a back squat exercise. National Strength and Conditioning Association International Conference, Madrid, Spain, September 2018.

LINKING SPORT SCIENCE AND APPLICATION

Effects of different set structures on RPE, velocity and power decrement during a back squat exercise

Ivan Jukić, Mike Young & James J. Tufano



Introduction

Traditional Sets: 2 sets of 12 repetitions with 120-second inter-set rest

Total Rest: 120 seconds
Total Repetitions: 24

Cluster Sets: 2 sets of 12 repetitions with 30-second intra-set rest and 120-second inter-set rest

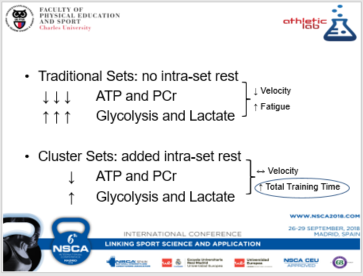
Total Rest: **240** seconds
Total Repetitions: 24

Rest Redistribution: 4 sets of 6 repetitions with 80-second inter-set rest

Total Rest: 120 seconds
Total Repetitions: 24

Tufano, Brown & Haff (2017).

WWW.NSCA2018.COM
26-29 SEPTEMBER, 2018 MADRID, SPAIN
INTERNATIONAL CONFERENCE
LINKING SPORT SCIENCE AND APPLICATION

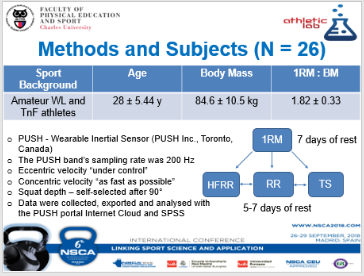


- Traditional Sets: no intra-set rest
  - ↓↓↓ ATP and PCr
  - ↑↑↑ Glycolysis and Lactate

↓ Velocity
↑ Fatigue

- Cluster Sets: added intra-set rest
  - ↓ ATP and PCr
  - ↑ Glycolysis and Lactate

↔ Velocity
↑ Total Training Time

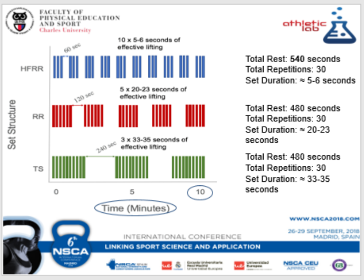


Methods and Subjects (N = 26)

Sport Background	Age	Body Mass	1RM : BM
Amateur WL and TnF athletes	28 ± 5.44 y	84.6 ± 10.5 kg	1.82 ± 0.33

- PUSH - Wearable Inertial Sensor (PUSH Inc., Toronto, Canada)
- The PUSH band's sampling rate was 200 Hz
- Eccentric velocity "under control"
- Concentric velocity "as fast as possible"
- Squat depth – self-selected after 90°
- Data were collected, exported and analysed with the PUSH portal Internet Cloud and SPSS

1RM
7 days of rest
HFRR
RR
TS
5-7 days of rest



10 x 5-6 seconds of effective lifting

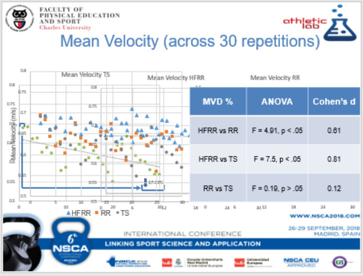
5 x 20-23 seconds of effective lifting

3 x 33-35 seconds of effective lifting

Total Rest: **540** seconds
Total Repetitions: 30
Set Duration: ≈ 5-6 seconds

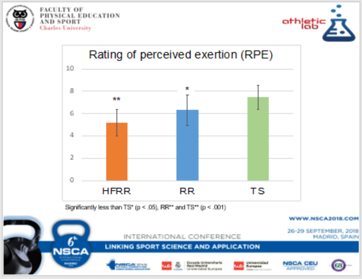
Total Rest: 480 seconds
Total Repetitions: 30
Set Duration: ≈ 20-23 seconds

