A BIOMECHANICAL ANALYSIS OF WEIGHTLIFTING PULLING DERIVATIVES AND THEIR APPLICATION TO PERFORMANCE PROGRAMMING

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List of Co-Authored Publications

The following peer reviewed publications resulted from work contained in this thesis:

1. ***Arising from Chapter 3**:* Meechan, D, Suchomel, TJ, McMahon, JJ, and Comfort, P. A comparison of kinetic and kinematic variables during the midthigh pull and countermovement shrug, across loads. J Strength Cond Res 34 (7): 1830–1841, 2020
2. ***Arising from Chapter 4**:* Meechan, D, McMahon, JJ, Suchomel, TJ, and Comfort, P. A comparison of kinetic and kinematic variables during the pull from the knee and hang pull, across loads. J Strength Cond Res 34 (7): 1819–1829, 2020
3. ***Arising from Chapter 5:*** Meechan, D, McErlain-Naylor, S, McMahon, JJ, Suchomel, TJ, and Comfort P. Comparing Biomechanical Time Series Data Across Loads During the Hang Pull. J Sports Sci (Accepted 2022)
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Declaration

I declare that the work contained in this thesis has not been submitted for any other award. I confirm that it is all my own work and fully acknowledges opinions, ideas, and contributions from the work of others. All work included in this thesis has received ethical approval from the Ethics Committee at the University of Salford.

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Date: 27th June 2022

Abstract

The aims of the studies within this thesis were to determine if kinetics and kinematics differences occur between weightlifting pulling derivatives across loads, and to provide greater context regarding biomechanical time series data across loads. Additionally, another aim was to determine the effect of inter-repetition rest during these exercises and establish how they may be more effectively implemented into training programmes. The results of study 1 showed that the countermovement shrug (CMS) elicited greater kinetics and kinematics than the mid-thigh pull (MTP) across all loads (40-140% one repetition maximum [1-RM] power clean [PC]), highlighting greater acute outputs. Similarly, the results of study 2 demonstrated greater kinetic and kinematic outputs during the hang pull (HP), across all loads (40-140% 1-RM PC), compared to the pull from the knee (PFK), highlighting the benefits of utilising the stretch shortening cycle. During the CMS (Study 3) and HP (Study 4) statistical parametric mapping was used to establish where differences exist across the entire movement, in addition to peak and mean values. Results indicated greater negative velocity at heavier loads early in the unweighting phase, and greater positive velocity at lower loads during the last 13-16% of the movement. At higher loads, the braking and propulsive phases commence at an earlier percentage of the time-normalised movement, and the total absolute durations increase with load. Study 5 was performed to examine the effect of rest redistribution (RR) on kinetics, kinematics and perceptual effort during the CMS and determined that there were no differences in kinetics and kinematics compared to traditional set (TS) configurations. Lastly, Study 6 was performed to determine the effects of RR on the kinetics, kinematics and perceptual effort during HP and showed that RR protocols did not result in greater kinetics or kinematics during the HP compared to TS, however performing 6x3 (RR_{72}) appears to be a better in maximising velocity compared to RR protocol compared to 9x2 (RR_{45}). The findings across the six studies provide practitioners with: 1) a greater insight into the acute differences between the MTP vs. CMS and PFK vs. HP, which may aid in exercise selection; 2) a greater understanding of how load affects the time-normalised waveform during the CMS and HP, using statistical parametric mapping, and where differences lie outside peak values; 3) RR protocols did not result in greater kinetics or kinematics during the CMS compared to TS, when total rest time was equated, likely due to the limited barbell displacement not resulting in a decline in performance during the TS.

Keywords: Weightlifting pulling derivatives, rest redistribution, sports performance; time normalisation

List of Commonly Used Abbreviations

1-RM: One Repetition Maximum.
2-D: Two-Dimensional
3-D: Three-Dimensional
4BT: 4-bounce test
ANOVA: Analysis of Variance
BM: Body Mass
BV: Barbell Velocity
BW: Bodyweight
CI: Confidence Intervals
CLU: Cluster Sets
CM: Centre of Mass
cm: Centimetre
CMJ: Countermovement Jump
CMS: Countermovement shrug
COM: Centre of Mass
CP: Clean Pull
CS: Cluster Sets
CT: Cluster Training
CV%: Coefficient of Variation
D-t: Displacement-Time
d: Cohen's *d* effect size
ES: Effect Size
EW:R: Equal Work to Rest Ratio
F-t: Force-Time
FP: Force Plate
FPS: Frames per Second
g: Hedge's *g* effect size
GRF: Ground Reaction Force
HHP: Hang High Pull
HP: Hang Pull
HPC: Hang Power Clean
Hz: Hertz
ICC: Intraclass Correlation Coefficient
IMP: Impulse
IMTP: Isometric Mid-thigh Pull
IRR: Inter-repetition rest
JH: Jump Height
JS: Jump Squat
JShrug: Jump Shrug
Kg: Kilogram
LPT: Linear Position Transducer
m: Meter
m.s-^{1}: Meters per Second
MASS: Mass
MF: Mean Force
MK: Margaria-Kalamen
MP: Mean Power
MRFD: Mean Rate of Force Development
ms: Milliseconds
MSV: Mean System Velocity
MTCP: Mid-Thigh Clean Pull
MTP: Mid-Thigh Pull
MTPC: Mid-Thigh Power Clean
MV: Mean Velocity
MVIC: Maximal Voluntary Isometric Contraction
N: Newtons
N.s: Newtons per Second
NCAA: National Collegiate Athletic Association
P-t: Power-Time
PBV: Peak Barbell Velocity
PHV: Peak Height Velocity
PLYO: Plyometric
PP: Peak Power
PRFD: Peak Rate of Force Development
PSV: Peak System Velocity
PUSH™: Push Accelerometer
PV: Peak Velocity
RFD: Rate of Force Development
RM: Repetition Maximum
ROM: Range of Motion
RPE: Rate of Perceived Exertion
RR: Rest Redistribution
RT: Resistance Training
s: Seconds
S&C: Strength & Conditioning
SD: Standard Deviation

SJ: Squat Jump
SPM: Statistical Parametric Mapping
SSC: Stretch Shortening Cycle
TOV: Take Off Velocity
TPF: Time to Peak Force
TPP: Time to Peak Power
TS: Traditional Sets
TUT: Time Under Tension
V-t: Velocity-Time
VGRF: Vertical Ground Reaction Force
VJ: Vertical Jump
W: Watts
W/Kg: Watts per Kilogram
WL: Weightlifting

Chapter 1: Introduction

The implementation of weightlifting movements (Snatch, and Clean and Jerk) and their derivatives are commonly included in training programmes in an attempt to improve athletic performance characteristics such as power and force (307). This is due to their ability to develop the rapid triple extension movement of the hips, knees, and ankles (plantar flexion), which are performed in a multitude of sporting tasks (36, 301, 302). Hence, performance during weightlifting movements has been shown to be correlated to sprint, jump and change of direction performance (154). Since many modalities exist to develop these characteristics, it is essential that practitioners prescribe the most appropriate methods during the appropriate training cycle/phase to develop enhance performance. Further, due to the existence of many modalities to train the rapid triple extension movement, optimal exercise selection and prescription may be challenging.

Prior research has demonstrated that although exercises such as plyometrics (274), sprints (351) and kettlebells (197, 258) may improve lower body strength-power characteristics, weightlifting movements may provide a greater training stimulus (258, 326) and are regularly implemented to develop strength-power characteristics (247). Research on weightlifting biomechanics demonstrated that the second pull phase produces the greatest force and power applied to the barbell in experienced weightlifters during the clean and power clean (PC) (91, 286). Interestingly, recent research on weightlifting pulling derivatives (i.e. those that exclude the catch phase) indicate that such exercises may provide a comparable (46) or greater (302, 316) training stimulus compared to catch derivatives, with prior research demonstrating that much of the benefit from weightlifting exercises comes from the pull rather than the catch (91, 313). Moreover, pulling derivatives permit supra-maximal loads (>100% 1 repetition maximum

[1-RM] of a catching derivative) to be performed (52, 55, 181), which has shown to elicit greater peak force (PF), rate of force development (RFD) and impulse than loads <1-RM PC (52, 55). This provides an overload stimulus of the triple extension movement, potentially producing superior strength-power characteristics (301, 302).

One issue in the literature is the different methodologies used when performing the weightlifting exercises and their derivatives. Some authors have performed these exercises from a static position from the floor (42, 64, 81, 82, 105, 107-109, 126, 285, 286), blocks (80, 83, 124, 181, 305), held at various positions (45, 46, 52, 53, 55), initiated with a prior countermovement (79, 298, 301-304, 310, 315, 316) and across a variety of loads (0-140% 1-RM) (47, 56, 79-83, 153, 154, 185, 188, 298-305, 307-310, 313-316). Each of these differences makes comparisons between studies problematic, for example the inclusion of a countermovement should stimulate the stretch shortening cycle (SSC) and therefore result in higher force, velocity and therefore power, although no direct comparisons between exercises performed with and without a countermovement have been published.

It would be worthwhile to identify if the addition or exclusion of the countermovement affects kinetic and kinematic variables during such exercises to determine if commencing from a static position (e.g., pull from knee/mid-thigh pull [PFK/MTP) or by stimulating the SSC via starting with a countermovement (e.g., hang pull/countermovement shrug [HP/CMS]), is most beneficial for enhancing force-time characteristics. If athletes perform certain variations of a derivative, then this may place different physiological demands throughout a periodised training cycle, and thus a potential for a different training adaptation. Depending upon the starting position and whether a countermovement or static start is used, a different stimulus may occur (302). Therefore, it is important for practitioner's to apply the most appropriate training stimulus at the correct time, based upon biomechanical and physiological characteristics (301). The way these movements are performed (i.e., one from a static position (PFK) and the other initiated with a countermovement [HP]) may allow athletes to develop greater concentric force-time characteristics (force, impulse, power) when initiated with a countermovement, which will ultimately determine optimal exercise selection. Therefore, further research is needed to establish differences between start positions, and how practitioners can implement these to enhance athletic performance.

When assessing differences in kinetics and kinematics in weightlifting derivatives, many researchers have primarily investigated discrete data i.e., differences between one time point during peak and mean outputs. While these results provide essential information about the peak and average mechanical outputs of the lifter-barbell system, derived from ground reaction force data, they only provide information about differences at one point in time, or the average across the propulsive phase. Additionally, given that typical mechanical peak values commonly occur during the second pull phase, these analyses often disregard parameters from the first and second pull phases, or the unweighting or braking (sometimes referred to as eccentric) phases, when a countermovement is used. To assess these limitations, researchers have used curve analyses to examine complete force-time, velocity-time, or power-time curves between weightlifting derivatives at one relative load (185, 313, 314). These types of analyses may benefit practitioners by providing not only instantaneous values along the curve, but also providing a greater mechanistic understanding of performance (314). Given the fact that no researcher has investigated the effect of load across the entire movement, it would be of benefit to practitioners to further enhance the understanding of the biomechanical mechanisms involved throughout the entire movement, and what impact this may have on training prescription, or the demands of each sub phase (e.g., unweighting, braking and propulsion durations and percentage of movement time). The findings of such research may offer novel insight into the differences between loads to inform subsequent load programming in different training cycles.

Although key exercise movements such as squats, pulling and pressing exercises may be implemented in all training phases (301), weightlifting exercises and their derivatives may be prescribed in specific phases due to the physiological and biomechanical characteristics that are associated with these movements (301, 302). Therefore, it is plausible that these exercises may be prescribed to meet the aims and training demands of each block of training. To determine the output of a specific training phase, the sets and repetitions of that phase should be properly structured for optimal performance. Within strength and strength-power blocks of training, overloading the triple extension movement with high force movements may be of interest to practitioners, with the ability to load weightlifting pulling exercises in excess of 1-RM (52, 55, 79-81, 126, 174, 176, 181, 301, 302). Regardless of the load lifted, performing many repetitions consecutively (i.e., traditional sets [TS]) with maximal effort is fatiguing, and increasing acute training volume further leads to decreases in velocity and power output (126, 176). Although many studies have broken TS into smaller more frequent sets (174, 176) to maintain velocity and power, these exercises have been performed from the floor (i.e., clean pull) which may be more fatiguing than when a shorter range of motion is performed in supramaximal weightlifting pulling derivatives (i.e. mid-thigh or hang derivatives). Therefore, it would be beneficial for practitioners to establish if these differences occur in exercises such as the HP and CMS, which have a lower range of motion compared to a clean pull (79, 83).

1.1. STATEMENT OF THE ORIGINALITY OF THE RESEARCH

The work contained in this thesis is to the best of my knowledge and belief; original, having not been published previously or written by another person except where due reference is made. The body of research contained within this thesis highlight those differences exist between kinetics and kinematics during weightlifting pulling derivatives across loads and between exercises, which have subsequently been published (See Chapters 3 and 4 for a comprehensive discussion on this). Chapters 5 and 6 are the first studies of their kind to compare biomechanical time series data across CMS loads and HP loads respectively. Chapters 7 and 8 are the first studies in which traditional set structures and rest redistribution set structure have been compared across supramaximal loads during the CMS and HP. It is anticipated that the results yielded from this research will be of high impact and great benefit to S&C coaches and sports performance researchers.

1.2. OVERARCHING AIMS

The overarching aim of the thesis is to investigate if differences exist in kinetics and kinematics between weightlifting pulling derivatives across loads, and to provide greater context and exercise prescription guidelines regarding practical applications of these exercises and how they may be implemented into training programmes.

The objectives of this thesis are:

1. To compare the effect of a countermovement on the mid-thigh pull (MTP) and establish if any differences occur between exercises, which may impact exercise prescription **(Chapter 3, Study 1).**

2. To compare the effect of a countermovement on the pull from the knee (PFK) and establish if any differences occur between exercises, which may impact exercise prescription **(Chapter 4, Study 2).**

3. To investigate the effects of load on temporal phase characteristics during the countermovement shrug (CMS), providing a more detailed and comprehensive analysis on the CMS **(Chapter 5, Study 3).**

4. To investigate the effects of load on temporal phase characteristics during the hang pull (HP), providing a more detailed and comprehensive analysis on the HP **(Chapter 6, Study 4).**

5. To determine if differences in kinetic and kinematics exist between traditional set structures and rest redistribution during the CMS at supramaximal loads and how this may impact exercise prescription **(Chapter 7, Study 5).**

6. To determine if differences in kinetic and kinematics exist between traditional set structures and rest redistribution during the HP at supramaximal loads and how this may impact exercise prescription. **(Chapter 8, Study 6).**

Chapter 2: Critical Review of the Literature

2.1. CHAPTER OVERVIEW

This literature review provides a background for the work conducted in this project and presents a clear rationale for the overall direction taken in this thesis. The literature review is broken down into three subsections: Power training methods (2.2), Kinetics and kinematics of weightlifting derivatives (2.3) and set configurations (cluster sets and rest redistribution) (2.4).

2.2. POWER TRAINING METHODS

2.2.1. Strength Development

Maximal strength can be defined as the heaviest load that can be lifted for a 1-RM (72), and is generally performed with multi-joint exercises with relatively high loads (85-95% 1-RM), for 4-6 sets per muscle group of 2-6 repetitions, with a 3-5 minute rest between sets, with a frequency of 2-3 days per week (282). Suchomel et al. (311) suggested that lower set prescription (e.g., 2-3 sets per exercise) may be sufficient to develop strength in less-trained individuals, whereas a greater number of sets (e.g., 4-6 sets per exercise) may be required to attain the same level of improvement in well-trained athletes.

When considering the ability to develop power, strength is a primary factor in dictating how powerful an individual is (68, 125, 292). It has been advocated that strength training should be considered as a foundational quality that is the basis for power development (9, 11, 12, 14, 19, 68, 122, 125, 290, 292, 294, 311, 312) in which greater strength levels have been shown to produce greater power output (9, 11, 19, 65, 66, 68, 87, 101, 253, 287, 292). The results of previous studies have demonstrated that an increased strength levels are associated with a greater power output (9, 12-14, 63, 65-67, 179, 195, 218, 253, 266, 292, 335).

Baker and Nance (12) reported strong correlations (r = 0.79) between a 3-RM back squat and 3-RM hang power clean (HPC) performance, with stronger correlations between 3-RM back squat and jump performance (r = 0.81). The same authors also showed very strong correlation (r = 0.89) between 3-RM bench press and incline bench throw. Similarly, Baker (9) demonstrated very strong correlations (r = 0.82) between 1-RM bench press and bench throw for combined national level league players (NRL) and city level players. However, when split by ability levels, the NRL players showed a moderate correlation of (r = 0.58), whilst city players demonstrated strong correlations (r = 0.85). In both above studies, power was assessed via inverse dynamics, which may be an issue as the combined approach will result in an overestimation of velocity of the barbell and thus power, as velocity of the barbell, centre of mass of the body and system (body plus barbell) centre of mass yield different results (198, 217)

Stone, O'Bryant, McCoy, Coglianese, Lehmkuhl and Schilling (292) investigated the relationship of the 1-RM back squat to power output during the loaded countermovement jump (CMJ) and squat/static jump (SJ), in which power was assessed via inverse dynamics. The authors demonstrated that stronger athletes (1-RM = 2.00 ± 0.24 kg/kg) produced greater barbell peak power (PP) during the SJ (5464 ± 2507 W vs. 3842 ± 443 W) and CMJ (5079 ± 2363 W vs. 3785 ± 376 W) compared to weaker athletes (1-RM = 1.21 ± 0.18 kg/kg) at 10% 1-RM load. The authors also reported moderate to strong correlations of (r = 0.60-0.88) for the CMJ PP and 1-RM and (r = 0.75-0.94), with correlations increasing from 10-50% 1-RM, then showing a linear decrease at loads > 50% 1-RM. Critical to this study is that the stronger athletes produced the greatest power at 40 % during the CMJ (5391 ± 2566 W) and SJ (5635 ± 2577 W), whilst the weaker athletes produced power at 10% CMJ (3785 ± 376 W) and SJ (3482 ± 443 W). This however, is in contrast to earlier research which demonstrated that stronger athletes maximised PP at 51% 1-RM back squat compared to weaker subjects who maximised PP at higher loads (55%) (13). Careful consideration must be made as the inverse dynamics assessment shown above has been shown to affect the load that elicits PP and the overall power output (58, 59, 153, 198, 217).

Peterson, Alvar and Rhea (266) investigated the effects of lower body strength and measures of explosiveness in 54 male and female collegiate athletes and demonstrated that 1-RM back squat demonstrated moderate to high correlations to CMJ PP both males ($r = 0.66$), females ($r = 0.72$) and all athletes ($r = 0.92$). However, PP was calculated with the use of the Sayers equation and not directly assessed, likely leading to a misrepresentation of velocities of the system as a force plate was not used to directly measure force or velocity. In contrast, Hori, Newton, Andrews, Kawamori, McGuigan and Nosaka (154) investigated the relationship between strength and power measures in the back squat, front squat and HPC in semi-professional Australian rules football players. When split into two stronger and weaker groups based off 1-RM HPC, stronger subjects displayed greater measures of squat strength, jump height, loaded CMJ PP at 40 Kg, CMJ PP, relative loaded and unloaded CMJ PP than the weaker groups. Although PP was higher in the stronger groups, only relative PP was significantly greater in the stronger groups, concluding that athletes who possess greater 1-RM performances, produces greater magnitudes of strength and power than weaker athletes. Similarly, Nuzzo, McBride, Cormie and McCaulley (253) also found strong correlations between 1-RM back squat and CMJ PP ($r = 0.84$), relative 1-RM back squat PP ($r = 0.68$), 1-RM PC and CMJ PP ($r = 0.86$), and relative 1-RM PC ($r = 0.71$) in collegiate football and track and field athletes. Further, Speranza, Gabbett, Johnston and Sheppard (287) investigated the effects of strength and power and tackling ability is semi-professional rugby players of various age groups. The authors demonstrated that the first-grade players were stronger and more powerful than younger players when assessed by 1-RM back squat, bench press CMJ and plyometric push up PP. The authors also reported correlations of (r = 0.36-0.57) for 3-RM back squat and CMJ PP across each age group. Therefore, it seems plausible that developing force generating capacity allows for a greater degree of power expression and subsequent athletic performance improvement (122).