Total Rest: 480 seconds
Total Repetitions: 30
Set Duration: ≈ 33-35 seconds

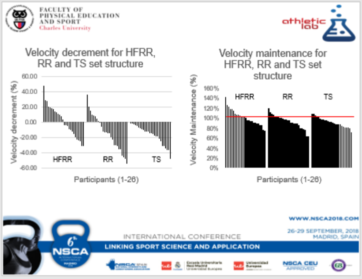


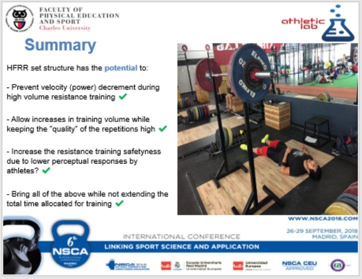
Mean Velocity (across 30 repetitions)

MVD %	ANOVA	Cohen's d
HFRR vs RR	F = 4.91, p < .05	0.61
HFRR vs TS	F = 7.5, p < .05	0.81
RR vs TS	F = 0.19, p > .05	0.12



Significantly less than TS* (p < .05), RR** and TS** (p < .001)





Summary

HFRR set structure has the potential to:

- Prevent velocity (power) decrement during high volume resistance training ✓

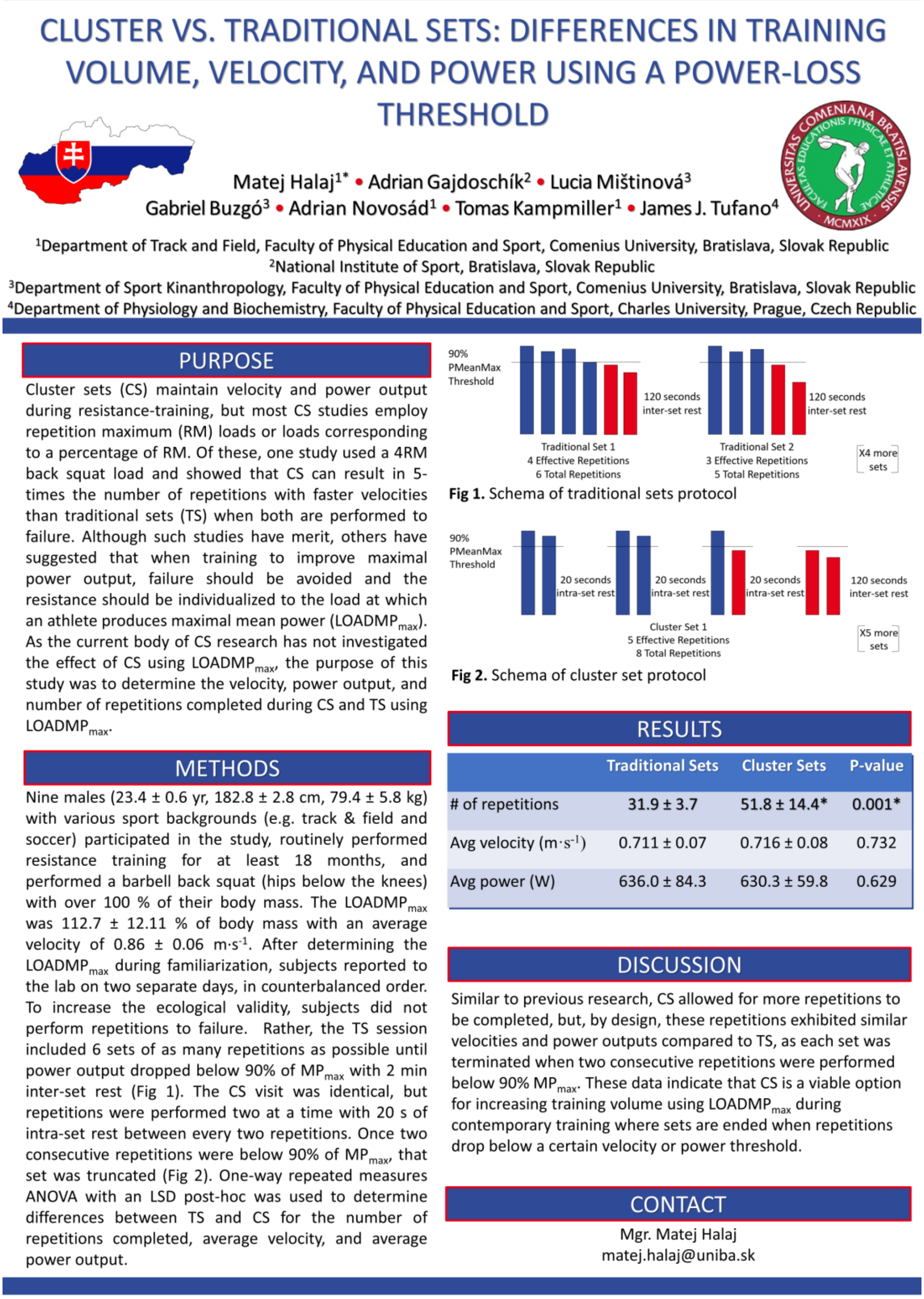
- Allow increases in training volume while keeping the "quality" of the repetitions high ✓

- Increase the resistance training safetyness due to lower perceptual responses by athletes? ✓

- Bring all of the above while not extending the total time allocated for training ✓

Chapter 8

Halaj M, Gajdoschík A, Mištinová L, Buzgó G, Novosád A, Kampmiller T, **Tufano JJ**. Cluster vs traditional sets: differences in training volume, velocity, and power using a power-loss threshold. National Strength and Conditioning Association International Conference, Madrid, Spain, September 2018.



CLUSTER VS. TRADITIONAL SETS: DIFFERENCES IN TRAINING VOLUME, VELOCITY, AND POWER USING A POWER-LOSS THRESHOLD

Matej Halaj[1*] • Adrian Gajdoschík[2] • Lucia Mištinová[3]
Gabriel Buzgó[3] • Adrian Novosád[1] • Tomas Kampmiller[1] • James J. Tufano[4]

[1]Department of Track and Field, Faculty of Physical Education and Sport, Comenius University, Bratislava, Slovak Republic
[2]National Institute of Sport, Bratislava, Slovak Republic
[3]Department of Sport Kinanthropology, Faculty of Physical Education and Sport, Comenius University, Bratislava, Slovak Republic
[4]Department of Physiology and Biochemistry, Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic

PURPOSE

Cluster sets (CS) maintain velocity and power output during resistance-training, but most CS studies employ repetition maximum (RM) loads or loads corresponding to a percentage of RM. Of these, one study used a 4RM back squat load and showed that CS can result in 5-times the number of repetitions with faster velocities than traditional sets (TS) when both are performed to failure. Although such studies have merit, others have suggested that when training to improve maximal power output, failure should be avoided and the resistance should be individualized to the load at which an athlete produces maximal mean power (LOADMP_{max}). As the current body of CS research has not investigated the effect of CS using LOADMP_{max}, the purpose of this study was to determine the velocity, power output, and number of repetitions completed during CS and TS using LOADMP_{max}.

METHODS

Nine males (23.4 ± 0.6 yr, 182.8 ± 2.8 cm, 79.4 ± 5.8 kg) with various sport backgrounds (e.g. track & field and soccer) participated in the study, routinely performed resistance training for at least 18 months, and performed a barbell back squat (hips below the knees) with over 100 % of their body mass. The LOADMP_{max} was 112.7 ± 12.11 % of body mass with an average velocity of 0.86 ± 0.06 $m{\cdot}s^{-1}$. After determining the LOADMP_{max} during familiarization, subjects reported to the lab on two separate days, in counterbalanced order. To increase the ecological validity, subjects did not perform repetitions to failure. Rather, the TS session included 6 sets of as many repetitions as possible until power output dropped below 90% of MP_{max} with 2 min inter-set rest (Fig 1). The CS visit was identical, but repetitions were performed two at a time with 20 s of intra-set rest between every two repetitions. Once two consecutive repetitions were below 90% of MP_{max}, that set was truncated (Fig 2). One-way repeated measures ANOVA with an LSD post-hoc was used to determine differences between TS and CS for the number of repetitions completed, average velocity, and average power output.

Fig 1. Schema of traditional sets protocol

Fig 2. Schema of cluster set protocol

RESULTS

	Traditional Sets	Cluster Sets	P-value
# of repetitions	31.9 ± 3.7	51.8 ± 14.4*	0.001*
Avg velocity ($m{\cdot}s^{-1}$)	0.711 ± 0.07	0.716 ± 0.08	0.732
Avg power (W)	636.0 ± 84.3	630.3 ± 59.8	0.629

DISCUSSION

Similar to previous research, CS allowed for more repetitions to be completed, but, by design, these repetitions exhibited similar velocities and power outputs compared to TS, as each set was terminated when two consecutive repetitions were performed below 90% MP_{max}. These data indicate that CS is a viable option for increasing training volume using LOADMP_{max} during contemporary training where sets are ended when repetitions drop below a certain velocity or power threshold.