Classic work from Hakkinen and Komi (128) partly substantiates the above statement, in which eleven males participated in an intense strength programme of 3 sessions per week for 24 weeks with loads between 70-120% 1-RM (1-10 repetitions per set, and 18-30 repetitions per session), with the authors concluding that there was average of 30.2% increase in strength, with a 7.3% increase in vertical jump performance, which demonstrates an increase in power generating capacity. Similarly, Cormie, McGuigan and Newton (65) investigated the effects of 10 weeks of strength training during the back squat (75-90% 1-RM) versus power training (0-30%) during the jump squat (JS) on relatively week males and demonstrated greater improvements of strength in the strength training compared to the power group with improvements in back squat 1-RM of 31.2 ± 11.3% and 4.5 ± 7.1%. However, similar improvements were demonstrated in jump and sprint performance, highlighting the importance in developing strength, particularly in weaker groups.

Another study by the same group demonstrated similar improvements in athletic performance capacity in stronger (1-RM/BM = 1.97 ± 0.08 kg/kg) and relatively weaker males (1-RM/BM = 1.32 ± 0.14 kg/kg) after 10 weeks of power training utilising the JS exercise (0-30% 1-RM). However, effect sizes showed a practical tendency towards greater improvements in the stronger group (66). It is important to note that the power group in both studies used loads of 0-30% 1-RM during the loaded jump, however, the findings may be different if the subjects trained with weightlifting exercises instead of low load, high velocity exercises where the optimal loads which acutely elicit PP output during the PC (53, 59, 60, 64), MTCP (53, 181) and HPC (53, 179, 183) are >30% 1-RM. Performing resistance training with the intention to lift the load as fast as possible is a common training method (318), with many coaches instructing their athletes to perform the given exercise as rapidly as possible and often with lighter loads (249).

One of the concerns when using traditional strength methods to maximise power development is the likelihood of end range deceleration (68, 90, 248, 249), which will result in a different force-velocity profile that would occur compared to a ballistic exercise i.e. JS or bench press throw, where the load is accelerated through the entire range of motion (249, 318), with previous studies showing a deceleration of 51.7% during a submaximal load (81% load) in the bench press (90). When the movement is performed rapidly with a lower load of 45% of 1-RM in an attempt to maximise sports specificity, the deceleration phase is approximately 40-50% of the total movement duration (68, 249). Additionally, to stop the load at the end of the range of motion, it appears that there is an increased muscle activation of the antagonist muscles and a decrease of agonist muscle activation during the deceleration phase (90, 249). At 1-RM load, the deceleration phase has been shown to be as much as 23.3% of concentric duration (90).

One proposed method of attempting to overcome the deceleration phase is to manipulate the load through variable resistance methods such as bands chain resistance (16, 28, 89, 111, 220, 228, 318). Ebben and Jensen (89) reported that the inclusion of chain resistance had no effect on force and surface electromyography during the back squat. Similarly, Coker, Berning and Briggs (43) reported that although the subjects rated that the inclusion of chain load was more difficult to perform during the snatch, no differences in power or velocity was reported.

Additionally, Berning, Coker and Briggs (28) investigated whether a conventional barbell with chains compared to a conventional barbell (80-85% 1-RM) without chains (75% and 80% plus 5% chain load) would affect the performance and demonstrated that no significant difference between methods. McCurdy, Langford, Ernest, Jenkerson and Doscher (220) found no differences in the bench press performed with either chain or plate loaded resistance after 9 weeks of strength training. In contrast, Baker and Newton (16) reported that the inclusion of chain load (17.5 kg) significantly increased mean and peak lifting velocities compared to traditional loading during the bench press. In agreement, Swinton, Stewart, Keogh, Agouris and Lloyd (318) investigated the effects of additional chain resistance of 20% and 40% of 1-RM deadlift performance resulted in greater force and impulse across a greater range concentric phase, although velocity, power and RFD decreased as expected. Conflicting findings from the above research are likely due to both load and exercise selection, with Swinton, Stewart, Keogh, Agouris and Lloyd (318) using higher loads than previous reported (28, 43, 89, 220).

It appears from the above research that there is a clear relationship between strength and power, and that strength is the underlying characteristic that promotes power adaptations. Researchers have shown that strength training leads to an increase in absolute or relative external power (129, 149, 241, 288, 311, 312). Strength training effectiveness is likely explained by Newton's second law of motion (∑ forces acting on an object = object's mass • object's acceleration). The change in motion of an object (i.e., acceleration) is directly proportional to the forces applied to the object. If greater forces are applied over a given time, greater impulse and acceleration occurs and therefore greater velocity. If both force and velocity increases, power will also increase (power = force x velocity) (312).

Given that much of the research concludes strength and power differences between strength levels, age groups, starters and non-starters in a vast array of sports, it is clear that the focus should be on developing baseline strength measures using traditional methods until adequate strength levels are developed (back squat ≥ 1.9 x bodyweight [BW]), as this has been shown to be more beneficial than ballistic training in lesser trained subjects (65, 66). Once adequate strength levels are reached, athletes are able to maximise the benefits of incorporating specific training activities (i.e. plyometric, ballistic exercises, and complex or contrast training) designed to optimise power development (122). To develop long term maximal power development, enhancing maximal strength is vital (68, 235, 352).

2.2.2. Power/Ballistic Methods

Whilst traditional exercises have been previously shown to be an integral component of strength and power development, once athletes have established adequate strength levels, they are then able to maximise the benefits of incorporating specific training activities (i.e., plyometric, ballistic exercises, and complex or contrast training) to further elicit gains in maximal power production (68, 122). Ballistic power training is commonly used to target improvements in maximal power output and athletic performance (65).

Exercises including the JS, hexagonal barbell jump and bench press throw remove any deceleration phase as the athletes project the barbell or body into the air and therefore accelerate through the full range of movement (i.e. take-off or release) have been termed ‘ballistic’ in the literature (65, 68, 247-249, 319), and can be overloaded by increasing the load that is projected (68). Typical loads for ballistic training range from BW to loads of 80% (0-80% 1-RM) in a biomechanical similar exercise to the traditional variation i.e. back squat or bench press (68).

The load that elicits maximal power production in a specific movement is commonly referred to as the ‘optimal’ load and have been extensively studied in several exercises such as elbow flexion. Much of the optimal load research is a result of classic work by Kaneko, Fuchimoto, Toji and Suei (177) who demonstrated that PP output occurred at 30% of maximal voluntary isometric contraction (MVIC) during the elbow flexion exercise. This research was progressed by Toji, Suei and Kaneko (325) who investigated if training with 0% and 30% MVIC or 30% or 100% would result in specific in force, power and velocity in 3 sessions per week for 11 weeks in 12 males. Results demonstrated that training at the higher loads were more advantageous in power development than no load training. To develop this further, Toji and Kaneko (324) investigated the effects of multiple training loads (30% and 60% MVIC, 30% and 100% MVIC, and 30%, 60% and 100% MVIC) during matched repetition over an 8 week training study, and demonstrated that load of 30%, 60% and 100% MVIC resulted in the greatest velocity, force and ultimately power. However, practically, single joint studies have limitations to multi-joint actions seen in many sporting environments. With multi-joint exercises, the optimal load for power production varies for ballistic type exercises, with the JS demonstrating the optimal load to be at 0% 1-RM squat (BW load) (29, 61, 64-66) and 30-55% 1-RM bench press for the bench throw exercise (13, 29, 250).

The effects of ballistic training in longitudinal studies has been previously investigated in various populations. Wilson, Newton, Murphy and Humphries (346) investigated the effects of loaded squat jumps (ballistic), traditional back squat (strength training) and drop jump (plyometric) on vertical jump performance over 10 weeks in previously trained males and demonstrated that both strength and ballistic training improved jump performance, but not plyometric. Lyttle, Wilson and Ostrowksi (209) investigated 8 weeks of ballistic training consisting of weighted jumps and bench press throws and combined strength and plyometric performance on several performance measures. The authors demonstrated that both modalities improved jump performance in non-elite subjects, with no significant difference between groups. Newton, Kraemer and Hakkinen (248) investigated whether 8 weeks of ballistic JS training in well trained male volleyball players would improve sport specific jumping tasks better than a traditional trained group and demonstrated that the ballistic group resulted in a significantly greater change in sport-specific vertical jump performance than training with traditional resistance training exercises.

McBride, Triplett-McBride, Davie and Newton (219) investigated the effects of an 8-week training program with heavy (80% 1-RM squat) or light-load (30% 1-RM) JS on various physical performance measures in 26 athletic males. Findings of this study demonstrated that there were significant increases in PP and PV in the JS at 30, 55 and 80% for the light load group ($p < 0.05$), whilst the heavier loaded group showed significant increase in both PF and PP at jumps of 55 and 80%, but not 30% and highlighted that light loaded ballistic jumps result in increased velocities. Cormie, McCaulley and McBride (63) investigated the effects of 12 weeks of optimal load (body mass only) power training during jumps and combined training (jumps and strength training) across various performances measures such as loaded jumps from 0-80% 1-RM), jump height and PP. The authors demonstrated significant improvements in PP in the unloaded and 20 kg load conditions, whilst combined method improved PP across all loads highlighting the potential benefits of a mixed load approach to training.

It appears that the development of strength should be the primary focus before targeted power training is performed with a minimum target of approximately 2 x BW squat recommended (122). To maximise the transfer of training to performance, power training should involve similar movement patterns, loads and velocities that are specific to the demands of the individual's sport (68). Due to the underpinning relationship between strength and maximal development of power, strength training should be maintained throughout the training phases as a decline in strength (force) is likely to decrease the ability to generate maximal power (68, 122).

2.2.3. Plyometric and Combined Methods

In muscular work, two types of muscle actions are primarily utilised; eccentric and concentric, with the eccentric muscle action preceding the concentric muscle action in an alternating cycle (192), this is known as the SSC (190-192, 196, 251) and this eccentric/concentric coupling of muscular contraction produces a more powerful contraction and greater work than that which would result from a purely concentric action (190, 337). The SSC natural form of muscle function, and it is evident in daily activities, such as walking and running, as well as in more challenging actions, including throwing and jumping, and the ability to utilises the SSC is a critical factor in many sports (96, 221).

Plyometric exercises are widely used to develop muscular power to enhance athletic performance, and to prevent injury (171, 311, 339) and are characterised by a rapid eccentric muscle action which stimulates the stretch reflex and storage of elastic energy, and immediately is followed by a rapid concentric muscle action, thereby stimulating the SSC (211, 214, 267, 312). These exercises are widely implemented to develop maximal force in the shortest time (222, 267). It has been suggested that the increased work output seen after a countermovement can be explained by the time to build up force development, storage, and reuse of elastic energy, potentiation of contractile machinery, and reflex contributions (337, 347).

Potach and Chu (267) recommend that beginners, intermediate and advanced level athletes should perform 80-100, 100-120 and 120-140 repetitions per session, with 2-4 sessions per week on non-consecutive days, with 5-10 s rest between repetitions, 2-3 mins rest between sets, with volume modifications based on the intensity of the plyometric exercise (e.g., depth jump, bound etc.). Plyometric / SSC exercises are generally classified into two groups consisting of long contact times (>250 ms), with large angular displacement of the lower body triple extensors, or fast contact times (<250 ms), with reduced angular displacements of these joints (96, 122, 281, 347). It is not uncommon that S&C coaches prescribe either slow, fast or a combination to improve specifically targets the demands of the sport. Examples of slow SSC plyometrics may include vertical jumps and box jumps, while fast SCC exercises may include bounding, depth jumping and repeated variations (96).

Numerous researchers have demonstrated that plyometric training can improve athletic performances in jumping and change of direction (1, 4, 6, 27, 93, 144, 209, 214, 222, 233, 289, 326, 341, 346). Adams, O'Shea, O'Shea and Climstein (1) investigated the effect of 6 weeks of strength training (parallel squats), plyometric training (depth jump, double leg hops and split squats and combined plyometric and strength training on vertical jump performance in 48 male university students training 2 sessions per week. The authors demonstrated that all three groups improved jump height (strength group = 3.30 cm; plyometric group = 3.81 cm, and combined group 10.67 cm), with the combined group resulting in significantly greater improvements ($p < 0.0001$) than both strength and plyometrics alone. Similarly, Fatouros, Jamurtas, Leontsini, Taxildaris, Aggelousis, Kostopoulos and Buckenmeyer (93) investigated the effected of weight training, plyometric training and combined training on jump height in 3 sessions per week for 12 weeks in 41 recreationally trained males and demonstrated that all methods significantly improved jump height, however the combined group resulted in significantly greater improvements. Further, Harris, Stone, O'Bryant, Proulx and Johnson (144) compared the effects of 9 weeks of high force training, high power training and combined training methods on 1-RM squat, ¼ squat, MTP, CMJ, estimated MP and PP, standing long jump, Margaria-Kalamen stair-climbing test (MK), 30 m sprint, and 10 yd shuttle run (10 yd) in 51 moderately trained males. Results demonstrated that the high force group significantly improved squat, ¼ squat, MK and MTP, whereas the combined group significantly improved squat, ¼ squat, MTP, CMJ, CMJ power, MK, and 10 yd sprint, highlighting superior benefits with a combined training approach.

Fletcher and Hartwell (98) investigated the effects of 8 weeks combined strength and plyometric training (2 sessions per week), on golf drive performance (club head speed and driving distance) in 11 skilled golfers. Results showed no significant changes, in the control group, while the experimental group showed a significant increase ($p \leq 0.05$) in both club speed and driving distance, likely attributed to both improves in force production and sequential acceleration of body parts. Tricoli, Lamas, Carnevale and Ugrinowitsch (326) investigated the short-term effects of heavy resistance training combined with either weightlifting movements or the vertical jump in 32 males training 2 sessions per week for 8 weeks. The authors showed that the SJ and 10-m sprint speed time improved significantly for the combined strength and weightlifting group only group only (9.56% and 3.66%, respectively). Additionally, both groups improved CMJ performance, but the WL group had a greater increment than the VJ group (6.60% and 5.72%, respectively). Both groups showed an increase in the ½ squat 1-RM, but the VJ group had superior improvement when compared to the WL group (47.8% and 43.7%, respectively).

Positive improvements have also been shown children who have undertaken plyometric training. Meylan and Malatesta (233) investigated the effects of an 8-week plyometric training (i.e., jumping, hurdling, bouncing, skipping, and footwork) within regular soccer practice on explosive actions of early pubertal soccer players during early in-season training. Following baseline measures, plyometric training was associated with significant decreases in 10 m sprint time (22.1%) and agility test time (29.6%) and significant increases in jump height for the CMJ (7.9%) and ground contact test (10.9%).

Fathi, Hammami, Moran, Borji, Sahli and Rebai (92) investigated the effects of a 16-week pre-season plyometric training program on the athletic performance of 68 young male volleyball players with subjects split into a plyometric group, (combined group and a control group and performed 2 sessions per week in addition to their regular volleyball training. The authors demonstrated that both the combined training group and plyometric only training group resulted in improvements in 5 m sprint (ES: -0.69 and -0.46) 10 m sprint (ES: -0.31 and -0.3), lower body muscle power (ES: 0.44 and 0.36) and upper body muscle power (ES: 1.32 and 0.7), however, better improvements were observed in the combined group.

Lloyd, Radnor, De Ste Croix, Cronin and Oliver (207) investigated the effects of 6 weeks of strength, plyometric and combined training, performed twice weekly, on sprinting and jumping performance in 80 school-aged boys who are either pre or post peak height velocity (PHV), and had no formal strength and conditioning (S&C) programmes. The authors demonstrated that plyometric training elicited the greatest gains across all performance variables in pre-PHV boys, whereas combined training was the most effective in eliciting change in all performance variables for the post-PHV boys, although all groups made performance improvements regardless of intervention. However, improvements from high neural demand exercises such plyometric training could have magnified an age-related training response that coincided with natural growth and maturation in pre-PHV boys. Additionally, the authors did not match training volumes with the strength group performing 120 repetitions, plyometric group 74–88-foot contacts and the combined group 32-38.

Recently, McKinlay, Wallace, Dotan, Long, Tokuno, Gabriel and Falk (222) examined the effects of 8 weeks of free-weight resistance training (RT) and plyometric (PLYO) training on maximal strength, explosiveness, and jump performance in 41 youth soccer players. The authors showed that while both the RT (10.0%) and PLYO (16.9%) group both improved jump performance, only the PLYO group was significantly greater than the control group. In contrast to the above studies, Lyttle, Wilson and Ostrowksi (209) investigated the differences between a maximal power training programme and a combined strength and plyometric programme, during dynamic performance tests such as the jumps, squats, throws and sprints in 33 recreationally trained males over 8 weeks. The authors demonstrated that both groups significantly improved jump height (maximal power group- SJ = 7.1 cm, CMJ = 3.8 cm; combined group- SJ = 6.7 cm, CMJ = 5.6 cm), however no significant differences between groups was reported. The results should be interpreted with caution as power was assessed via inverse dynamics which has since been shown to miscalculate power (58, 59, 198, 217). Additionally, the combined group performed strength training at loads which allowed 6-10 repetitions which are not in line with previous reported repetitions that are used to maximise strength (8, 311). Additionally, Arabatzi, Kellis and Saez-Saez de Villarreal (4) compared the effects of weightlifting, plyometric training and combined training on CMJ and SJ performance in 36 male subjects performing 3 sessions per week for 8 weeks. Results showed improved CMJ and SJ during the weightlifting group (CMJ = 34.6 ± 7.5 cm vs 39.8 ± 6.8 cm [15%]; SJ = 28.1 ± 5.7cm vs. 33.8. ± 5.5 cm [20.3%]), plyometric group (CMJ = 31.5 ± 6.3 cm vs. 36.1

± 6.4 cm [14.6% increase]; SJ = 29.7 ± 8.6 vs. 33.9 ± 7.9 cm [16.9% increase) and combined group (CMJ = 34.4 ± 8.3 vs. 39.6 ± 8.6 cm [7.3% increase; SJ = 29.4 ± 7.9 vs. 33.7 ± 7.3 cm [14.6% increase). It should be noted that the control group also increased CMJ and SJ performance by 5.7% and 5.4%, and non-significant differences between groups were reported.

Daehlin, Haugen, Haugerud, Hollan, Raastad and Ronnestad (75) compared the effects of combined plyometric and strength training on ice hockey players' skating sprint performance versus strength training only, in 18 males who performed 5 sessions per week for 8 weeks. The authors demonstrated that the combined group had a greater reduction than the strength in time spent on 10 m skating (–2.8 ± 3.1% vs 0.4 ± 1.4%), however while both groups improved 35 m time, 1-RM, broad jump and specific aerobic power, no differences existed between groups. In contrast, Ronnestad, Kvamme, Sunde and Raastad (272) compared the effects of combined strength and plyometric training with strength training alone on power-related measurements in professional soccer players. The authors reported no significant differences between the strength and combined group on 1-RM ½ squat, CMJ, SJ, 4-bounce test (4BT), PP in ½ squat with 20 kg, 35 kg, and 50 kg (PP_{20}, PP_{35}, and PP_{50}, respectively), sprint acceleration, peak sprint velocity, and total time on 40-m sprint, although both groups significantly improved jump, sprint, and strength performances. Generally, the inclusion of strength training when performing plyometric training seems to be a critical component in power related variables as the combined method resulted in greater outputs when each characteristic was training separately (1, 93, 144), highlighting the importance of muscular strength on power development (68, 122).

2.3. KINETICS AND KINEMATICS OF WEIGHTLIFTING DERIVATIVES

The clean and jerk and snatch are the two competition lifts which are performed in weightlifting competitions and are caught in a full depth catch or receiving position due to near maximal load attempts. In contrast, in the field of S&C, variations of these exercises are performed from the floor with lighter loads (PC and power snatch), from the hang position (HPC and snatch), from the second pull position (MTPC and snatch) in which the athlete catches the bar above parallel in a ¼ squat position. Additionally, the full competition lifts are further modified by removing the catch phase which results in derivatives such as the clean and snatch pull, HP, hang snatch pull, mid-thigh clean pull, MTP and snatch pull, CMS and JS (79-83, 302).