CONTACT

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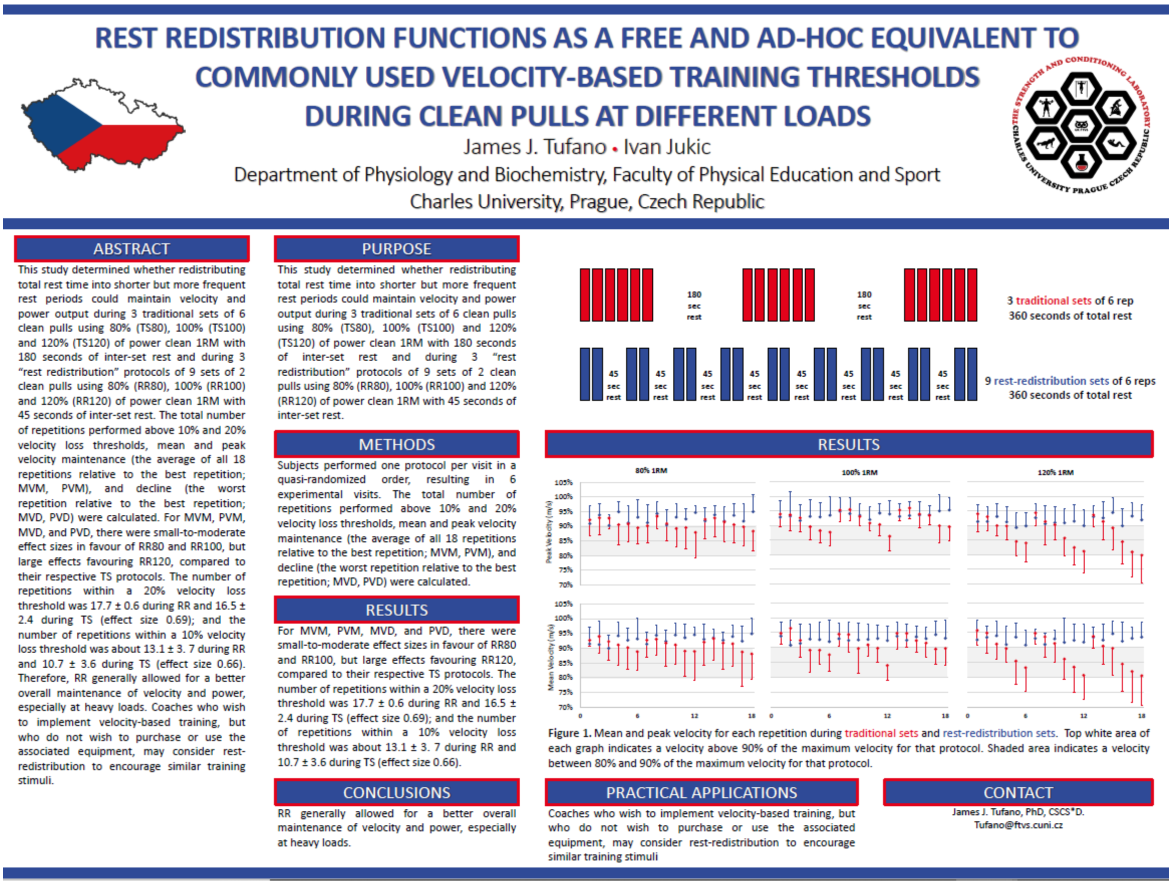
Chapter 9

Tufano JJ, Jukic I. Rest redistribution functions as a free and ad-hoc equivalent to commonly used velocity-based training thresholds during clean pulls at different loads. National Strength and Conditioning Association Annual Conference, Washington DC, July 2019.



REST REDISTRIBUTION FUNCTIONS AS A FREE AND AD-HOC EQUIVALENT TO COMMONLY USED VELOCITY-BASED TRAINING THRESHOLDS DURING CLEAN PULLS AT DIFFERENT LOADS

James J. Tufano • Ivan Jukic
Department of Physiology and Biochemistry, Faculty of Physical Education and Sport
Charles University, Prague, Czech Republic