The sport of weightlifting comprises of two lifts, the snatch, and the clean and jerk, in which athletes have three attempts at the snatch, and if successful, three attempts at the clean and jerk. The competition snatch and clean and jerk techniques are rather complex and involve movements of the whole body (40, 165). Given these high technical requirements of weightlifting, its foundations should be centred on, and further quantified by biomechanical principles, which allows for further understanding into how to increase performance (39, 202). Five key phases include the following: the first pull, transition, second pull, turnover under the bar, and recovery are deemed the most important phases of the lifts (114-116, 150) Table 2.1. The acceleration phase during the snatch (i.e., pull) can be subdivided into three phases: 1st pull, transition/unweighting, and 2nd pull (91, 285). A visual representation of the phases of a full weightlifting clean is shown in the Table 2.1-PHOTOS.

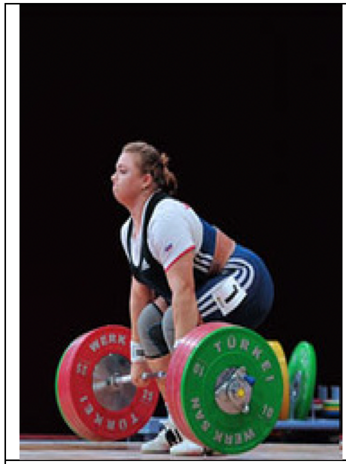
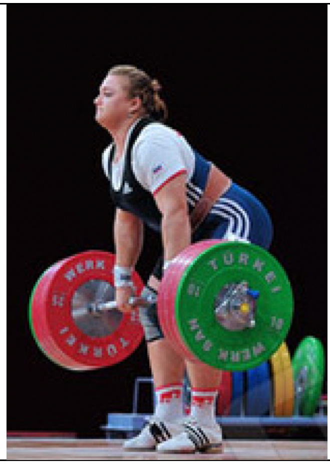
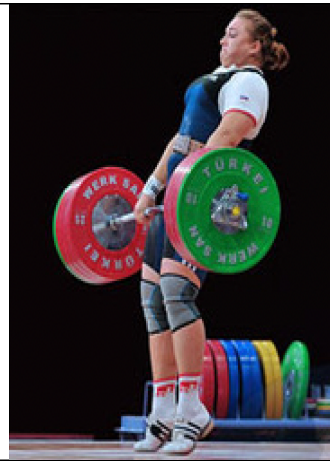
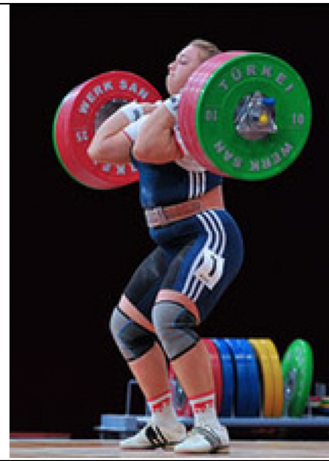
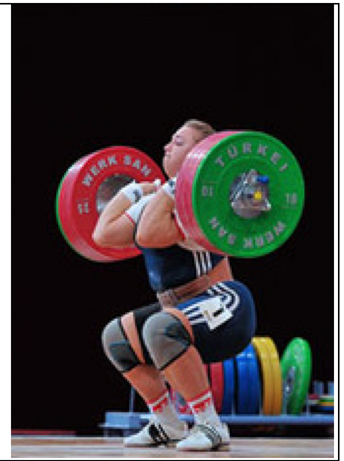
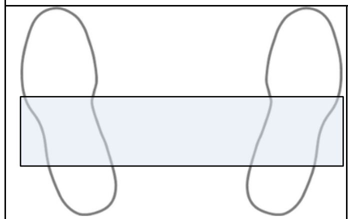
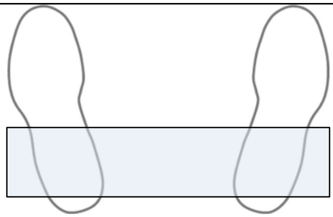
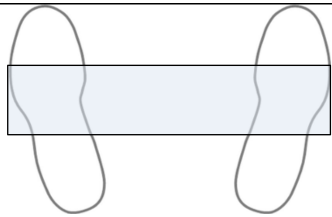
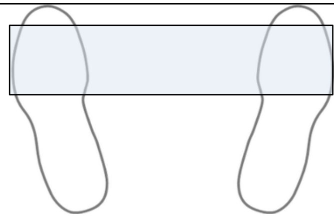
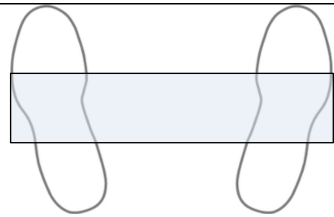
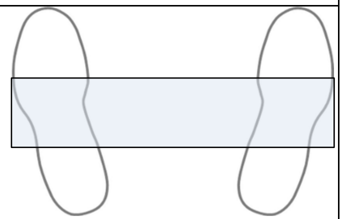
During competition lifts, the first phase is termed the 1st pull. When the lifter addresses the barbell, the barbell should be placed directly above the point at which the centre of pressure is being applied, which should be midfoot (39), with the barbell being over the foot arch. The importance of the 1st pull is critical and has been shown to differentiate between elite and district-level weightlifters, where elite weightlifters displayed greater relative maximal force than district-level lifters (39, 178). During this phase, the barbell is lifted off the ground and moves back towards the knee of the lifter (39, 81, 82) and the centre of pressure moves back towards the heels, with the shins ending up vertical. The end of the 1st pull occurs when the barbell passes the knees. Importantly, this position is also the start point of weightlifting derivatives such as the pull from the knee (83) and the mid-point for hang variations such has the hang pull, hang high pull and jump shrug (83, 303-305).

The transition phase begins with shifting from knee extension to flexion, via dorsi-flexion, to adopt the power position where the shoulders, hips, and heels are inline (150). The transition is often defined as when the knees first start to flex after the end of the 1st pull and are moving into the power position/2nd pull position (39), however a decrease in force (91) and velocity (107) has been observed in elite weightlifters during the transition phase The lifter's centre of pressure shifts from near the heel to the mid foot, with the lifter ideally staying flat footed throughout, with the barbell reaching hip height, which is required to develop vertical force through the legs in the 2nd pull. The transition phase is characterised by the double knee bend (244). The key here is to ensure the barbell is kept close to the body to optimise vertical force being applied into the barbell during the 2nd pull when the barbell reaches mid-thigh (39).

The end of the transition phase also coincides with the start of the power position (39, 79, 80) (start of the mid-thigh pull position). This power position represents the start of the 2nd pull phase, where maximal vertical acceleration of the barbell occurs and subsequently, the peak rate of force development, peak vertical velocity and peak power occur during this phase (118, 164, 244). During the 2nd pull, the barbell moves toward the lifter and weight distributions on midfoot, with the lifter being upright with optimal hip and knee angle shown to be between 140–150° and 125–145°, respectively (26, 48, 51). The vertical barbell velocity at the end of the 2nd pull (maximum vertical velocity) corresponds to the sum of the impulses of each sub-phase of the entire acceleration phase (277), in which the shins are near vertical and weight distribution and centre of pressure is on the forefoot. The turnover can be defined from the second maximum knee extension to the moment at which peak barbell height is achieved, and the lifter has begun to descend underneath it in preparation to receive the barbell in either the clean or snatch position (39, 150).

Due to the complexity of the above competition weightlifting exercises, it is common for practitioners to perform less complex derivatives of these full movements (302). These movements typically broken down to train specific phases that include the 1st pull only (82), 2nd pull only (i.e., mid-thigh power clean) (79, 80) or exercises that contain both the transition phase and 2nd pull (i.e., power clean from the knee, hang power clean) (302-305) or omit the turnover, catch and recovery phase (i.e., pulling derivatives, such as the clean pull, hang high pull, mid-thigh pull etc.) (302).

Table 2.1-Components and centre of pressure during the weightlifting clean exercise

					
Components of the clean and derivitives					
1. Set up position. 2. Start of 1st pull	1. End of 1st pull. 2. Start of transition 3. Start position of pull from the knee. 4. Mid point of hang variations.	1. End of transition 2. Power position 3. Mid-thigh position 4. Start of 2nd pull	1. End of 2nd pull 2. End of mid-thigh pull 3. End of countermovement shrug	1. Catch position during power clean	1. Catch position during clean
Centre of Pressure during each phase					
					
Adapted from Chavda, Hill, Martin, Swisher, Haff and Turner (39)					

2.3.1. Methodological Concerns with Power Assessment

The ability to develop high levels of muscular power is considered a primary component of success in many sporting activities. Enhancing muscular power is often the desired result of resistance training programmes for increasing sports performance (10). According to Stone, Stone and Sands (291) power is the most important characteristic to develop for most sports. In Newtonian mechanics, power is defined as the product of force applied to an object and the velocity of the same object (204). The assessment of power requires the force applied to and the velocity of an object (primarily the 'type of some sort of barbell', centre of mass or system centre of mass (58-60, 153, 198, 217, 242). Generally, the two most commonly applied methods of power assessment in S&C during various exercises (170) are the force plate method (153, 204) and combined method (58, 59, 86), each characterised by limitations, which will be discussed further. Many studies have measured both peak and mean power in performance tasks such as jumping (5, 58-60, 64, 103, 153-155, 253, 259), weightlifting derivatives (44, 46, 49, 53-55, 59, 60, 64, 126, 153, 154, 156, 179, 182, 183, 188, 299, 300, 316), deadlifts (24, 30, 34, 70, 237, 317, 318) and hexagonal bar jumps (212, 334) and the impact on performance measures.

The measurement of power has been a contentious issue in the field of applied S&C and biomechanical research with various methods implemented to measure power in exercises such as the JS and back squat, and several investigations have attempted to address this (59, 86, 153, 198, 242). Dugan et al. (86) and Hori et al. (153) highlighted four methods of calculating JS power data, whilst Cormie, McBride and McCalluey (59) suggested six methods of assessing power, which will be discussed in more depth in this chapter.

According to Dugan et al. (86) and Hori et al. (156) the four methods which can be used to calculate power are highlighted and discussed below;

Method 1: Calculation from barbell displacement and known mass

(Barbell mass and lifter's body mass)

Method 2: Calculation from barbell displacement and known mass

(Barbell mass only)

Method 3: Calculation from GRF and known mass (barbell mass and

lifter's body mass)

Method 4: Calculation from barbell displacement and GRF

Method, one involves calculating the acceleration of the load (e.g., barbell) using a transducer that outputs a voltage proportional to the gravitational acceleration. Therefore, force can be calculated by multiplying the acceleration at any given time point by the mass of the body. Velocity data are derived by single integration of the acceleration data with respect to time. Power can then be calculated as the product of force and velocity (86). Further in-depth review of the inclusion and exclusion of body mass will be discussed later in the chapter.

In method two, the first method used the displacement of the bar and the associated durations to estimate power production. Therefore, with knowledge of displacement and time between samples, the instantaneous velocities of the bar can be calculated for its entire path by differentiating the displacement data (86). A second derivative of displacement data will provide instantaneous acceleration of the bar, this process is known as double differentiation (156). At this point, adding acceleration due to gravity to the calculated instantaneous acceleration of the bar or body system, then multiplying by the mass of the system can be used calculate the total force acting on the system (86). Force is then calculated by multiplying the known mass (barbell mass and lifter's body mass) by the acceleration data (F = m x a). Power is calculated by multiplying the force data by the velocity data (P = F x V) (86). One key limitation of this method is the assumption that the displacement of the system mass is the same as barbell displacement (86, 198, 217, 242).

Method three involves the measurement of direct force measurement via a force plate using the impulse-momentum calculation or forward dynamics approach, which involves integrating (calculation of area under the curve) the force-time data and dividing by the known mass to determine change in velocity between consecutive samples (156). Impulse is equal to a change in momentum, or force multiplied by time. As the force, mass, and initial velocity, (which needs to zero) are known; the instantaneous velocity can be calculated using this approach. Similar to method 1, power can then be calculated as force multiplied by velocity (86). Method four involves a combination of direct force measurement via a FP and displacement time data via an LPT. In this method, force is calculated from the FP, whilst the velocity is obtained from barbell displacement data. Thus, power is obtained as the product of the force and velocity data. Similar to other methods, the lifter's body mass and barbell mass is included in the calculations since the force data is directly obtained from force platform as GRF. In this method, data are sampled from the FP and LPT simultaneously (86). Force plates are used to measure GRF, either exclusively or in conjunction with one of the devices listed above. Other technology devices such as LPT's are most useful for accurate measurement of bar displacement and time; therefore, velocity and acceleration may be indirectly assessed via subsequent calculations. Although other methods such as a V-scope which uses infrared and ultrasound technology to track displacement (292) are documented, the FP and LPT represent the two most commonly used technologies in recent literature (41, 58, 59, 71, 86, 118, 153-156, 284, 343).

Lake, Lauder and Smith (198) demonstrated that during the back squat, the bar and body move independently as power derived from GRF and barbell velocity resulted in a significant overestimation of power applied to the centre of mass (COM) when compared with power obtained by multiplying GRF by the velocity of COM derived from either 3-D motion analysis (18.7%; $d = 1.06$; $p < 0.001$) or GRF data (23%; $p < 0.001$; $d = 1.21$). Although Lake et al. (198) investigated barbell kinematics during back squats, assumptions can be made that there would be greater differences in barbell velocity, COM velocity and system centre of mass velocity would be present during weightlifting derivatives due to the centre of mass starting lower, and finishing higher in these exercises compared to the squat. Furthermore, depending on which modality is used, and subsequent methodological calculation to for velocity or force, alters PP output and the load that elicits this output, due to an over or underestimation of force, unless accurate force measurements are recorded on a FP (58-60, 86, 153, 198, 217).

2.3.2. Methods of Assessing Kinetic Variables- Force Platform Method

During the FP method, the velocity of the system centre of mass is calculated by the numerically integration of FP acceleration data (derived from Newton's second law) (59, 86, 153, 204, 242). Within this method, the force applied to the system (body and external loads COM is directly measured via the FP, therefore it is essential that the total system mass is recorded prior to the movement onset (153, 217). System centre of mass velocity is obtained by time integration using the Simpson or trapezoidal method (242, 259, 296).

The forward dynamics method which uses the impulse-momentum relationship method is also prone to errors in the velocity and power calculation as the integration process magnifies any slight measurement errors in force (156). For this reason, it is critical that the FP system calibrated and zeroed prior to data collection (86). Another key consideration is start position of the bar. As the force is measured directly via a FP, the system mass (barbell and body mass) must be recorded as one. In the case of a mid-thigh weightlifting derivative, JS or hang position movement, then the system mass is accurately recorded. However, if a clean, snatch, deadlift or hexagonal bar deadlift variation is performed from the floor or blocks, then the resultant system forces are not transmitted through the FP as the barbell weight will be on the floor or the blocks. This is shown in studies assessing the dynamic MTP where the bar was on the rack prior to each lift (119, 120, 124) in which bar mass and system mass are different. If the bar is resting on the blocks, then during the initiation of the pulling movements, the bar mass is then applied to the system mass on the FP once it leaves the blocks, therefore, this will give a variable change in kinetic and kinematic measures and subsequent power calculations.

Several researchers have addressed this in their methodologies to allow for weightlifting exercises and their derivatives to accurately measure kinetic and kinematic variables during the PC from the floor, in which the bar was held off the ground for a short pause to enable system mass to be measured and power to be calculated forwards dynamics approach (44-46, 49, 53). Whilst this may seem plausible at the lower loads (30-80% 1-RM) described in the studies, initiating a pause slightly off the floor prior to the PC or supramaximal clean pulls, may be difficult at loads >80% 1-RM due to strength and technical issues in the subjects. Additionally, a tare function on certain FPs allows you to accurately measure the system force when the weight starts from the floor by eliminating the subject's body mass when additional force is produced. This method is clearly observed in much of the common weightlifting derivative research, which measures kinetic variables (45, 46, 49, 53, 55, 299, 300, 307, 316).

Within sports performance context, the aim when performing weightlifting movements and the derivatives is to maximise the vertical displacement of the system centre of mass, it is suggested by many researchers that this should be measured via a FP (58-60, 153, 217). For the sport of weightlifting, it could be suggested that the barbell power, displacement and velocity is of a primary determinant of performance outcome, whilst for most other athletes who's primary purpose of performing weightlifting movements is to improve lower body kinetic and kinematic output, the motion and or trajectory of the barbell is of a lower importance, with a focus on improving power applied to the system centre of mass a primary focus, in line with earlier recommendations (198, 217).

2.3.3. Methods of Assessing Kinetic Variables- Combined Method

Another method of determining power output is known as the combined method (58, 59, 64, 86, 153, 198, 218, 219, 348). As research shows that both LPT and FP each have their own limitations, Cormie, McBride and McCalluey (59) proposed that a superior approach to data collection would involve both pieces of equipment, known as the combined method. With reference to the combined method, the velocity of the system mass is calculated by the differentiation of displacement data of a barbell during a loaded jump or unloaded jump, which is collected using various motion capture equipment e.g. a LPT (58, 59, 153), two LPTs (58, 59), camera system (204, 236), whilst force is calculated directly via the FP. This method may seem attractive to researchers, as force and displacement are measured independently and therefore the risk of error seems lower (59, 86). Lake, Lauder and Smith (198) showed that multiplying GRF by the velocity of the barbell resulted in a significant overestimation of power applied to the CM when compared with measures of power obtained by multiplying GRF by the velocity of CM derived from either three dimensional (3-D) motion or GRF data, Mundy et al. (242) showed the combined method calculations of mean force, peak velocity (PV), mean velocity, PP and mean power were significantly ($p < 0.0001$) greater than the force method calculations across all loads, determining that even the smallest differences between the FP method and combined proved unacceptable, and that previous studies may be confounded with methodological issues in the assessment of power.

The combined method is based on the belief that the velocity of the barbell is equivalent to the velocity of the system, however this assumption has previously been questioned (153, 204) and clearly different for weightlifting exercises and their derivatives. Power calculated with the use of the combined method has been shown to overestimate power when compared to a FP method (59, 153, 198, 204). When this assumption is violated, this results in the calculation of erroneous power output values due to a mismatch of parameters (198, 204).

McBride, Haines and Kirby (217) demonstrated a linear increase in percentage difference from 20.8% to 70.2% in PV across a 3-D videography system. Similarly Lake, Lauder and Smith (198) also demonstrated that the velocity of the barbell was 16.1% ($p < 0.05$) greater than the velocity of the COM during back squats when measured via video systems synchronised with a FP. Regardless of the equipment used for measurement, it appears that when a barbell mass is chosen to represent the system mass, it will overestimate the velocity of the system COM due to a poor estimation of the system COM.

When comparing different six methodologies of power measurement in ten Division one males, Cormie, McBride and McCalluey (59) demonstrated that the combined methods of 1-LPT + FP and 2-LPT+ FP over estimated PP and MP in the JS when compared to FP only method. Additionally, the authors demonstrated a similar trend in the PC exercise, in which PP and MP was overestimated in the combined methods. Further evidence of this can be seen in the work of Lake, Lauder and Smith (198) and Mundy et al. (242) who showed that the combined method of multiplying the GRF and barbell velocity resulted in a significant overestimation of power applied to the COM when compared with measures of power obtained by multiplying GRF by the velocity of COM derived from either 3D motion analysis (18.7%; $d = 1.06$; $p < 0.001$) or GRF data (23%; $p < 0.001$; $d = 1.21$). From these findings, the authors conclude that the combined method is not a valid measurement (198). Furthermore, Hori et al. Hori, Newton, Andrews, Kawamori, McGuigan and Nosaka (153) also demonstrated that the combined method overestimate PP in both the loaded JS and HPC when compared to the FP method.

Clearly from the evidence shown that there is disagreement in the literature into the criterion method for measure power output. Each of the discussed methods has shown to have both positive and negative aspects, which may affect practicality of data collection. The affordability, portability, and accessibility of a LPT over FP technology provide a strong justification for their widespread use in practical settings, however they have been shown to significantly overestimate power output. Whilst many authors suggest a FP to be the criterion method (153, 204, 242), there is usually a significant cost involved, however recent reductions in cost and the mobility of certain types of FP allow for greater access and portability and may be similar in cost to LPT’s or more cost effective. As the VGRF data assessed during the FP method and the combined method are often identical, this overestimation seems feasible that the external load moving at a significantly greater velocity than that of the system COM (198, 204). From a practical standpoint, an LPT may provide a reliable method of data collection, if the findings are not directly compared to other methods, however the use of a FP is recommended. Further, an LPT should only be used during assessment and monitoring barbell velocity and should not be used to calculate power. During weightlifting movements and derivatives, power applied to the system should be assessed to monitor training adaptations, rather than power applied to the bar, as the latter might be improved due to improvements in lifting technique (58, 59, 64, 153, 217).

Cormie, McBride and McCalluey (59) investigated the validity of power measurement techniques utilising various kinematic and kinetic devices during the JS, squat, and PC in ten well trained division one male athletes. In the study six methods of calculating PP were assessed: one linear position transducer (1-LPT), two linear position transducers (2-LPT), one linear position transducer plus mass (1-LPT+MASS), force plate only (FP), FP plus one linear position transducer (1-LPT+FP) and FP plus two linear position transducers (2-LPT+FP). The purpose of the 2-LPT method is to provide a more accurate measurement of velocity and displacement in multi-dimensional movement, which include both a vertical and horizontal movements (59). The squat and JS were investigated across a spectrum of loads from 0-85% of 1-RM whilst the PC loads were 30-90% 1-RM. The different loads were selected as in weightlifting movements, the bar moves independently from the body when compared to squat and JS. Results of this study showed that both the 1-LPT and 2-LPT methods over estimated PP in the JS when compared to the 2-LPT+FP method (1-LPT, 6497 ± 1136 W, 2-LPT, 6405 ± 1168 W, 2-LPT+FP, 6332 ± 1085 W), the squat (1-LPT, 4215 ± 1227 W, 2-LPT, 4104 ± 1162 W, 2-LPT+FP, 3206 ± 411 W), and PC (1-LPT, 5834 ± 1531 W, 2-LPT, 5707 ± 1537 W, 2-LPT+FP, 4843 ± 882 W). The combined methods which used FP and LPT data resulted in greater power when compared to the FP only method, due to greater barbell velocity when compared to system COM velocity which has also been shown previously (198, 217).

2.3.4. Methods of Assessing Kinetic Variables- Single Point method

When the FP method is unavailable, another method for estimating force is using kinematic measurement systems such as LPT's and accelerometers. These devices becoming increasing popular in the measurement of kinetic and kinematic variables (58, 59, 71, 73, 99, 131, 136, 145, 153). LPT technology involves a tethered cord, typically attached to equipment (bar) or a subject to measure displacement-time data, whilst accelerometers measure movement velocity in resistance exercises by integrating the acceleration data with respect to time (18, 38). From this, the process termed differentiation using a known mass allows the estimation of force (73, 153). Velocity is calculated from displacement and time [velocity = displacement (s)/time (t)] and acceleration is calculated from velocity and time [acceleration = velocity (v)/time (t)] (145). Accelerometer devices such as the PUSH™ device determines velocity by measuring the linear accelerations and angular velocities of the movement and vertical velocity was calculated by the integration of acceleration with respect to time. The estimation of force is then calculated from the system mass multiplied by the acceleration data, whilst power is then therefore calculated from the product of the force and velocity curve data (17, 18). As mentioned during the description of the combined method approach, the kinematic single point method assumes that the external load movements in parallel with the centre of mass (58, 59, 86). Chiu, Schilling, Fry and Weiss (41) compared jumping PF measured by FP and estimated by a LPT via differentiation. Subjects performed loaded SJ and CMJ with 30%, 50% and 70% of previously established 1-RM squat. The authors reported high correlations between LPT and FP measurements, concluding that the use of an LPT was a valid and reliable method of estimating force data. However, it should be noted that this study had a low sample size (n = 6), nor did they compare power or velocity differences between methods.

Due to the development and advancement of technology, portable FPs appear to be a reliable method of force-time variable data collection when compared to laboratory FP, thus also making them more accessible and cost effective to S&C practitioners. However, whilst likely a cheaper alternative to laboratory FP, they still lack complete portability and can usually only be used in S&C facilities. On the other hand, an LPT is a relatively cost-effective evaluation tool in comparison to equipment such as a FP. The LPT is also highly portable; therefore, the LPT can be used in multiple areas of the S&C environment. The portability of the LPT also allows the S&C coach to use an LPT as a testing and monitoring tool when traveling with teams to competition or training camps (145). The use of an LPT is advantageous for the measuring of velocity-based training, however it is limited in terms of its ability to assess force and power with certainty.

2.3.5. Onset of Movement Thresholds

Assessment of human neuromuscular performance can be evaluated by the analysis of the force-time data collected via a FP and determined during a number of performance measures such as isometric squats (20-22, 31, 50, 213, 253, 327), IMTP (51, 84, 85, 117, 120, 123, 124, 168, 181, 201, 227, 253, 295, 321, 322, 343) and jumping performance (50, 73, 103, 132, 133, 146, 147, 234, 253, 322, 327).

Critically, the subject's posture and any associated movement prior to the assessment can impact the noise during BW weighing periods, and therefore subsequent movement thresholds may be more difficult to identify, although this noise may be reduced with the researchers following a strict testing protocol (84, 210). Similarly, it is also likely that using a low threshold such as 20 N as observed (168) would result in an early onset of contraction, particularly in heavier subjects or with subjects performing movements with a large system mass, as 20 N would represent 2.04% of BW in a 100 Kg subject, whilst it would represent 4.98% of BW in a 50 Kg subject. Further, the use of an arbitrary threshold may discriminate between subjects of varying statures, and thus when performing movements with large external loads where barbell flexion and oscillation may occur, the potential for measurement errors also may increase.

There is inconsistency in the literature regarding phase identification in jumping tasks such as the vertical jump and when movement is identified. The vertical jump (VJ) is used commonly to both assess athletic ability and to monitor the effectiveness of athletic training programs for elite athletes (88). In an attempt to identify onset of movement in VJ tasks, various methods of determining movement have been used such as 5 standard deviations (SD) of BW (259, 343) relative measures (234), arbitrary values (297) and manual selection (137). Owen, Watkins, Kilduff, Bevan and Bennett (259) used 5SD of BW during the stance phase in elite rugby players, and the initiation of the jump was the time point where the VGRF was 5SD of BW sampled over the first 1 second of quiet standing prior to sampling, minus 30 ms in this phase. Accordingly, if this threshold was set too low, then early triggering of the onset of movement is likely to occur due to early movement during the stance phase, while a higher threshold would result a delayed identification of the jump (259). The authors identified that this threshold would significantly reduce the probability of early onset triggering ($p = 0.0000006$).

In contrast, Meylan, Nosaka, Green and Cronin (234) used three relative BW measures of 2.5%, 5% and 10% when assessing CMJ performance in Australian soccer players. In this study, initiation of the jump was determined when the force-time curve dropped below a threshold of 2.5, 5 and 10% BW. Key findings from this study show that the various onsets of movement thresholds provide varying force-time variables. From their findings, Meylan, Nosaka, Green and Cronin (234) recommended that using a relative BW threshold of 2.5% will retain most of the signal for analysis as a higher threshold resulted in significant amounts of the eccentric phase being lost in the analysis and thus impacting kinetic and kinematic variables during the CMJ. Further, during the eccentric phase of the jump, the 10% BW showed significantly different values ($p < 0.05$) compared to 2.5% BW in ground contact time, time to peak force (TPF) and time to peak power (TPP). Conversely, all force time variables during the concentric phase were elevated at 10% BW threshold compared to 2.5%. This is also demonstrated by Dos' Santos, Jones, Comfort and Thomas (84) who showed that BW 10% and BW 75 N onset thresholds resulted in inflated values for time-specific force values and RFD; while also demonstrating lower reliability measures during the IMTP. Moreover, Eagles, Sayers, Bousson and Lovell (88) showed differences between methodologies result in significant differences in the durations of both the eccentric and concentric phases and key variables such as RFD and TPF during the CMJ. Giving the fact that the CMS and HP are similar to the CMJ (without the take-off phase), it is reasonable to use the gold standard method in identifying the onset of movement in weightlifting movements.

There is certainly conflicting literature regarding onset thresholds during these movements when assessing force-time data. Whilst identifying onset movement is critical for data comparison between studies, many authors have not stated the start time of the CMJ. Body weight can be defined as the average GRF during 1 second of stance during the weighing phase (84, 259). The onset of movement is defined as the point in which the GRF exceeded BW plus or minus 5SD, therefore, a change in force that exceeds this threshold is almost certainly a meaningful change which demonstrates the onset of contraction (84, 259). Researchers should therefore select an onset of movement threshold of 5SD BW in the weighing phase as it considers signal noise during the weighing phase (84, 259, 343).

2.3.6. Weightlifting Exercises- Kinematic Analysis

Early research into the kinematic assessment of full weightlifting movements was performed by Garhammer (105) on seven elite weightlifters and determined that PP output (calculated by bar velocity and system mass) and peak bar velocity (calculated via inverse dynamics from displacement time data) was greatest during the second pull phase, with power ranging from 2206 W in the 56 Kg category to ≥ 4267 W in weight classes ≥100 Kg. However, barbell velocity in the study was determined via using displacement time data from video analysis (25 fps) and power calculated through the inverse dynamics method, which may not provide an accurate measurement due low frame rate. Further analysis was performed at a much higher frame rate (50 fps) by the same author during elite competition (World Championships and Olympic Games) which may provide a more accurate measurement of velocity and therefore power. Similar to the first study, the second pull phase produced the highest power when assessed via inverse dynamics in gold medal weightlifters (107).

Garhammer (108) further developed the research in both elite male and female weightlifting competition by comparing data between the aforementioned studies and the female inaugural world championships in nine medallists, utilising a 50-fps camera. Similar to the above studies, the second pull phase was shown to produce the greatest relative power in both male and female, with the males producing (52.7 ± 4.5 W/Kg and 52.5 ± 8.9 W/Kg) and the females (40.1 ± 5.0 W/Kg and 38.3 ± 3.3 W/Kg) in the snatch and clean components. Whilst it could be suggested that the kinematic measurement devices provide a low frame rate and measurements may not be accurate, the subjects assessed are world class weightlifters and the use of kinematic analysis at that time, was the primary method of successfully determining measurements in world class competition which makes the findings practically significant and relevant.

The kinematic assessment of weightlifting has been expanded in recent years through both two dimensional (2-D) and 3-D kinematic analysis during elite weightlifting training and competition (2, 35, 40, 114-116, 118, 138, 139, 151, 164, 194, 206, 243, 246, 280, 345, 350). Gourgoulis et al. (114) investigated snatch kinematics in elite weightlifters and showed that the second pull phase produced greater power (2482 ± 393 W) when compared to the first pull in men (1158 ± 237 W) and in woman (550 ± 328 W vs 1589 ± 113 W). Similarly, Akkus (2) demonstrated that the second pull produced greater power (1848 ± 336 W) and velocity (1.68 ± 0.14 $m.s^{-1}$) compared to the first pull (643 ± 159 W, 0.99 ± 0.19 $m.s^{-1}$) in elite female lifters in the 2010 World Championships when assessed via barbell velocity and inverse dynamics. Moreover, Hadi, Akkus and Harbili (118) investigated barbell kinematics in the snatch at loads of 60%, 80% and 100% 1-RM in seven elite weightlifters and demonstrated that the second pull produced greater power than the first pull at 60% 1-RM (2027 ± 443 W vs 818 ± 239 W), 80% (2310 ± 463 W vs 1008 ± 232 W) and 100% (2595 ± 569 W vs 1081 ± 199 W) and increased with load.

There are clear methodological flaws that are clear when using 2-D analysis on weightlifting performance. The use of 2-D videography is limited to the sagittal plane and therefore might not record movement in the frontal plan that occurs during the catch phase (150). Additionally, the use of one camera to measure the movement at one end of the barbell may not be a precise measurement due to barbell deformation (42) or bar asymmetries (198). It is likely that velocity or power applied to the bar may be more appropriate for throwing and weightlifting athletes, however, for other athletes such as sprinters and jumpers, power applied to the system may be more advantageous (217). A summary of studies showing kinematic measurements in weightlifting movements shown below in Table 2.2.

Table 2.2-Kinematic measurements of weightlifting movements

Study	Sample	Exercises	Method
Akkus (2)	7 elite female weightlifters	Snatch	3-D videography (50 fps)
Arabatzi and Kellis. (3)	26 male students	Power clean, snatch, Clean and Jerk, high pull	3-D videography
Campos et al. (35)	33 elite junior male weightlifters	Snatch	3-D videography (50 fps)
Canavan et al. (36)	7 male collegiate athletes	Hang Snatch	3-D videography (50 fps)
Chiu et al. (42)	9 collegiate weightlifters	Clean pull	2-D videography (30 fps)
Chiu et al. (40)	19 elite weightlifters	Snatch	3-D videography (50 fps)
Cunanan et al. (74)	153 elite female and 167 elite male Olympic weightlifters	Snatch	2-D videography (240 fps)
Garhammer (104)	World class Olympic weightlifters	Snatch	2-D videography
Garhammer (105)	7 World class Olympic weightlifters	Snatch, clean and Jerk	2-D videography
Garhammer (106)	World Class Olympic weightlifters	Snatch	2-D videography
Garhammer (107)	World class Olympic weightlifters	Snatch, clean and jerk	2-D videography (50 fps)
Garhammer (108)	World class Olympic weightlifters	Snatch, clean and jerk	2-D videography (50 fps)
Garhammer (109)	World class Olympic weightlifters	Snatch, clean and jerk	2-D videography (50 fps)
Garhammer (110)	junior elite weightlifters	Snatch, clean and jerk	2-D videography (50 fps)
Gourgoulis et al. (116)	12 elite male weightlifters	Snatch	3-D videography (60 fps)
Gourgoulis et al. (114)	12 elite male weightlifters	Snatch	3-D videography (60 fps)
Gourgoulis et al. (115)	7 high level male weightlifters	Snatch	3-D videography (60 fps)
Hadi et al. (118)	7 elite male weightlifters	Snatch	3-D videography (50 fps)
Harbili (138)	9 elite male and 9 elite female weightlifters	Snatch	3-D videography (50 fps)
Harbili and Alptekin (139)	9 elite male adolescent weightlifters	Snatch	2-D videography (50 fps)
Ikeda et al.(164)	10 elite female weightlifters	Snatch	3-D videography (60 fps)
Hoover et al. (151)	10 elite female weightlifters	Snatch	2-D videography (60 fps)
Isaka et al.(166)	6 top level Asian Weightlifters	Snatch	videography
Kauhanen et al. (178)	7 elite weightlifters	Snatch, clean and jerk	2-D videography (40 fps)
Kipp et al. (187)	9 male trained weightlifters	Clean	3-D videography (250 Hz)
Kipp (184)	7 collegiate weightlifters	Clean	3-D videography (250 Hz)
Kipp et al. (186)	6 competitive male weightlifters	Snatch	3-D videography (250 Hz)

Korkmaz and Harbili. (194)	10 junior elite female weightlifters	Snatch	3-D videography (50 fps)
Liu et al. (206)	6 elite, 6 sub-elite weightlifters	Snatch	3-D videography (50 Hz)
Musser et al. (243)	36 elite female weightlifters	Snatch	2-D videography (60 Hz)
Mastalerz et al. (215)	14 elite female weightlifters	Snatch	3-D videography (50 Hz)
Nagao et al. (244)	61 elite senior and junior weightlifters	Snatch	2-D videography (60 Hz,1/500 fps)
Nagao et al. (245)	20 men, recreationally trained men	Power clean	3-D videography- 10 camera infrared motion capture system, (250 Hz)
Pennington et al. (265)	20 division 1 male football athletes	Power clean and snatch	LPT
Sato et al. (278)	12 nationally ranked weightlifters	Snatch	Accelerometer (100 Hz)
Sandau et al. (277)	14 elite male weightlifters	Snatch	2-D videography (50 fps)
Sandau et al. (275)	30 elite male weightlifters	Snatch	2-D videography (50 fps)
Sandau et al. (276)	8 elite weightlifters (3 male,5 female)	Snatch and snatch pull	Videography
Schilling et al. (280)	25 elite male weightlifters	Snatch	2-D videography (60 Hz)
Whitehead et al. (345)	24 elite male weightlifters	Snatch	2-D videography (30 fps)
Young-Jin et al.(350)	10 elite Asian weightlifters	Snatch	3-D videography (120 Hz)
Key: 3-D = Three-Dimensional Videography; 2-D = Two-Dimensional Videography; Hz = Hertz; FPS = Frames Per Second; LPT = Linear Position Transducer			

2.3.7. Weightlifting Exercises- Kinetic Analysis

There is limited research assessing the kinetic variables during the phases that occur during weightlifting movements. Enoka (91) used a FP to assess the vertical forces applied to the barbell and system (lifter + barbell) in five experienced weightlifters at loads of 70%, 85% and 100% 1-RM across the three phases of the clean: weighting I, unweighting I and weighting II. The authors demonstrated than the second pull produced a greater VGRF than the first pull (2471 N vs 2809 N), with Hakkinen, Kauhanen and Komi (127) showing similar results in 13 weightlifters with the second pull demonstrating the greatest PF at 150% of the system load. More recent research by Souza, Shimada and Koontz (286) demonstrated that during the PC at loads of 60% and 70% in ten collegiate weightlifters, the second pull produced greater GRF when compared to the first pull, although not significantly greater when measured by a FP.

2.3.8. The Effect of Load on Kinetics and Kinematics and Loading During Weightlifting Exercises and its Derivatives

2.3.9. Clean Variations with Catch

The kinetics and kinematics of the clean and its variations have been much more extensively investigated when compared to the snatch and its variations. The increasing amount of research on the clean and its derivatives has resulted in conflicting results. Weightlifting exercises elicit the greatest amount of power of all resistance exercises (180, 302). Identifying the optimal load that that power is produced during the PC has been previously investigated (49, 59, 60, 64, 348). Winchester, Erickson, Blaak and McBride (348) demonstrated that in 18 healthy males, 70% 1-RM elicited greater PP (derived from force-time curves and video markers on the barbell) than 50% and 90%, but no other loads were tested.

Cormie, McBride and McCalluey (59) investigated six different methods of kinetic and kinematic measurement on the PC at loads of 10-90% in 10% increments of 1-RM in ten well trained males and concluded that the method of measurement produced differing results. To expand, when assessing power using kinematic only data, PP was identified at 30% 1-RM using LPT technology only, which is likely a result of an overestimation of force from the LPT's, whilst using a FP to measure kinetic data, PP was identified at 80% 1-RM. Interestingly, all six methods resulted in different power outputs which clearly suggests that methods cannot be used interchangeably.

Cormie, McBride and McCaulley (60) investigated the effects of the addition of body mass, the inclusion of body mass minus the shank mass in 10-90% of 1-RM PC, with 10% increments in twelve well trained males. Similar to the above study, optimal load was identified at 80% in all three techniques with the major findings concluding that the exclusion of body mass resulted in significantly lower power ($p < 0.05$) due to the underestimation of force, although no significant differences between 70 and 90%. Similarly, Cormie, McCaulley, Triplett and McBride (64) identified that PP in the PC was at 80% of 1-RM using methods described previously in the aforementioned studies. Peak force was maximised at 90% 1-RM, which was not significantly ($p > 0.05$) different to 70-80%, whilst bar PV was fastest at 30% and significantly greater than all other loads ($p < 0.05$).

McBride, Haines and Kirby (217) investigated the effect of loading on bar power, body power and system power in 9 males during the PC using the combined method to assess power and demonstrated that the highest PP was at 90%, 90% and 80% respectively. The maximum bar PP observed during the PC was significantly different from 30, 40, and 50% ($p \leq 0.05$). The maximum body PP was significantly different from 50% ($p \leq 0.05$). The maximum system PP was significantly different from 30% ($p \leq 0.05$). Bar, body, and system PF in the PC was highest at 90%, 80%, and 90% respectively, whilst bar, body, and system PV in the PC was highest at 30%, 30%, and 60% respectively.