ABSTRACT

This study determined whether redistributing total rest time into shorter but more frequent rest periods could maintain velocity and power output during 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest and during 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. The total number of repetitions performed above 10% and 20% velocity loss thresholds, mean and peak velocity maintenance (the average of all 18 repetitions relative to the best repetition; MVM, PVM), and decline (the worst repetition relative to the best repetition; MVD, PVD) were calculated. For MVM, PVM, MVD, and PVD, there were small-to-moderate effect sizes in favour of RR80 and RR100, but large effects favouring RR120, compared to their respective TS protocols. The number of repetitions within a 20% velocity loss threshold was 17.7 ± 0.6 during RR and 16.5 ± 2.4 during TS (effect size 0.69); and the number of repetitions within a 10% velocity loss threshold was about 13.1 ± 3. 7 during RR and 10.7 ± 3.6 during TS (effect size 0.66). Therefore, RR generally allowed for a better overall maintenance of velocity and power, especially at heavy loads. Coaches who wish to implement velocity-based training, but who do not wish to purchase or use the associated equipment, may consider rest-redistribution to encourage similar training stimuli.

PURPOSE

This study determined whether redistributing total rest time into shorter but more frequent rest periods could maintain velocity and power output during 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest and during 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest.

METHODS

Subjects performed one protocol per visit in a quasi-randomized order, resulting in 6 experimental visits. The total number of repetitions performed above 10% and 20% velocity loss thresholds, mean and peak velocity maintenance (the average of all 18 repetitions relative to the best repetition; MVM, PVM), and decline (the worst repetition relative to the best repetition; MVD, PVD) were calculated.

RESULTS

For MVM, PVM, MVD, and PVD, there were small-to-moderate effect sizes in favour of RR80 and RR100, but large effects favouring RR120, compared to their respective TS protocols. The number of repetitions within a 20% velocity loss threshold was 17.7 ± 0.6 during RR and 16.5 ± 2.4 during TS (effect size 0.69); and the number of repetitions within a 10% velocity loss threshold was about 13.1 ± 3. 7 during RR and 10.7 ± 3.6 during TS (effect size 0.66).

CONCLUSIONS

RR generally allowed for a better overall maintenance of velocity and power, especially at heavy loads.

3 traditional sets of 6 rep
360 seconds of total rest

9 rest-redistribution sets of 6 reps
360 seconds of total rest

RESULTS

Figure 1. Mean and peak velocity for each repetition during traditional sets and rest-redistribution sets. Top white area of each graph indicates a velocity above 90% of the maximum velocity for that protocol. Shaded area indicates a velocity between 80% and 90% of the maximum velocity for that protocol.

PRACTICAL APPLICATIONS

Coaches who wish to implement velocity-based training, but who do not wish to purchase or use the associated equipment, may consider rest-redistribution to encourage similar training stimuli

CONTACT

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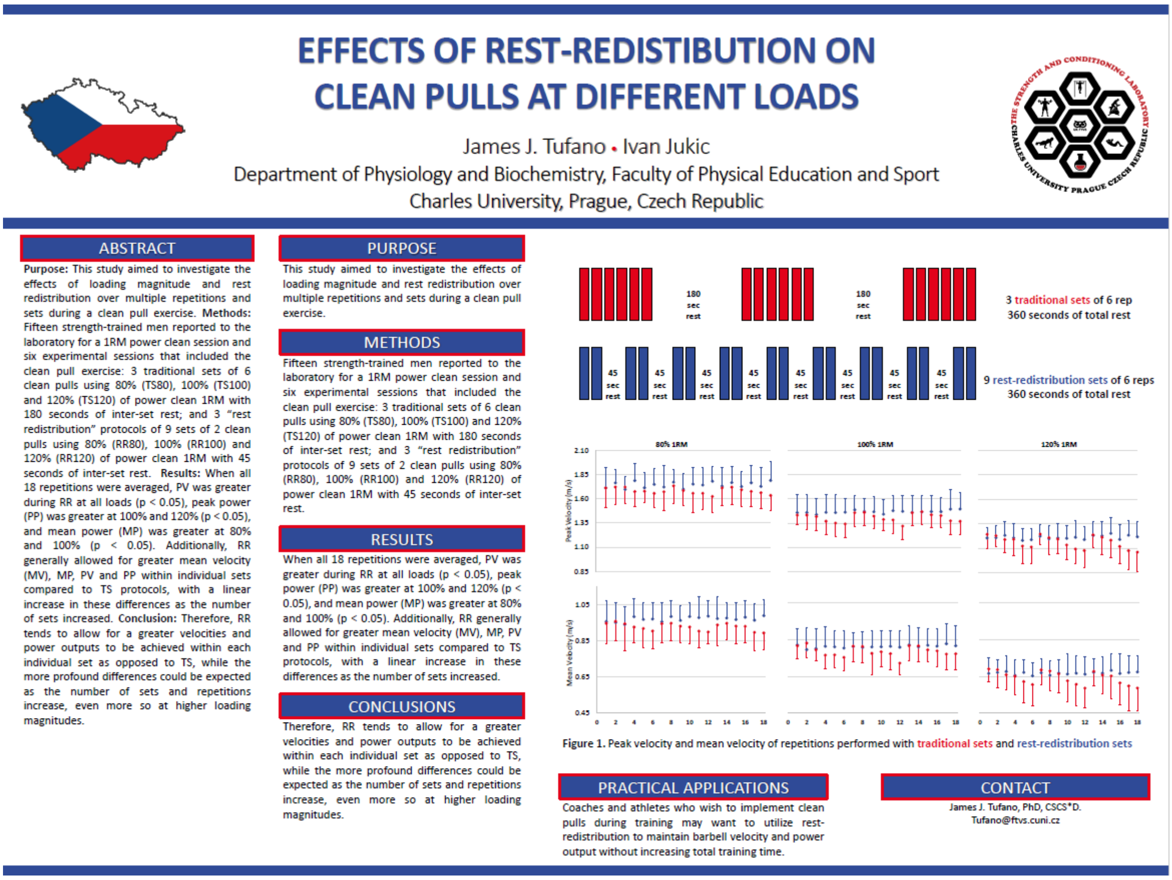
Tufano@ftvs.cuni.cz