Comfort, Fletcher and McMahon (49) investigated the effects of loads on PP in the PC in collegiate athlete's across loads of 30-80% in 10% increments and concluded that PP occurred at 70% 1-RM, although this was not statistically different to 60% or 80% ($p > 0.05$). Peak force was greatest at 80% 1-RM (1939 ± 321 N) and progressively increased with load, which was significantly greater ($p < 0.001$) than all loads apart from 70% ($p > 0.05$). Additionally, PRFD generally increased with load with the greatest PRFD occurring at 70% 1-RM (10742 ± 4291 $N.s^{-1}$); however, this was not significantly different ($p > 0.05$) to the RFD produced with any other load. A summary of studies showing clean variations including the catch are shown below in Table 2.3.

Table 2.3-Kinetics and kinematics of clean variations that include the catch phase

Study	Sample	Exercise(s) and methods	Methods of Measurement	Results
Comfort et al. (45)	11 elite rugby players	1 set of 3 repetitions at 60% 1-RM PC in PC, HPC, MTPC, MTCP	FP	Significantly greater PF during MTCP compared to HPC and PC. Significantly greater PRFD during MTCP compared to HPC and PC.
Comfort et al. (46)	16 elite rugby players	1 set of 3 repetitions at 60% 1-RM PC in PC, HPC, MTPC, MTCP	FP	Significantly greater PP during MTCP compared to HPC and PC. Significantly greater PF during MTCP compared to HPC and PC. Significantly greater PRFD during MTCP compared to HPC and PC.
Comfort et al. (49)	19 male collegiate athletes	30, 40, 50, 60, 70 and 80% 1-RM PC	FP	PP greatest at 70% 1-RM. Not significantly greater than 60 or 80%.
Comfort et al. (53)	16 female collegiate athletes (1-RM PC 51.5 ± 2.65 kg)	3 repetitions of HPC, PC, MTPC at 60, 70 and 80% 1-RM PC.	FP	MTPC PF maximised at 70%; HPC PF maximised at 80%; PC PF maximised at 80%. MTPC RFD maximised at 60%; HPC RFD maximised at 80%; PC RFD maximised at 80% MTPC PP maximised at 70%; HPC PP maximised at 70%; PC PP maximised at 80%. MTPC resulted in greater PF compared to HPC and PC across all loads. No significant differences between variations or load. No significant differences in PP or RFD across loads or variation
Comfort et al. (54)	11 recreational trained males	1 set of 3 repetitions of MTPC, SJ and PPress at 50, 60 and 70% of respective 1-RM (1-RM PC = 93.7 ± 6.8 kg; (1-RM BS = 142.5 ± 12.3 kg; (1-RM PPress = 85.4 ± 8.3 kg;	FP	MTPC resulted in greatest PP. Not significantly greater than PPress or SJ. MTPC at 70% resulted in significant greater PP than PPress at 50%. There were no other significant effects
Comfort et al. (56)	10 collegiate athletes. (Relative 1-	3 repetitions at 90% of 1-RM PC during CK, PCK, CPK.	FP	MF load absorption greatest in CPK. Significantly greater than CK. Workload absorption greatest in CK. Significantly greater than CPK. CPK Significantly greater than PCK.

	RM PC 1.28 ± 0.18 kg.kg^{-1})			
Comfort et al. (47)	18 professional youth soccer players (11 completed the study) 26 Collegiate athletes (23 completed the study) Catch group (1-RM PC = 0.93 ± 0.15 kg.kg^{-1}) Pull group (1-RM PC = 1-RM PC 0.91 ± 0.18 kg.kg^{-1})	Two strength matched groups completed the twice weekly training sessions either including or excluding the catch phase of the PC derivatives in 2 x 4-week mesocycles	FP	The Catch and Pull groups demonstrated significant and meaningful improvements in CMJ height (10.8 ± 12.3%, 5.2 ± 9.2%), PC 1-RM (9.5 ± 6.2%, 8.4 ± 6.1%) and IMTP performance (force [F]100: 14.9 ± 17.2%, 15.5 ± 16.0%, F150: 16.0 ± 17.6%, 16.2 ± 18.4%, F200: 15.8 ± 17.6%, 17.9 ± 18.3%, F250: 10.0 ± 16.1%,10.9 ± 14.4%, PF: 13.7 ± 18.7%, 9.7 ± 16.3%). The Catch group achieved moderate improvements in the SJ height (12.6%) across the duration of the intervention. Pull group demonstrated trivial increases (2.1%).
Cormie et al. (64)	12 Division I collegiate athletes (1-RM PC: 112.75 ± 13.15 kg)	30-90% 1-RM PC	FP + 2-LPT	PP maximised at 80% 1-RM. Relative PP maximised at 80% 1-RM. PF maximised at 90% 1-RM, significantly greater from 30-60% 1-RM PV maximised at 30% 1-RM, significantly greater from all other loads
Cormie et al. (59)	10 Division I collegiate athletes (1-RM PC: 112.75 ± 13.15 kg)	30-90% 1-RM PC	FP +2-LPT FP + 1-LPT FP 2-LPT 1-LPT 1-LPT + MASS	PP maximised at 80% 1-RM PP maximised at 80% 1-RM PP maximised at 80% 1-RM (significantly different from FP + 2-LPT) PP maximised at 30% 1-RM (significantly different from FP + 2-LPT)

				PP maximised at 30% 1-RM (significantly different from FP + 2-LPT) PP maximised at 80% 1-RM
Cormie et al. (60)	12 Division I collegiate athletes (1-RM PC: 112.75 ± 13.15 kg)	30-90% 1-RM PC	EBM, IBMS, IBM FP +2-LPT	IBM- PP maximised at 80% (Significant difference between IBM and EMB at all loads) EMB- PP maximised at 80% (Significant difference with 30-40%) IBMS- PP maximised at 80% (Significant difference between IBMS and EMB at all loads)
Kawamori et al. (179)	15 trained males (1-RM HPC: 107 ± 18.8 kg)	50, 60, 70, 80, 90% 1-RM HPC	FP	PP maximised at 70%, not significantly greater than 50, 60, 80 and 90%. MP maximised at 70%, not significantly greater than 40, 50, 60, 80 and 90%. PF maximised at 90% Relative PF maximised at 90%, not significantly greater than all loads, except 70-80% and 80-90%. MF maximised at 90%, Relative MF maximised at 90%, not significantly greater than all loads. Relative PRFD maximised at 50%, not significantly greater than all loads. PV maximised at 60%. PV at 60% and 70% significantly greater than 90%. MV maximised at 60%, MV at 50% and 60% significantly greater than 30%. Time to PF greatest at 90%, not significantly greater than all loads. Time to PRFD greatest at 80%, not significantly greater than all loads.
Kilduff et al. (183)	12 elite rugby union players (1-RM HPC 107 ± 13)	30-90% 1-RM HPC	FP	PV maximised at 50% 1-RM. No significant difference between all loads. PF maximised at 90% 1-RM. No significant difference between 80%.

				PRFD maximised at 90% 1-RM. No significant difference between all loads PP maximised at 80% 1-RM. No significant difference between 50,60,70 and 90% 1-RM.
Kipp et al. (188)	15 male lacrosse players (1-RM HPC 100.4 ±8.1 kg) Relative HPC (1.25 ± 0.13 $kg.kg^{-1}$)	3 sets of HPC and JS at loads at 30%, 50% and 70% 1-RM HPC	FP and Motion analysis	Positive mechanical work in HPC ($J \cdot kg^{-1}$), 30%- Hip (1.06 ± 0.24), Knee (0.09 ± 0.08), Ankle (0.46 ± 0.25); 50%- Hip (1.35 ± 0.17), Knee (0.10 ± 0.06), Knee (0.62 ± 0.22), 70%- Hip (1.61 ± 0.26), Knee (0.13 ± 0.09), Ankle (0.86 ± 0.25). Positive mechanical work in JS ($J \cdot kg^{-1}$), 30%- Hip (1.12 ± 0.30), Knee (0.18 ± 0.08), Ankle (1.12 ± 0.28); 50%- Hip (1.24 ± 0.23), Knee (0.19 ± 0.10), Knee (1.16 ± 0.23), 70%- Hip (1.38 ± 0.30), Knee (0.17 ± 0.13), Ankle (1.27 ± 0.21). Duration (ms) of the propulsive (i.e., concentric) phase HPC 30%- Hip (288 ± 43), Knee (165 ± 26), Ankle (155 ± 50); 50%- Hip (328 ± 58), Knee (181 ± 70), Knee (226 ± 135), 70%- Hip (356 ± 45), Knee (195 ± 22), Ankle (218 ± 41). Duration (ms) of the propulsive (i.e., concentric) phase JS 30%- Hip (303 ± 45), Knee (154 ± 11), Ankle (143 ± 37); 50%- Hip (328 ± 58), Knee (184 ± 59), Knee (166 ± 42), 70%- Hip (371 ± 38), Knee (192 ± 15), Ankle (185 ± 28). Peak positive mechanical power ($W \cdot kg^{-1}$) propulsive (i.e., concentric) phase HPC 30%- Hip (8.2 ± 1.6), Knee (3.5 ± 2.6), Ankle (5.9 ± 3.1); 50%- Hip (10.1 ± 1.9), Knee (4.2 ± 2.2), Knee (7.4 ± 2.6), 70%- Hip (11.2 ± 2.0), Knee (4.7 ± 2.9), Ankle (8.9 ± 2.4). Peak positive mechanical power ($W \cdot kg^{-1}$) propulsive (i.e., concentric) phase JS 30%- Hip (8.9 ± 2.2), Knee (13 ± 5.1), Ankle (14.9 ± 3.4); 50%- Hip (9.8 ± 2.3), Knee (11.7 ± 4.6), Knee (14.4 ± 2.8), 70%- Hip (9.1 ± 2.7), Knee (10.8 ± 4.0), Ankle (13.7 ± 1.7).

Kipp et al. (185)	15 male lacrosse players (1-RM HPC 100.4 ±8.1 kg) Relative HPC (1.25 ± 0.13 kg.kg$^{-1)}$	HPC and JS at loads of 30,50,70% 1-RM (70% was used for analysis)	FP	Force-time data analysis- Curve analysis indicated significant differences between the VGRF of the HPC and JS between ~46 and 50% (between 0.029 < *p* < 0.037) and between ~82 and 100% of the movement phase (all *p* < 0.001). SPM procedure indicated a significant difference between the vertical GRF of the HPC and JS between ~85 and 100% of the movement phase. Velocity-time data analysis- Curve analysis indicated significant differences between the VGRF of the HPC and JS, between ~72 and 76% (between 0.038 < *p* < 0.046) and between ~88 and 100% of the movement phase (all *p* < 0.001). SPM indicated a significant difference between the barbell-lifter system velocity during the HPC and JS between ~ 90 and 100% of the movement phase

				Power-time Data analysis-Curve analysis indicated significant differences between the barbell-lifter system power of the HPC and JS between 70 and 76% (between $0.032 < p < 0.037$) and between ~84 and 100% of the movement phase (all $p < 0.001$). SPM procedure indicated a significant difference between the barbell-lifter system power of the HPC and JS between ~90 and 100% of the movement phase ($p < 0.001$)
Lopes Dos Santos et al. (208)	15 males with weightlifting training experience-1-RM HPC (1.12± 0.13 $kg.kg^{-1}$)	MTCP, HHP, HPC at relative loads of 30,40,50,60,70,80,90% BM	FP and Motion analysis	HPC PPO and PF – greatest at 90% BM, significantly greater than all loads except 80%. PV greatest at 90%, significantly greater than 30-60% HHP PPO – 90% BM, significantly greater than 30 and 40%. PF- greatest at 90% BM, significantly greater than 30-60%. PV greatest at 70%, not significantly different to any load MTCP PPO – 80% BM, significantly greater than 30%. PF- greatest at 90% BM, significantly greater than 30-50%. PV- greatest at 30% BM, significantly greater than 90%.
McBride et al. (217)	9 males (1-RM HPC 97.1 ± 6.36 kg)	PC at 30-90% 1-RM	FP + Videography	Bar PP- maximised at 90% 1-RM. Significantly greater than 30% and 40% 1-RM. Body PP- maximised at 90% 1-RM. Significantly greater than 50% 1-RM. System PP- maximised at 80% 1-RM. Significantly greater than 30% 1-RM. Bar PF- maximised at 90%. Significantly greater than all loads. Body PF- maximised at 80%. Significantly greater than 30% to 60% 1-RM. System PF- maximised at 90%. Significantly greater than 30% to 70% 1-RM. Bar PV- maximised at 30%. Significantly greater than 40% to 90% 1-RM.

				Body PV- maximised at 30%. Not significantly greater than any load. System PV- maximised at 30%. Not significantly greater than any load.
Suchomel et al. (299)	14 men (1-RM HPC 104.89 ± 15.10 kg)	HPC at 30, 45, 65 and 80% 1-RM HPC.	FP	PF greatest at 80% 1-RM. Significantly greater than 30% 1-RM. PV greatest at 45% 1-RM. Not significantly greater than any load. PP greatest at 80% 1-RM. Not significantly greater than any load. F_{PP} greatest at 80% 1-RM. Significantly greater than 30% and 45% 1-RM. V_{PP} greatest at 45% 1-RM. Not significantly greater than any load. RFD greatest at 30% 1-RM. Not significantly greater than any load.
Suchomel et al. (316)	17 athletic males (1-RM HPC 111.12 ± 20.40 kg)	HC, JS and HHP at 30%, 45%, 65%, 80% 1-RM HC	FP	PP significantly greater during the JS compared to HC and HP. PF significantly greater during the JS compared to HC and HP. PF not significant different between HHP and HC. PV significantly greater during the JS compared to HC and HHP, PV significantly greater during HP than HC. PP greatest at 45% HC. Significantly greater than 65% and 80%, but not 30%. PF greatest at 65% HC. Significantly greater than 30%. Not significantly greater than any other load. PV greatest at 30% HC. Significantly greater than 65% and 80%, but not 45%. PP in HC greatest at 65%. PF greatest at 80%. PV greatest at 45%. PP in JS greatest at 30%. PF greatest at 65%. PV greatest at 30%. PP in HP greatest at 45%. PF greatest at 80%. PV greatest at 30%.
Suchomel et al (307).	12 resistance trained men. (1-RM HPC 108.50 ± 14.6 kg; relative 1-RM HPC 1.3 ± 0.2 kg · kg^{-1})	HPC, JS, HHP at loads 30%, 45%, 65%, 80% 1-RM HPC	FP	JS produced significantly more load averaged work compared to HPC and HHP. HHP produced significantly more load averaged work compared HPC. Significantly more exercise averaged work at 80% compared to 30%, 45% and 65%. 65% was significantly greater compared to 30%, but not 45%. JS load averaged MF was significantly greater than HPC and HHP.

				Exercise averaged MF was significantly greater at 80% than all other loads. MF at 65% significantly greater than 30%. Load-averaged load absorption duration of the HHP was significant longer than HPC and JS.
Suchomel et al. (306)	11 Division I male lacrosse players (1-RM HPC: 100.4 ± 8.1 kg) (relative 1-RM HPC: 1.25 ± 0.13 kg · kg^{-1})	HPC and JS at 30%, 50%, 70%	FP and Motion analysis	JS = greater load absorption joint work compared with the HPC performed at the hip ($p < 0.001$, $d = 0.84$), knee ($p < 0.001$, $d = 1.85$), ankle joints ($p < 0.001$, $d = 1.49$). JS = Greater joint work compared with the HPC performed at 30% ($p < 0.001$, $d = 0.89$), 50% ($p < 0.001$, $d = 0.74$), and 70% 1-RM HPC ($p < 0.001$, $d = 0.66$) JS = longer loading duration compared with the HPC at the hip ($p < 0.001$, $d = 0.94$), knee ($p = 0.001$, $d = 0.89$), and ankle joints ($p < 0.001$, $d = 0.99$). JS = loading duration compared with the HPC performed at 30% ($p < 0.001$, $d = 0.83$), 50% ($p < 0.001$, $d = 0.79$), and 70% 1-RM HPC ($p < 0.001$, $d = 0.85$).
Stone et al. (294)	11 well trained college throwers, 5 males and 6 females	PP at 30% and 60% of MVIC PP at 30% and 60% of MVIC	FP and V-Scope	(Baseline) T1 –PP (W) at 30% (2065 ± 921); PP (W) at 60% (1621 ± 589) T1 –PF (N) at 30% (2370 ± 627); PF (N) at 60% (2809 ± 745) (4 weeks) T2- PP (W) at 30% (2427 ± 871); PP at 60% (2025 ± 792) T2 –PF (N) at 30% (2393 ± 581); PF (N) at 60% (2851 ± 765) (8 weeks) T3- PP (W) at 30% (2434 ± 683); PP at 60% (2178 ± 686)

				T3 –PF (N) at 30% (2566 ± 517); PF (N) at 60% (3006 ± 677)
Takei et al. (320)	8 competitive weightlifters (1.59 ± 0.17 kg· kg^{-1})	HHP and HPC at loads of 40, 60, 80, 100% 1-RM HPC	2D video and FP	Significant differences in PP between HHP and HPC at 40%, 60%, & 70% ($p < 0.001$; $p = 0.003$; $p = 0.002$), no statistical difference in peak power between the exercises at 80,90, 95, and 100% Peak bar height was significantly greater during the HHP than during the HPC at 40, 60, and 70% 1-RM, whereas no significant differences were found at 80, 90, 95, and 100%
Winchester et al. (348)	18 healthy adult males	PC Training 3 x per week for 4 weeks at loads of 50% (5x5),70% (4x3) and 90% (1x3) 1-RM PC.	2D video and FP	50% Pre-test- PP- 3430 ± 1280 W; 50% Post-test- PP- 4230 ± 1326 W. 70% Pre-test- PP- 3896.83 ± 1035 W; 70% Post-test- PP- 4048.3 ± 1326 W. 90% Pre-test- PP- 3461.47 ± 1172 W; 90% Post-test- PP- 3709.65 ± 1225 W. 50% Pre-test- PF- 936 ± 38 N; 50% Post-test- PF- 1299 ± 384N. 70% Pre-test- PF- 1216.33 ± 1035 N; 70% Post-test- PF- 4048.3 ± 1326 N. 90% Pre-test- PF- 1255.83 ± 329 N; 90% Post-test- PF- 1426 ± 321 N.

Key: PC = Power Clean; RM = Repetition Maximum; PP = Peak Power; PF = Peak Force; PRFD = Peak rate of force development; PBV = Peak Barbell Velocity = Peak displacement; MTPC = Mid-thigh power clean; MTCP = mid-thigh clean pull; CP = Clean pull; FP = Force Plate; LPT = Linear position transducer; IMP = Impulse; RPP = Relative Peak Power; RPF = Relative Peak force; PV= Peak system velocity HC = Hang Clean; JS = Jump shrug; F_{PP} = Force at Peak power; V_{PP} = Velocity at Peak power; HHP = Hang High Pull; JH = Jump Height; PF_{LAND} = Peak Landing Force; PE = potential energy of the lifter plus bar system; HHP = Hang High Pull; MF = Mean Force; SJ = Squat Jump; F100 = Force at 100 ms; F150 = Force at 150 ms; F200 = Force at 200 ms; F250 = Force at 100 ms; 2D = Two-dimensional videography; PPress = Push press; BS = Back Squat; CK = clean from knee; CPK = clean pull from knee; PCK = power clean from knee; IBM = Including body mass; EBM = Excluding body mass; IBMS = Including body mass minus shank mass; VGRF = Vertical ground reaction force

2.3.10. Clean Variations Excluding the Catch

Haff, Stone, O'Bryant, Harman., Dinan, Johnson and Ki- Hoon (124) investigated the kinetics of dynamic MTP (from blocks) at 80, 90 and 100% of 1-RM in eight trained males' whilst standing on a FP sampling at 500 Hz. Peak force was greater at 100% compared to 80 and 90%, although not statistically different. Whilst both PRFD and PP were maximised at 80% 1-RM, neither variable was statistically different across loads. However, it should be acknowledged the authors did not assess loads < 80%. In contrast, Kawamori, Rossi, Justice, Haff, Pistilli, O'Bryant, Stone and Haff (181) compared kinetics between the IMTP and dynamic MTP (from blocks) across a range of loads (30, 60, 90, 120% 1-RM PC), in eight male weightlifters (1-RM PC = 118.4 ± 15.4 Kg). Optimal loading for PP was produced at 60% 1-RM (2229 ± 192 W), however this was not statistically different to any other load when calculated via forward dynamics. Peak force was significantly greater ($p < 0.05$) at 120% 1-RM compared to all dynamic conditions, with a progressive increase with an increase in load. Peak rate of force development was maximised at 30% 1-RM (27607 ± 4608 $N.s^{-1}$) which was not significantly greater across loads and demonstrated a progressive decrease with an increase in load.

Comfort, Udall and Jones (55) assessed the effect of load on kinematics and kinetics during the MTP in sixteen subjects across loads (40-140% 1-RM) of 1-RM PC. Peak force showed a progressive increase as load increased; however, this was not statistically significant ($p > 0.05$) between 60%, 80% and 100%. Further, the greatest RFD occurred at 120% (26224 ± 2462 $N.s^{-1}$), which was significantly greater ($p \leq 0.004$) than the 40%, 60%, 80%, and 100% conditions. However, this was not significantly ($p > 0.05$) greater than 140%. Additionally, PP decreased significantly ($p < 0.001$) as load increased. Significantly greater PP (3713 ± 254 W) was achieved during the 40% condition compared to all loads; however, this was not statistically different to 60%. Impulse demonstrated a near linear increase with load with the greatest impulse over 100 ms (197 ± 77 Ns), 200 ms (416 ± 158 Ns), 300 ms (648 ± 252 Ns) was observed in the 140% 1-RM condition, which was significantly ($p \leq 0.005$, $p \leq 0.023$, $p \leq 0.011$, respectively) greater than all other loads. Similarly, total impulse was maximised at 140%, which was significantly greater ($p \leq 0.03$) than 40-100%, but not 120% ($p > 0.05$).

In another study Comfort, Jones and Udall (52) investigated the effect of sex and load on kinematics and kinetics during the mid-thigh clean pull (MTCP) following the same protocol as Comfort, Udall and Jones (55) in ten males and ten females with average training experiences of 3.5 ± 0.9 years. Similar findings were observed to the aforementioned study with PF being maximised in both groups at 140% 1-RM and significantly greater ($p < 0.05$) in both groups across loads. Males demonstrated the highest impulse at 200 ms with 140% 1-RM which was significantly ($p < 0.05$) greater than with 40% and 60% 1-RM, although not significantly ($p > 0.05$, $d \leq 0.53$) different from the 80-120% loads. Similarly, females demonstrated the highest impulse at 200 ms with 140% 1-RM, although this was not significantly ($p > 0.05$, $d \leq 0.60$) greater than the other loads. Also, in agreement with the previous study, system PP was maximised at 40% and significantly greater ($p < 0.05$) compared to all loads in both sexes and showed a progressive decrease across loads. Further, a similar trend was evident with 40% eliciting significantly greater ($p < 0.05$) bar PV and decreased across load. Interestingly, males produced a more rapid decline in bar velocity as load increased, whilst woman demonstrated significantly greater bar velocities compared to males with 120% ($p < 0.05$) and 140% ($p < 0.05$), potentially attributed to the greater absolute bar velocities in males. A summary of variations excluding the catch are shown below in Table 2.4

Table 2.4-Kinetics and kinematics of clean variations that exclude the catch phase.

Study	Sample	Exercise(s) and methods	Methods of Measurement	Results
Comfort et al. (45)	11 elite rugby players	1 set of 3 repetitions at 60% 1-RM PC in PC, HPC, MTPC, MTCP	FP	Significantly greater PF during MTCP compared to HPC and PC. Significantly greater PRFD during MTCP compared to HPC and PC.
Comfort et al. (46)	16 elite rugby players	1 set of 3 repetitions at 60% 1-RM PC in PC, HPC, MTPC, MTCP	FP	Significantly greater PP during MTCP compared to HPC and PC. Significantly greater PF during MTCP compared to HPC and PC. Significantly greater PRFD during MTCP compared to HPC and PC.
Comfort et al. (55)	16 healthy collegiate athletes	MTCP at 40%,60%,80%,100%,120%,140% 1-RM PC	FP and LPT	PP greatest at 40%. Significantly greater than all loads, except 60%. PBV greatest at 40%. Significantly greater than all loads. PF greatest at 140%. Significantly greater than all loads, except 60%. PRFD greatest at 120%. Significantly greater than all loads, except 140%. PD greatest at 40%. Significantly greater than all loads. IMP at 100 ms greatest at 140%. Significantly greater than all loads. IMP at 200 ms greatest at 140%. Significantly greater than all loads. IMP at 300 ms greatest at 140%. Significantly greater than all loads. Total IMP greatest at 140%. Significantly greater than all loads, except 120%.
Comfort et al. (52)	10 males (1-RM PC 86.7 ± 8.5 Kg) 10 females (1-RM PC 41.9 ± 4.2 Kg)	MTCP at 40%,60%,80%,100%,120%,140% 1-RM PC	FP and LPT	PP greatest at 40% in both males and females. Significantly greater than all loads. RPP at 40% in males. Significantly greater than all loads, except 60%. RPP at 40% in females. Significantly greater than all loads, except 60% and 80% PBV greatest at 40% in both males and females. Significantly greater than all loads PF greatest at 140% in both males and females. Significantly greater than all loads. RPF at 140% in both males and females. Not significantly greater than any load. PD greatest at 40% in both males and females. Significantly greater than all loads, except 60%. IMP at 200 ms greatest at 140% in males and females. Significantly greater than 40% and 60% in males. Not significantly different than any load in females.

Comfort et al. (47)	18 professional youth soccer players. (11 completed the study) 26 collegiate athletes. (23 completed the study) Catch group 1-RM PC = 0.93 ± 0.15 $kg.kg^{-1}$ Pull group 1-RM PC = 1-RM PC 0.91 ± 0.18 $kg.kg^{-1}$	Two strength matched groups completed the twice weekly training sessions either including or excluding the catch phase of the PC derivatives in 2 x 4-week mesocycles	FP	The Catch and Pull groups both demonstrated significant) and meaningful improvements in CMJ height (10.8 ± 12.3%, 5.2 ± 9.2%), PC 1-RM (9.5 ± 6.2%, 8.4 ± 6.1%) and IMTP performance (force [F]100: 14.9 ± 17.2%, 15.5 ± 16.0%, F150: 16.0 ± 17.6%, 16.2 ± 18.4%, F200: 15.8 ± 17.6%, 17.9 ± 18.3%, F250: 10.0 ± 16.1%,10.9 ± 14.4%, PF: 13.7 ± 18.7%, 9.7 ± 16.3%). The Catch group achieved moderate improvements in the SJ height (12.6%) across the duration of the intervention. Pull group demonstrated only trivial increases (2.1%).
Haff et al. (124)	8 trained males (1-RM PC 114.7 ± 8.0 kg)	CP at 80, 90, 100% 1-RM PC.	FP	PF greatest at 100% 1-RM PC. Not significantly greater than any load. PRFD greatest at 80%. Not significantly greater than any load. PP greatest at 80%. Not significantly different than any load.
Kawamori et al. (181)	8 collegiate weightlifters (1-RM PC 118.4 ± 5.5 kg)	MTCP (Blocks) across various loads (30, 60, 90, 120% 1-RM power clean)	FP	PP greatest at 60% 1-RM PC. Not significantly greater than any load. PF greatest at 120% 1-RM PC. Significantly greater to all loads. PRFD greatest at 30%. Not significantly greater to any load. General decline with load increase
Kipp et al. (188)	15 male lacrosse players (1-RM HPC 100.4 ±8.1 kg)	3 sets of HPC at JS at loads at 30%, 50% and 70% 1-RM HPC	FP and Motion analysis	Positive mechanical work in HPC ($J{\cdot}kg^{-1}$), 30%- Hip (1.06 ± 0.24), Knee (0.09 ± 0.08), Ankle (0.46 ± 0.25); 50%- Hip (1.35 ± 0.17), Knee (0.10 ± 0.06), Knee (0.62 ± 0.22), 70%- Hip (1.61 ± 0.26), Knee (0.13 ± 0.09), Ankle (0.86 ± 0.25). Positive mechanical work in JS ($J{\cdot}kg^{-1}$),

	Relative HPC (1.25 ± 0.13 kg.kg$^{-1)}$			30%- Hip (1.12 ± 0.30), Knee (0.18 ± 0.08), Ankle (1.12 ± 0.28); 50%- Hip (1.24 ± 0.23), Knee (0.19 ± 0.10), Knee (1.16 ± 0.23), 70%- Hip (1.38 ± 0.30), Knee (0.17 ± 0.13), Ankle (1.27 ± 0.21). Duration (ms) of the propulsive (i.e., concentric) phase HPC 30%- Hip (288 ± 43), Knee (165 ± 26), Ankle (155 ± 50); 50%- Hip (328 ± 58), Knee (181 ± 70), Knee (226 ± 135), 70%- Hip (356 ± 45), Knee (195 ± 22), Ankle (218 ± 41). Duration (ms) of the propulsive (i.e., concentric) phase JS 30%- Hip (303 ± 45), Knee (154 ± 11), Ankle (143 ± 37); 50%- Hip (328 ± 58), Knee (184 ± 59), Knee (166 ± 42), 70%- Hip (371 ± 38), Knee (192 ± 15), Ankle (185 ± 28). Peak positive mechanical power (W·kg^{-1}) propulsive (i.e., concentric) phase HPC 30%- Hip (8.2 ± 1.6), Knee (3.5 ± 2.6), Ankle (5.9 ± 3.1); 50%- Hip (10.1 ± 1.9), Knee (4.2 ± 2.2), Knee (7.4 ± 2.6), 70%- Hip (11.2 ± 2.0), Knee (4.7 ± 2.9), Ankle (8.9 ± 2.4). Peak positive mechanical power (W·kg^{-1}) propulsive (i.e., concentric) phase JS 30%- Hip (8.9 ± 2.2), Knee (13 ± 5.1), Ankle (14.9 ± 3.4); 50%- Hip (9.8 ± 2.3), Knee (11.7 ± 4.6), Knee (14.4 ± 2.8), 70%- Hip (9.1 ± 2.7), Knee (10.8 ± 4.0), Ankle (13.7 ± 1.7).
Kipp et al. (185)	15 male lacrosse players (1-RM HPC 100.4 ± 8.1 kg) Relative HPC (1.25 ± 0.13 kg.kg$^{-1)}$	HPC and JS at loads of 30,50,70% 1-RM (70% was used for analysis)	FP	Force-time data analysis- Significant differences between the VGRF of the HPC and JS between ~46 and 50% (between 0.029 < *p* < 0.037) and between ~82 and 100% of the movement phase (all *p* < 0.001). SPM procedure indicated a significant difference between the VGRF of the HPC and JS between ~85 and 100% of the movement phase. Velocity-time data analysis- Significant differences between the VGRF of the HPC and JS, between ~72 and 76% (between 0.038 < *p* < 0.046) and between ~88 and 100% of the movement phase (all *p* < 0.001). SPM indicated a significant difference between the barbell-lifter system velocity during the HPC and JS between ~ 90 and 100% of the movement phase Power-time Data analysis - Significant differences between the barbell-lifter system power of the HPC and JS between 70 and 76% (between 0.032 < *p* < 0.037) and between ~84 and 100% of the movement phase (all *p* < 0.001). SPM procedure indicated a significant difference between the barbell-lifter system power of the HPC and JS between ~90 and 100% of the movement phase (*p* < 0.001)

Lopes Dos Santos et al. (208)	15 males with weightlifting training experience (1-RM HPC 1.12± 0.13 kg.kg^{-1})	MTCP, HHP, HPC at relative loads of 30,40,50,60,70,80,90% BM	FP and Motion analysis	HPC PPO and PF – greatest at 90% BM, significantly greater than all loads except 80%. PV greatest at 90%, significantly greater than 30-60% HHP PPO – 90% BM, significantly greater than 30 and 40%. PF- greatest at 90% BM, significantly greater than 30-60%. PV greatest at 70%, not significantly different to any load MTCP PPO – 80% BM, significantly greater than 30%. PF- greatest at 90% BM, significantly greater than 30-50%. PV- greatest at 30% BM, significantly greater than 90%.
Suchomel et al. (298)	14 males (1-RM-HC 104.89 ± 15.07kg)	JS at loads 30%,45%,65%,80% 1-RM HPC	FP	PV greatest at 30%. Significantly greater than all loads. PF greatest at 80%. Not significant different to any load. PP greatest at 30%. Significantly greater than 65% and 80%. F_{PP} greatest at 65%. Significantly greater than 30% and 45%. V_{PP} greatest at 30%. Significantly greater than 65% and 80%.
Suchomel et al. (316)	17 athletic males (1-RM HPC 111.12 ± 20.40 kg)	HC, JS and HHP at 30%,45%,65%,80% 1-RM HC	FP	PP significantly greater during the JS compared to HC and HP. PF significantly greater during the JS compared to HC and HP. PF not significant different between HHP and HC. PV significantly greater during the JS compared to HC and HHP, PV significantly greater during HP than HC. PP greatest at 45% HC. Significantly greater than 65% and 80%, but not 30%. PF greatest at 65% HC. Significantly greater than 30%. Not significantly greater than any other load. PV greatest at 30% HC. Significantly greater than 65% and 80%, but not 45%. PP in HC greatest at 65%. PF greatest at 80%. PV greatest at 45%. PP in JS greatest at 30%. PF greatest at 65%. PV greatest at 30%. PP in HP greatest at 45%. PF greatest at 80%. PV greatest at 30%.
Suchomel et al. (300)	14 males (1-RM HPC (104.89 ± 15.10 kg)	HHP at loads 30%,45%,65%,80% 1-RM HPC	FP	PV greatest at 30%. Significantly greater than all loads, except 45% PF greatest at 80%. Significantly greater than 30% PP greatest at 45%. Significantly greater than all loads, except 30%. F_{PP} greatest at 80%. Significantly greater than all loads. V_{PP} greatest at 30%. Significantly greater than all loads, except 45%
Suchomel et al. (315)	15 resistance	JS at loads 30%,45%,65%,80% 1-RM HPC	FP	JH greatest at 30%. Significantly greater than all loads. PF_{LAND} greatest at 30%. Not significant different to any load. PE greatest at 30%. Significantly greater than all loads.

	trained males (1-RM HPC 109.10 ± 17.20 kg)			
Suchomel et al (307).	12 resistance trained males (1-RM HPC 108.50 ± 14.6 kg; Relative 1-RM HPC 1.3 ± 0.2 kg · kg^{-1}).	HPC, JS, HHP at loads 30%,45%,65%,80% 1-RM HPC	FP	JS produced significantly more load averaged work compared to HPC and HHP. HHP produced significantly more load averaged work compared HPC. Significantly more exercise averaged work at 80% compared to 30%, 45% and 65%. 65% was significantly greater compared to 30%, but not 45%. JS load averaged MF was significantly greater than HPC and HHP. Exercise averaged MF was significantly greater at 80% than all other loads. MF at 65% significantly greater than 30%. Load-averaged load absorption duration of the HHP was significant longer than HPC and JS.
Suchomel et al. (310)	15 resistance trained males, relative back squat (1-RM: 1.8 ± 0.3 kg·kg^{-1})	HEXJ, JShrug, JS at 20,40,60,80,100% BM	FP	Load-averaged HEXJ and JShrug PPRel statistically greater than the JS (both $p < 0.01$). Load-averaged JShrug FPP was statistically greater than both the JS and the HEXJ (both $p < 0.001$). Load- averaged JS and HEXJ VPP were statistically greater than the JShrug (both $p < 0.01$). HEXJ VPP was statistically greater than the JS ($p = 0.009$). PPRel was maximised at 40, 40, and 20% BM for the JS, HEXJ, and JShrug JShrug possessed statistically different power-time characteristics compared to both the JS and the HEXJ during the countermovement and propulsion phases. JShrug power-time curves were different from 41-62% and 68-84% of the total jump at BM and 20% BM, 34-60% and 66-81% of the total jump at 40 and 60% BM, and 29-54% and 66- 79% of the total jump at 80 and 100% BM.
Stone et al. (294)	11 well trained college throwers, 5 males and 6 females	PP AT 30% and 60% of MVIC PP AT 30% and 60% of MVIC	FP and V-Scope	(Baseline) T1 –PP (W) at 30% (2065 ± 921); PP (W) at 60% (1621 ± 589) T1 –PF (N) at 30% (2370 ± 627); PF (N) at 60% (2809 ± 745) (4 weeks) T2- PP (W) at 30% (2427 ± 871); PP at 60% (2025 ± 792) T2 –PF (N) at 30% (2393 ± 581); PF (N) at 60% (2851 ± 765) (8 weeks) T3- PP (W) at 30% (2434 ± 683); PP at 60% (2178 ± 686) T3 –PF (N) at 30% (2566 ± 517); PF (N) at 60% (3006 ± 677)

Takei et al. (320)	8 competitive weightlifters (1.59 ± 0.17 kg· kg^{-1})	HHP and HPC at loads of 40, 60, 80, 100% 1-RM HPC	2D video and FP	Significant differences in PP between HHP and HPC at 40%, 60%, & 70% ($p < 0.001$; $p = 0.003$; p = 0.002), no statistical difference in peak power between the exercises at 80,90, 95, and 100% Peak bar height was significantly greater during the HHP than during the HPC at 40, 60, and 70% 1-RM, whereas no significant differences were found at 80, 90, 95, and 100% 1-RM
Thomas et al. (323)	16 males, 14 females from collegiate sports	Hang Pull (fixed form and free form	Plyometric Power System	PP output across 30,40,50,60 and 70% 1-RM HP in males and females during fixed form and free form) Males- PP maximised at 40% (free form), 50% (fixed form) Females- PP maximised at 50% (free form), 40% (fixed form) 70% significant less than all loads in both males and females and exercises.
Key: PC = Power Clean; RM = Repetition Maximum; PP = Peak Power; PF = Peak Force; PRFD = Peak rate of force development; PBV = Peak Barbell Velocity; PD = Peak displacement; MTPC = Mid-thigh power clean; MTCP = mid-thigh clean pull; CP = Clean pull; FP = Force Plate; LPT = Linear position transducer; IMP = Impulse; RPP = Relative Peak Power; RPF = Relative Peak force; PV= Peak system velocity HC = Hang Clean; JS = Jump shrug; F_{PP} = Force at Peak power; V_{PP} = Velocity at Peak power; HHP = Hang High Pull; JH = Jump Height; PF_{LAND} = Peak Landing Force; PE = potential energy of the lifter plus bar system; HHP = Hang High Pull; MF = Mean Force; SJ = Squat Jump; F100 = Force at 100 ms; F150 = Force at 150 ms; F200 = Force at 200 ms; F250 = Force at 100 m; JShrug = Jump shrug; HEXJ = Hexagonal bar jump squat; PPrel = Relative peak power; V_{PP} = Velocity at peak power; F_{PP} = Force at peak power; BM = Body mass; VGRF = Vertical Ground Reaction Force.				

2.3.11. The Effect of Loading During the Hang Power Clean

The HPC is a variation of the PC in which the athlete starts in a standing position with the barbell at the mid-thigh, lowers the barbell down to a position just above their knee, returns to the mid-thigh position, performs the second pull, elevates the barbell, rapidly rotates their elbows under the bar, and catches the bar across their shoulders in a semi-squat position (179).

The optimal loading for the HPC has been previously investigated in various populations. Kawamori, Crum, Blumert, Kulik, Childers, Wood, Stone and Haff (179) investigated the optimal load for PP via forward dynamics in 15 trained males (Relative 1-RM = PC 1.2 ± 0.15 x body mass) across loads of 30-90% 1-RM. The authors demonstrated that PP was maximised at 70%, but not statistically different across loads of 50-90% 1-RM. Further analysis between stronger (1-RM ≥ 110 kg) and weaker subjects (1-RM < 110 kg) the strong group achieved PP (4281 ± 635 W) at 70% 1-RM and the weak group achieved PP (3983 ± 906 W) at 80% 1-RM, although these were still not significantly different to the values achieved at 50-90% 1-RM.