Chapter 10

Tufano JJ, Jukic I. The effects of rest redistribution on velocity and power during clean pulls at different loads. National Strength and Conditioning Association Annual Conference, Washington DC, July 2019.



EFFECTS OF REST-REDISTRIBUTION ON CLEAN PULLS AT DIFFERENT LOADS

James J. Tufano • Ivan Jukic
Department of Physiology and Biochemistry, Faculty of Physical Education and Sport
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ABSTRACT

Purpose: This study aimed to investigate the effects of loading magnitude and rest redistribution over multiple repetitions and sets during a clean pull exercise. **Methods:** Fifteen strength-trained men reported to the laboratory for a 1RM power clean session and six experimental sessions that included the clean pull exercise: 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest. **Results:** When all 18 repetitions were averaged, PV was greater during RR at all loads ($p < 0.05$), peak power (PP) was greater at 100% and 120% ($p < 0.05$), and mean power (MP) was greater at 80% and 100% ($p < 0.05$). Additionally, RR generally allowed for greater mean velocity (MV), MP, PV and PP within individual sets compared to TS protocols, with a linear increase in these differences as the number of sets increased. **Conclusion:** Therefore, RR tends to allow for a greater velocities and power outputs to be achieved within each individual set as opposed to TS, while the more profound differences could be expected as the number of sets and repetitions increase, even more so at higher loading magnitudes.

PURPOSE

This study aimed to investigate the effects of loading magnitude and rest redistribution over multiple repetitions and sets during a clean pull exercise.

METHODS

Fifteen strength-trained men reported to the laboratory for a 1RM power clean session and six experimental sessions that included the clean pull exercise: 3 traditional sets of 6 clean pulls using 80% (TS80), 100% (TS100) and 120% (TS120) of power clean 1RM with 180 seconds of inter-set rest; and 3 "rest redistribution" protocols of 9 sets of 2 clean pulls using 80% (RR80), 100% (RR100) and 120% (RR120) of power clean 1RM with 45 seconds of inter-set rest.

RESULTS

When all 18 repetitions were averaged, PV was greater during RR at all loads ($p < 0.05$), peak power (PP) was greater at 100% and 120% ($p < 0.05$), and mean power (MP) was greater at 80% and 100% ($p < 0.05$). Additionally, RR generally allowed for greater mean velocity (MV), MP, PV and PP within individual sets compared to TS protocols, with a linear increase in these differences as the number of sets increased.

CONCLUSIONS

Therefore, RR tends to allow for a greater velocities and power outputs to be achieved within each individual set as opposed to TS, while the more profound differences could be expected as the number of sets and repetitions increase, even more so at higher loading magnitudes.

Figure 1. Peak velocity and mean velocity of repetitions performed with traditional sets and rest-redistribution sets

PRACTICAL APPLICATIONS

Coaches and athletes who wish to implement clean pulls during training may want to utilize rest-redistribution to maintain barbell velocity and power output without increasing total training time.

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