Kilduff, Bevan, Owen, Kingsley, Bunce, Bennett and Cunningham (183) also used forward dynamics to calculate PP in 12 professional rugby players also across loads at 30-90% 1-RM. The results demonstrated that PP (4467 ± 477 W) occurred at 80% 1-RM, although this was not significantly greater than the PP at 40-90%. In contrast, Suchomel, Wright, Kernozek and Kline (316) investigated PP at loads of 30%, 45%, 65% and 80% 1-RM hang clean (HC) in 17 males with HC experience (1-RM = 111.12 ± 20.40 Kg) and determined that the greatest PP occurred at 45% 1-RM HC (5125 ± 1538 W) which was significantly greater than both 65% (p = 0.043, d =0.19) and 80% 1-RM HC (p = 0.004, d =0.40), however, that study only examined main effect differences. However, another study by Suchomel, Beckham and Wright (299) used a similar protocol to the above study and found that that PP was greatest at 80% 1-RM, although this was not statistically different to 30%, 45%, and 65% 1-RM. However, it should be noted that the subjects produced 12.9%, 11.7%, and 9.1% greater PP at the loads of 80%, 65%, and 45% 1-RM as compared to 30% 1-RM, highlighting the rationale for the use of heavier loads when attempting to maximise power. Additionally, PF increased with load was significantly greater ($p < 0.05$) at 80% 1-RM compared to 30% 1-RM. Further, PV was greatest at 45% 1-RM although not significantly greater than other loads. The greatest RFD occurred at 30% 1-RM, but was not statistically different from the RFD at 45%, 65%, and 80% 1-RM which is in line with previous research (181).

Kipp, Malloy, Smith, Giordanelli, Kiely, Geiser and Suchomel (188) investigated the HPC in 15 collegiate lacrosse players across loads of 30, 50 and 70% 1-RM HPC and determined that PP was greatest at 70% 1-RM HPC. Therefore higher loads are beneficial for producing greater power during the HPC in line with previous research (183). However, due to many of the studies not showing significance differences across various loads, it seems plausible that subjects will produce similar power across a variety of loads (299), due to the interaction between force and velocity or work / time resulting in comparable power.

Flores, Sedano and Redondo (100) recently investigated the optimal load and optimal power spectrum (maximal power load and similar loads with no significant differences between them (defined as the optimal power spectrum (OPS) during the snatch and clean in both international level weightlifters (IW) (n = 11, Sinclair coefficient 396 ± 19) and national level weightlifters (NW) (n = 11, Sinclair coefficient 304 ± 27) who had >13 years weightlifting experience, using accelerometer technology to measure barbell acceleration and inverse dynamics to calculate power. Subjects performed the snatch and clean at percentages of 30-90% of their 1-RM in line with previous work (179, 183), and results showed that the IW group produced greatest PP at 90% 1-RM in both the snatch (4186 ± 724 W) and clean (3753 ± 558), whilst the NW group was at 70% (3084 ± 421 W) and 90% 1-RM (2920 ± 430 W), with 90% been shown previously (217). The IW snatch showed no significant differences between the optimal load and 80%, whilst the clean was significantly different to all other loads ($p < 0.001$). Similarly, for the NW group, no significant differences were found between 70%, 80% and 90% of 1-RM during the snatch, whilst the clean demonstrated, no significant differences between 50-90%, which is in line with previous studies (49, 183). The greater load that power is produced in the IW group may be partly explained by their strength levels observed in this group, with Stone, O'Bryant, McCoy, Coglianese, Lehmkuhl and Schilling (292) demonstrating that stronger subjects produced greatest power at heavier loads when compared to weaker subjects, albeit in loaded jumps. However, it is essential to consider the methodological differences in power calculation (inverse vs forward dynamics) between the aforementioned studies which will have affected the results and comparisons between loads (59, 198, 217). The optimal load for PP in weightlifting derivatives is shown in Table 2.5.

Table 2.5-Optimal loading for peak power during weightlifting derivatives

Study	**Sample**	**Exercise**	**Optimal load for Peak power**	**Method of Calculating power**
Comfort et al. (55)	16 healthy collegiate athletes	MTCP at 40%,60%,80%,100%,120%,140% 1-RM PC	PP at 40% 1-RM. Significantly greater than all loads except 60%	Forward Dynamics
Comfort et al. (52)	10 males 10 females	MTCP at 40%,60%,80%,100%,120%,140% 1-RM PC	PP at 40% 1-RM. Significantly greater than all loads	Forward Dynamics
Comfort et al. (49)	19 male collegiate athletes	PC at loads of 30-80%	PP at 70% 1-RM. Not significantly different between 60 & 80%	Forward Dynamics
Comfort et al. (53)	16 healthy females' collegiate athletes	PC at loads of 60%, 70%, 80% HPC at loads of 60%, 70%, 80% MTPC at loads of 60%, 70%, 80%	PC PP at 80% HPC PP at 70% MTPC PP at 70%	Forward Dynamics
Cormie et al. (64)	12 Division I male athletes (112.5 ± 13.2 kg)	PC at loads 30-90% of 1-RM (MDS)	PP at 80% 1-RM.	Combined Method
Cormie et al. (60)	12 Division I male athletes (112.5 ± 13.2 kg)	PC at loads 30-90% (IBM) PC at loads 30-90% (IBMS) PC at loads 30-90% (EBM)	PP at 80% 1-RM PP at 80% 1-RM PP at 80%. Not Significantly different at 50-90% 1-RM (p>0.05)	Combined Method Combined Method Combined Method
Cormie et al. (59)	10 Division I male athletes (1-RM PC 112.75 ± 13.15 kg)	PC at loads 30-90% 1-RM	PP at 30% 1-RM PP at 80% 1-RM PP at 80% 1-RM	Inverse Dynamics Combined Method Forward Dynamics
Flores et al. (100)	11 International weightlifters (IW), (1-RM clean= 164 Kg, 1-RM snatch =132.5 Kg)	Snatch and clean	IW- Clean- 90% 1-RM IW- Snatch- 90% 1-RM No significant differences between 80-90% in snatch. significant differences between 90% and all other loads (p<0.001)	Inverse Dynamics

	11 National weightlifters (NW) (1-RM clean 129 Kg, 1-RM snatch =107 Kg		NW-Clean- 90% 1-RM NW-Snatch- 70% 1-RM. No significant differences between 50-90% in clean No significant differences between 70-90% in snatch.	
Haff et al. (124)	8 trained males (1-RM 114.7 ± 8.0 Kg)	MTCP at 80%, 90%, 100% 1-RM Power clean	PP at 80% 1-RM	Forward Dynamics
Kawamori et al. (179)	15 males (107 ± 18.8 kg)	HPC at loads 30-90%	PP at 70% 1-RM. Not significantly different between 50- 90% 1-RM.	Forward Dynamics
Kawamori et al. (181)	8 collegiate weightlifters (118.4 ± 5.5 kg)	MTCP at 30%, 60%, 90%, 120% 1-RM PC	PP at 60% 1-RM PC. Not significantly different to any load	Forward Dynamics
Kilduff et al. (183)	12 Professional rugby players (107 ± 13 kg)	HPC at loads 30-90%	PP at 80% 1-RM. Not significantly different between 50- 90% 1-RM.	Forward Dynamics
McBride et al. (217)	9 males (PC 1-RM 97.1+ 6.36 kg)	PC at loads 30-90% 1-RM	Bar power -90% 1-RM- significantly different from 30, 40, and 50% 1-RM. Body Power- 90% 1-RM- significantly different from 50% 1-RM. System Power-80% 1-RM- Significantly different from 30% 1-RM.	Inverse Dynamics Inverse Dynamics Forward Dynamics
Pennington et al. (265)	20 Division I football athletes	Power Clean 30-90% 1-RM Snatch 30-90% 1-RM	≥ 80% 1-RM in both lifts. no significant difference ($p > 0.05$) between 80-100% 1-RM	Inverse Dynamics
Suchomel et al. (298)	14 males (1-RM HC 104.89±15.07kg)	JS at loads 30%,45%,65%,80% 1-RM HPC	JS PP at 30% 1-RM. Significantly greater than 65%	Forward Dynamics

Suchomel et al. (316)	17 athletic males (111.12 ± 20.40 kg)	HP at loads 30%,45%,65%,80% 1-RM HC JS at loads 30%,45%,65%,80% 1-RM HPC HC at loads 30%,45%,65%,80% 1-RM HPC	HHP PP at 45% 1-RM. JS PP at 30% 1-RM. HC PP at 65% 1-RM.	Forward Dynamics
Suchomel et al. (299)	14 males (1-RM HPC 104.89 ± 15.10 kg)	HPC at loads of 30%,45%,65%,80% 1-RM	PP at 80% 1-RM. No significant differences between 30-80% 1-RM.	Forward Dynamics
Suchomel et al. (300)	14 males (1-RM HPC (104.89 ± 15.10 kg)	HHP at loads 30%,45%,65%,80% 1-RM HPC	PP at 45% 1-RM. Significantly greater than 65% and 80% 1-RM.	Forward Dynamics
Suchomel et al. (310)	15 resistance trained males, 1-RM BS (1.8 ± 0.3 Kg.Kg	HexJ, JS, JSq at 20,40,60,80,100% BM	Relative PP at 20% BW	Forward Dynamics
Takei et al. (320)	8 Elite male weightlifters (1.59 ± 0.17 kg/body mass)	HPC at loads 40%, 60%, 70%,80%, 90%, 95%, 100% 1-RM PC HHP at loads 40%, 60%, 70%,80%, 90%, 95%, 100% 1-RM PC	HHP should be used over the HPC at loads of 40–70% 1-RM, whereas the HPC and HHP can be interchangeably used at loads of 80–100% 1-RM. HHP PP at 60% 1-RM. HPC PP at 80% 1-RM.	Forward Dynamics
Winchester et al. (348)	18 healthy adult males	PC at 50, 70, 90% 1-RM	PP at 70% 1-RM PC	Combined Method
Key: HPC= Hang Power Clean, PC= Power Clean, MTCP= Mid-thigh clean pull, MTPC= Mid-thigh power clean, HC= Hang clean, HP= High Pull, JS= Jump shrug IBM= Including body mass, IBMS= Including body mass less shank mass, EBM= Excluding body mass, MDS= Maximal dynamic strength 1-RM + (Body mass – shank mass), IW=International weightlifters, NW-National Weightlifters, PP = Peak power; 1-RM = One repetition maximum				

2.3.12. Difference between Weightlifting Variations

The MTP and MTPC are weightlifting derivatives that have not been extensively researched when compared to the PC. Comfort, Allen and Graham-Smith (45) compared both PF and RFD between the PC, HPC and MTPC and MTCP in eleven elite rugby players at 60% 1-RM which was previously shown by Kawamori et al. (181) as the load to elicit the greatest PP during the MTCP. Bonferroni post hoc analysis revealed that a significantly ($p < 0.001$) greater peak PF (2802 ± 195 N) was evident during the MTPC and MTCP (2880 ± 236 N) when compared to both the PC (2306 ± 241 N) and the HPC (2443 ± 293 N), whilst no significant ($p > 0.05$) differences were found when comparing the PF between the MTPC and the MTCP. The findings in this study are in agreement with Enoka (91) who also showed comparable forces during the pull. A similar trend was shown with RFD with significantly ($p < 0.001$) greater RFD during the MTPC (14656 ± 4535 N.s^{-1}) and the MTCP (15321 ± 3533 N.s^{-1}) compared to both the PC (8840 ± 2940 N.s^{-1}) and the HPC (9769 ± 4012 N.s^{-1}). The greater PF and RFD observed in the mid-thigh variations is likely because the subjects must produce force quicker due to less time to apply force and when compared to the hang or floor positions.

Similarly, Comfort, Allen and Graham-Smith (46) compared kinetics of the MTPC, MTCP, PC and HPC in sixteen elite rugby players at 60% 1-RM and concluded that the MTPC (3566 ± 411 W) and MTCP (3687 ± 387 W) produced a significantly greater PP ($p < 0.001$) than both the HPC (3184 ± 309 W) and PC (2591 ± 646 W), although no significant differences occurred between the MTPC and MTCP or PC and HPC when assessed via forward dynamics. Further, a similar trend was observed with PF, with significantly ($p < 0.001$) greater PF during the MTPC (2802 ± 195 N) and the MTCP (2880 ± 236 N) compared with both the PC (2306 ± 241 N) and the HPC (2443 ± 293 N), with no significant differences reported in peak F_z between the MTPC and MTCP or PC and HPC. Similarly, instantaneous RFD also showed a similar trend with a significantly ($p < 0.001$) greater RFD during the MTPC (15050 ± 4416 $N.s^{-1}$) and the MTCP (15624 ± 3114 $N.s^{-1}$) compared with both the PC (8676 ± 2747 $N.s^{-1}$) and the HPC (10314 ± 4238 $N.s^{-1}$). It should be noted that the above studies (45, 46) initiated the pull with no countermovement and this may result in lower kinetics when compared to a countermovement immediately prior to the initiation of the pull and further investigation is warranted.

A common theme in the literature in the use of weightlifting derivatives that include that catch phase is the ability to 'decelerate and absorb' a load (302). However, Suchomel, Taber and Wright (315) demonstrated that JS at 30% produced greater landing forces when compared to 80%, highlighting the ability of weightlifting derivatives that omit the catch to provide the 'load deceleration' stimulus. The above finding is a result of jump height decreasing with an increase in external load and therefore time for gravitational acceleration is reduced, resulting in a lower velocity on ground contact, in which athletes will land with a more compliant strategy with a heavier load compared to a lighter load. Further support from this can be seem in the work from Suchomel, Lake and Comfort (307) who investigated load absorption force-time characteristics of weightlifting catching and pulling derivatives following the second pull in twelve males who performed the JS, HPC and HHP at loads of 30%, 45%, 60% and 80% 1-RM HPC. The authors demonstrated that the JS produced significantly greater load absorption MF compared to the HPC ($p < 0.001$, $d = 2.85$) and HHP ($p < 0.001$, $d = 3.75$), while no difference existed between the HPC and HHP ($p = 0.253$, $d = 0.37$). Additionally, significantly more load absorption work was performed during the JS compared to the HPC ($p < 0.001$, $d = 5.03$) and HHP ($p < 0.001$, $d = 1.69$), while HHP load absorption work was also significantly greater compared to the HPC ($p < 0.001$, $d = 4.81$). These findings have practical significance as they refute the claims that catch derivatives allow for a greater ability to decelerate load, albeit at loads from 30-80% 1-RM HPC.

2.3.13. Jump Shrug

The JS is a weightlifting derivative which are similar to HC, however the catch phase is omitted (298, 299, 302, 304, 315). Suchomel, Beckham and Wright (298) investigated the effects of load (30%, 45% ,65% and 80% 1-RM HC) on the JS in fourteen active males (1-RM HC = 104.89 ± 15.07 Kg). Results from this study showed that 30% 1-RM produced statistically greater PV compared to all loads, highlighting that the lowest loads produce the greatest velocity. Similarly, forward dynamics PP was also greatest at 30% and decreased with load and was significantly greater ($p < 0.01$) than 65% and 80% ($p < 0.001$), whilst PF was greatest at 65%, which was not statistically significant to other loads. Further, Suchomel, Wright, Kernozek and Kline (316) compared system PP, PF and PV during the JS, HC and high pull (HP) across loads of 30%, 45%, 60% and 80% 1-RM HC in seventeen athletic males. Findings of the study highlighted that the JS produced significantly greater PP (5851 ± 1355 W) compared with both the HC (4124 ± 1135 W) ($p < 0.001$, d =1.38) and HP (4737 ± 1196 W) ($p < 0.001$, $d = 0.87$). Similar results were observed during PF, with greater PF during the JS (3594 ± 666 N) compared with both the HC (3267 ± 698 N) ($p < 0.001$, $d = 0.48$) and the HP (3337 ± 710 N) ($p < 0.001$, $d = 0.37$) although, no significant difference in PF existed between the HC and HP ($p = 0.309$, $d = 0.10$). Further, PV was significantly greater during the JS (2.15 ± 0.3 m.s^{-1}) when compared to the HC (1.68 ± 0.26 m.s^{-1}) ($p < 0.001$, d =1.67) and HP (1.87 ± 0.26 m.s^{-1}) ($p < 0.001$, d =1.00). The greater PP and PV during the JS is likely explained by the greater ballistic nature of the JS as the athletes must project themselves into the air. Recently, Kipp et al. (185) compared normalised time differences via statistical parametric mapping (SPM) in the same exercises at 70% 1-RM HPC and also found that the JS produced greater force, system velocity and power in the last 15% of the movement, likely due to greater intent.

The concern of performing loaded jumping activities such as the JS is the excessive landing forces that may occur (315). To investigate the effect of load on landing force, Suchomel, Taber and Wright (315) performed loaded JS from 30%-80% 1-RM in 15% increments of 1-RM HPC in fifteen resistance trained males and demonstrated that PF at landing was greatest at 30% and decreased with an increase in load from 45% to 80% 1-RM, however these forces were not significantly different across loads. However, it should be noted that small effect sizes existed between 30% 1-RM and 45% (d = 0.29) and 65% 1-RM (d = 0.55), while a moderate effect size existed between 30% 1-RM and 80% 1-RM (d = 0.70). The authors concluded that practitioners could prescribe greater loads in the JS, without increasing landing forces. Due to a decrease in jump height with load, the time for gravitational acceleration is reduced at the higher loads, which results in lower velocity on ground contact and likely a comparable momentum. Recently, Kipp, Malloy, Smith, Giordanelli, Kiely, Geiser and Suchomel (188) investigated the joint- and load-dependent changes in the mechanical demands of the lower extremity joints during the HPC and JS in fifteen male NCAA Division One lacrosse players who performed three sets of the HPC and JS at 30%, 50%, and 70% of 1-RM HPC. The authors showed that that the JS is characterised by greater hip, knee, and ankle joint mechanical demands compared to the HPC, particularly at loads of 30-50%, which was attributed to greater positive joint work, and greater knee and ankle peak concentric joint power. This study therefore highlights mechanical differences between exercises that may need to be considered during exercise prescription.

2.3.14. Hang High Pull

The hang high pull (HHP) or HP is weightlifting derivative which omits the catch phase, and allows for rapid training of the triple extension movement. Thomas, Kraemer, Spiering, Volek, Anderson and Maresh (323) compared a free- form HP to a fixed-form (Smith Machine) HP across loads 30-70% 1-RM in both males and females. The authors showed no significant interaction difference regarding the variation the HP and that PP was maximised between 30 and 60% 1-RM, although this was assessed via inverse dynamics.

Suchomel, Beckham and Wright (300) investigated the effect of various loads on the force-time characteristics associated with PP during the HHP in fourteen athletic males, with power calculated via forward dynamics at loads of 30, 45, 65 and 80% 1-RM HC. In line with previous research, PF was progressively increased with load at maximised at 80%, which was statistically different ($p < 0.001$) than 30% only. Similarly, PV at 30% 1-RM HPC was statistically greater than the PV at 65% ($p < 0.001$, d =1.33, CI = 0.13-0.39) and 80% 1-RM HPC ($p < 0.001$, d =1.83, CI = 0.23-0.51), but not statistically different than the PV at 45% 1-RM HPC ($p = 0.199$, d =0.46, CI = 20.03 to 0.21). The PP at 45% 1-RM HPC was statistically greater than the PP at 65% ($p = 0.015$, d =0.33, CI = 51.27–549.25) and 80% 1-RM HPC (p = 0.011, d =0.45, CI = 82.99–729.19), but not statistically greater than the PP at 30% 1-RM HPC (p = 1.000, d =0.11, CI = 2158.82 to 392.46). The PP is similar to the study by Thomas, Kraemer, Spiering, Volek, Anderson and Maresh (323), although that study inverse dynamics to calculate power.

2.4. SET CONFIGURATION (CLUSTER SETS AND REST REDISTRIBUTION)

2.4.1. Introduction

When planning resistance training programmes, there are many variables that coaches need to implement to elicit specific adaptations to enhance physical performance. This includes the manipulation of exercise selection, speed of exercise, rest periods, number of sets or repetitions, and the structure of the set. When an athlete performs certain exercises, they perform the prescribed repetitions without rest for a given number of sets, which usually results in a decrease in kinetic and kinematic output (167). During resistance training, fatigue occurs when the number of repetitions in the set increases, which results in a decrease in velocity and power (330). Tufano et al. (330) investigated the effects of TS and two cluster (CLU) protocols (Clusters of four or two repetitions) during high volume back squat at 60% 1-RM on PF, MF, PV, MV, PP, and MP, and concluded that when averaged across all repetitions, there was a decline of >20% in MP, PP, MV and PV which was statistically different from both CLU protocols ($p < 0.01$), which showed a decline in of approximately 1-6%. However, the implementation of cluster sets is one method to employ variation to a training programme (121). To expand, the number of repetitions, training intensity, and rest periods contained within a set can be manipulated to alter the proposed training stimulus (328). Typically when designing strength training programmes, S&C coaches prescribe sets with either a traditional structure TS or CLU (121). Traditional set configuration entails performing repetitions in a continuous manner, near to muscular failure, (163), whilst a CLU is a set structure in which rest periods are more frequent than TS (328). When performing TS, concentric velocity decreases as the number of repetitions increases (142). Therefore, as power is the product of force and velocity a decrease in velocity would likely result in a decrease in power (330).

Baker and Newton (15) investigated the change in power output across a high repetition set of bench throws and JS in highly trained athletes incorporating 1x10 repetitions at 60 Kg, which represented 45% of 1-RM bench press and 35% 1-RM squat and concluded that there was a significant decline from the sixth repetition and the degree of decline by the tenth repetition was 11.2 and 5.0% for the bench throw and JS respectively. They recommended that to maximise power, a repetition range of 2-5 should be prescribed, as velocity and power are maintained across this range.

Gorostiaga, Navarro-Amezqueta, Cusso, Hellsten, Calbet, Guerrero, Granados, Gonzalez-Izal, Ibanez and Izquierdo (113) investigated the effects of 10-RM leg press on metabolic by-products and power output over five and ten repetitions in six recreationally trained males. The authors showed that there was a major reduction in phosphocreatine (PCr) concentration within the first five repetitions of exercise, whereas muscle lactate accumulation was more substantial during the second five repetitions, whilst there was a decrease in power in the second set of five repetitions. This suggests that the high number of repetitions performed during a TS may have a negative impact on kinetic output due to the increase of metabolic by-products, when the aim to maximise velocity and power characteristics.

Another method of designing resistance training programmes is the rest-pause method or CLU structure (97, 121, 126, 293, 328, 330). In this type of set configuration, an inter-repetition rest (IRR) interval of 10–30 seconds (s) is typically employed between each repetition performed (126). However, other research has implemented CLU style structure after small clusters of two and four repetitions respectively (330). Previous research on cluster training has examined the effects of CLU on PF (134, 135, 143, 257, 330), MF (77, 237, 330), PV (102, 126, 134, 135, 143, 240, 257, 330), MV (161, 257, 330), PP (126, 134, 135, 141, 143, 240, 330), MP (77, 172, 200, 237, 256, 257, 330), impulse (77) and displacement (126, 141).

The use of CLU and its role in performance programming has been investigated during various exercises such as squat variations (134, 161, 163, 254, 256, 257, 330), deadlifts (237), jumps (7, 134, 135, 240), bench press (102, 199, 200), PC (134, 140, 141, 143), leg extensions (163) and clean pull (126, 134). It is suggested that the use of CLU helps to improve the kinetic and kinematic profile of the training sets, which may influence performance outcomes (121, 134). This is based on the consensus that the subsequent rest period will allow for partial recovery through PCr replenishment, whilst a TS with no IRR results in higher lactate accumulation and an associated decrease in velocity (113, 126). This chapter will discuss the use of CLU structures and how this may enhance performance variables.

2.4.2. Acute Effects on Kinetics and Kinematics with Cluster Training

Early research into the effects of set manipulation was performed in 1994 by Rooney et al. (273) who investigated the effects of rest vs no rest in 6-RM unilateral bicep curl in 42 untrained subjects over six weeks. In this study, one group performed 6-10 repetitions of 6-RM continuous elbow flexion with another group performing 30 s rest after each repetition and a control group who did no training. The authors demonstrated that the continuous group improved strength to a greater extent than the rest group, concluding that the role of fatigue may be an important factor in the development of strength. However, in terms of isometric strength, there were no significant difference between intervention groups (22.1 vs. 19.8%). Tufano, Conlon, Nimphius, Brown, Seitz, Williamson and Haff (330) demonstrated that at 60% 1-RM back squat, CLU sets of two repetitions showed a significantly greater MV and PV when compared to CLU of four repetitions and TS, and therefore reduced time under tension (TUT). In contrast, another study by Tufano, Conlon, Nimphius, Brown, Banyard, Williamson, Bishop, Hopper and Haff (329) showed that CLU of two and four repetitions resulted in a greater TUT than TS ($p \leq 0.001$), likely due to the increased loads in the CLU protocols and therefore decreased repetition velocity when compared to the TS.

The first study to investigate the effects of the term ‘cluster training’ structure on performance was conducted in trained male athletes (126). Haff, Whitley, McCoy, O’Bryant, Kilgore, Haff, Pierce and Stone (126) examined the effect of three different types of set configurations consisting of a TS, CLU, and an undulating CLU on performance in the clean pull at loads of

90% and 120% 1-RM PC. The TS and CLU were performed with five repetitions at an intensity of 90% and 120% of 1-RM PC. The undulating sets consisted of five repetitions performed at an average intensity of 90% or 120% of the subject 1-RM PC. Subjects performed one repetition at 85%, 90%, 100%, 90%, and 85% of the subject's 1-RM PC for an average five-repetition intensity of 90% or one repetition 110%, 120%, 140%, 120%, and 110% of the subject's 1-RM PC for a repetition average intensity of 120%, with kinetic and kinematic data measured via a V-Scope device, as previously described (292). The authors concluded that the CLU resulted in significantly (90%: $p = 0.007$; 120%: $p = 0.009$) faster barbell velocities than the TS in both loading conditions. Additionally, there were no differences in barbell velocities between the undulating set and the CLU or TS at the 90 or 120% intensity. Further, the performance of CLU resulted in significantly greater ($p = 0.01$) barbell displacements when compared with the traditional set at the 120% intensity. That authors concluded the CLU structure may be beneficial to enhance barbell velocity and displacement, which may aid in weightlifting performance. Similarly, Hardee, Triplett, Utter, Zwetsloot and McBride (142) reported that during 20 s IRR (P20) rest intervals, PV and PP decreased less over 3x6 repetitions during the PC when compared with six repetitions performed in a TS (P0) in ten recreationally trained weightlifters (PC 1-RM = 1.39 x BW). Kinetic and kinematic data was collected via a FP and 2 LPTs using the combined method as previously outlined (59). When IRR was increased to 40 s (P40), the PV and PP of each repetition was better maintained than when P20 seconds of IRR was performed. To expand, PP significantly decreased by 15.65% (repetition 1: 4564 ± 655 W, repetition 6: 3882 ± 502 W) during P0 in comparison with a decrease of 5.50% (repetition 1: 4303 ± 567 W, repetition 6: 4055 ± 582 W) during P20 and a decrease of 3.30% (repetition 1: 4549 ± 659 W, repetition 6: 4363 ± 476 W) during P40. Peak force significantly decreased by 7.34% (repetition 1: 2861 ± 247 N, repetition 6: 2657 ± 225 N) during P0 in comparison to a decrease of 2.67% (repetition 1: 2811 ± 327 N, repetition 6:

2730 ± 285 N) during P20 and an increase of 0.40% (repetition 1: 2861 ± 323 N, repetition 6: 2862 ± 280 N) during P40. Peak velocity significantly decreased by 10.21% (repetition 1: 1.97 ± 0.15 $m.s^{-1}$, repetition 6: 1.79 ± 0.11 $m.s^{-1}$) during P0 in comparison with a decrease of 3.76% (repetition 1: 1.89 ± 0.13 $m.s^{-1}$, repetition 6: 1.82 ± 0.12 $m.s^{-1}$) during P20 and a decrease of 1.70% (repetition 1: 1.93 ± 0.17 $m.s^{-1}$, repetition 6: 1.89 ± 0.14 $m.s-^{1}$) during P40. This study highlights that longer IRR periods result in maintenance of PP, PF, and PV in the PC during multiple sets performed at 80% 1-RM PC, which is similar to a previous study (126), and therefore may be beneficial to target performance measures.

Further use of CLU structures and the benefit to weightlifting derivatives is evident (141). The authors demonstrated that the use of CLU structures greater than 20 s IRR rest maintain PC technique to a greater extent than a TS configuration across 3x6 at 80% 1-RM PC in recreational weightlifters (PC 1-RM = 1.39 x BW). The authors demonstrated that during the first and second TS, the catch and first pull resulted in a more forward position during repetition 6 as compared to repetition 1 respectively, whilst no differences were found between repetitions 1 and 6 with a CLU configuration with P20 IRR. Furthermore, the second set of P40 IRR showed differences in horizontal displacement between repetitions 1 and 6, with the second pull and loop demonstrating increased forward position during repetition 6 compared to repetition 1 ($p \leq 0.05$). In addition, mean peak vertical displacement during repetition 1 were 1.02 + 0.07 m, 0.98 + 0.06 m, and 0.98 + 0.06 m (P0, P20, and P40, respectively). Average mean vertical displacements during repetition 6 were 0.94 + 0.06 m, 0.96 + 0.07 m, and 0.97 + 0.06 m (P0, P20, and P40, respectively). Significant decreases in peak vertical displacement were found during P0 for each set ($p \leq 0.05$). Peak vertical displacement decreased 7.3% between repetitions 1 and 6 during P0 ($p \leq 0.05$). There were no differences in peak vertical displacement between repetitions 1 and 6 within each set of P20 and P40, therefore suggesting that CLU maintain technical ability in the PC.

Hardee, Lawrence, Utter, Triplett, Zwetsloot and McBride (140) investigated the effects of IRR on the rate of perceived exertion (RPE) during the 3x6 PC in ten recreationally trained weightlifters at 80% 1-RM, with methods previously described (141, 142). Whilst all three protocols resulted in a decrease in power (2.1-9.0%), the IRR of 40 s resulted in a lower RPE score when compared to the TS and 20 s IRR, which may be attributed to the replenishment of PCr to a greater extent. Further, average RPE for P0 and P20 were significantly different from P40 (7.43 ± 0.34, 6.46 ± 0.47, and 5.30 ± 0.55, respectively). Therefore, it could be proposed that as volume was equated across each protocol, implementing an IRR protocol would allow for a greater volume to be completed due to a lower level of reported fatigue, which has the potential to enhance performance, particularly at higher loads, as fatigue is shown to be detrimental to weightlifting technique. The above studies show that CLU both maintain kinetic, kinematic variables and weightlifting technique and should be implemented as an alternative to TS structure to enhance performance in weightlifting exercises as successful performance in weightlifting is dependent on vertical barbell displacement (91).

The use of CLU structures is also evident in a number of non-weightlifting exercises such as the squats (134, 161, 172, 254, 256, 257, 330), bench press (77, 199, 200, 254), deadlifts (237) and ballistic activities (7, 102, 135, 240). Acute CLU studies have been widely used in the squat exercise to determine the effectiveness of kinetic and kinematic performance. Tufano, Conlon, Nimphius, Brown, Seitz, Williamson and Haff (330) investigated kinetic and kinematic differences between TS, CLU of two repetitions and CLU of four repetitions in 3x12 of 60% 1-RM back squat in twelve resistance trained males, with an intraset rest of 120 s.

Similar to other studies investigating CLU, the authors demonstrated when averaged across all repetitions, PV, MV, PP, MP were greater in sets of two repetitions and sets of four repetitions than in the TS ($p < 0.01$), whilst both MF and PF showed no change in all three protocols. Specifically, when the set configuration included more frequent rest (CS2), PV, MV, PP and PP were all significantly different to TS ($p < 0.01$) and CS4 ($p < 0.01$-0.05), whilst CS4 was also significantly different to TS ($p < 0.01$).

Similarly, Joy, Oliver, McLeary, Lowery and Wilson (172) compared the difference between TS and CLU in the back squat in nine relatively strong males (1-RM =1.76 x BW). The TS condition consisted of 4x10 repetitions (4x10) with 120 s inter-set rest, while the CLU condition consisted of 4 x (2 x 5 repetitions) with 60 s inter-set rest and 60 s intra-set rest between clusters at 75% 1-RM. The purpose of this CLU structure was to equate total time between conditions. The authors demonstrated that the CLU group produced greater MP during latter repetitions of each set (repetition 6, ES = 0.94, $p = 0.002$; repetition 7, ES = 1.09, $p = 0.003$; repetition 8, ES = 1.12, $p = 0.002$; repetition 9, ES = 1.00, $p = 0.004$; repetition 10, ES = 0.51, $p = 0.022$) compared to TS, whilst the TS group produced greater electromyography, therefore highlighting the possibility of TS group being superior for hypertrophic stimulus but not power output.

Oliver, Kreutzer, Jenke, Phillips, Mitchell and Jones (257) compared the kinetics and kinematics of CLU and TS during back squat in 24 trained (back squat = 1.7 x BW) and untrained males (back squat = 1.1 x BW) at loads of 70% 1-RM and showed similar results, with CLU demonstrating greater MP was produced in the later repetitions of each set and was largely driven by higher average velocities. Interestingly, the TS group showed a reduction in load in set four when compared to the CLU group. It could be surmised that a reduction in load would allow for an increase in velocity during the latter sets and repetition, however this was not evident therefore highlighting how fatigue affects technique.

Similarly, Oliver, Kreutzer, Jenke, Phillips, Mitchell and Jones (256) showed similar findings in which CLU allowed greater total volume load, shorter TUT, greater average power, similar anabolic hormonal response, and less metabolic stress. Moreno, Brown, Coburn and Judelson (240) investigated the effects of CLU vs. TS on jump power, GRF, take-off velocity (TOV), and JH in twenty-six recreationally trained males performing BW jumps. In this study, the subjects performed three different set configurations: TS (2 x 10 with 90 s rest between sets), CLU1 (4 x 5 repetitions with 30 s rest between sets), and CLU2 (10 x 2 with 10 s rest between sets), therefore equating the total rest time between groups. The authors showed that 10 x 2 jumps with 10 s of rest and had greater maintenance of power, TOV and JH when compared with the traditional method of 2 x 10 with 90 s rest.

Whilst the subjects in the above study performed unloaded jumps, Hansen, Cronin and Newton (135) investigated the effects of CLU using loaded JS in semi-professional and professional rugby players across 4 different protocols. In the study, the subjects performed training sessions comprising 4 x 6 repetitions of a JS using four different set configurations. The first method involved a TS of 4 x 6 repetitions with 180 s of rest between sets, the second (C1) 4 x 6 singles (1 repetition) with 12 of rest between repetitions, the third (C2) 4 x 2 doubles (2 repetitions) with 30 s of rest between pairs, and the fourth (C3) 4 x 3 triples (3 repetitions) with 60 s of rest between triples. The authors demonstrated that in the traditional structure, a decline in both PP and PV was evident. However, the use of CLU protocols attenuated the decreased in these variables in an acute setting, and therefore suggested that CLU are beneficial to the development of ballistic training.

Whilst most of the aforementioned studies focusing on measures of power and velocity in weightlifting exercises, squats and jumping exercises, Moir, Graham, Davis, Guers and Witmer (237) investigated the effects of CLU on the concentric force, concentric TUT, impulse, work, power, and fatigue during the deadlift, an exercise which is concentric in nature. In the study, 11 resistance trained males performed four repetitions of the deadlift exercise with a load equivalent to 90% of 1-RM under three different set configurations: TS, doubles cluster (repetitions 1 and 2, and 3 and 4 performed continuously with a 30 s rest inserted between repetitions 2 and 3) and singles cluster (30 s rest between repetitions). Interestingly, in this study the authors showed that the use of CLU configuration showed a greater reduction in power when compared to a TS and the authors suggest that decreases in power output recorded in the present study is likely to related to the absence of the SSC in the affected repetitions (237), whilst the increase in impulse observed in the CLU was likely due to a decrease in velocity and subsequent increase in time as force was unchanged during the set. The authors concluded that the use of CLU to maintain power may not be warranted in concentric only exercises, however in the study, the authors used 90% 1-RM deadlift, and this therefore may not be evident in concentric only movements such as SJ or weightlifting derivatives at various submaximal and supramaximal loads, therefore further investigation into this is required across a range of loading parameters, repetitions, and rest periods.

The use of CS configuration during upper body exercises has also been investigated (77, 102, 200). Lawton et al. (200) reported that power output was maintained when an equal work to rest ratio (EW:R) protocol was compared with TS set in a group of 26 elite junior male soccer and basketball players. Subjects performed 6 repetitions of the bench press with a 6-RM load using TS and 3 different EW:R strategies. The EW:R protocols consisted of 6 x 1 repetition with 20 s rest between sets, 3 x 2 with 50 s rest between sets, and 2 x 3 with 100 s rest between sets. By implementing these set structures, each protocol contained 100 s of rest and the final repetition, of all 3 protocols was completed 118 s after the start of the first repetition, assuming 3s was needed to complete each repetition. The authors showed significantly ($p < 0.05$) greater repetition power outputs (25–49%) were observed in the later repetitions (4-6) of the singles, doubles, and triples loading schemes. Significantly greater total power output (21.6–25.1%) ($p < 0.05$) was observed for all IRR interventions when compared to traditional continuous 6-RM. Additionally, the TS group showed a near linear power decrease across repetitions.

Denton and Cronin (77) examined the differences between TS and CLU on kinetic, kinematic and lactate response during a bench press exercise at 6-RM and 24 repetitions. In this study, three variations of set configurations were performed with the TS group lifting 4 x 6-RM with 302 rest between each set, the second set configuration comprised 8 x 3 performed with a 6-RM load with each cluster of 3 repetitions separated by 130 s (cluster 1 = C1). The third grouping was identical to the second with the exception that every other set was performed to failure (C2). The authors demonstrated that the C2 configuration resulted in significantly greater repetitions (~30) when compared to C1 (~24) and the traditional (~23.6) set configurations. When examining the MP, total work, and impulse of the set's configurations, C2 were significantly higher than both C1 and TS, which were not different. The blood lactate response for C2 was consistently higher than both TS and C1. The results demonstrate that increasing the IRR, the ability to perform more work at a higher quality is evident, which clearly has a strong influence on kinetic performance.

Additionally, Garcıa-Ramos, Padial, Haff, Argu¨elles-Cienfuegos, Garcıa-Ramos, Conde-Pipo´ and Feriche (102) investigated the effects of different IRR periods on barbell velocity loss during the ballistic bench press exercise, in relatively weak college aged males (1-RM Bench Press = 1.02 x BM). The subjects performed ballistic concentric bench press throws at 30, 40 and 50% 1-RM bench press in either a TS consisting of 15 repetitions continuous, 6 s IRR or 12 IRR. The authors showed that across all loads, PV decreased significantly ($p \geq 0.05$) by 13.1% at 30%, 24% at 40% and 38.2% at 50% for the TS, whilst 6 s IRR showed a decrease of 4.7%, 10.7% and 18.5% and the 12 IRR resulted in a 1%, 4.5% and 8.9% decreased in PV across a set of 12 repetitions, whilst no differences were observed between the TS and IRR6 protocols until the repetition 7 at 30% RM and 40% RM and until the repetition 5 at 50% RM, highlighting that the greater the IRR, the smaller the decline in kinematic variables at relatively lighter loads.

Iglesias, Boullosa, Dopico and Carballeira (160) investigated the effects of maximal number of repetitions in single sets of 70% during the bench press and bicep curl and the use of a 30 s CLU set at 90% and showed that the CLU set allowed for a greater number of repetitions (21.85 ± 11.06 vs. 18.54 ± 12.84 in bench press and biceps curl, $p > 0.05$), when compared to the 70% condition (16.31 ± 2.59 vs. 8.77 ± 3, $p < 0.05$) and therefore volume and intensity. However, the sample group in this study was relatively low (n = 13) with lower levels of strength. A summary of studies investigating acute and chronic effects in strength and ballistic exercises are shown in Table 2.6 and Table 2.7.

Table 2.6-Summary of acute & training studies using cluster sets during strength exercises

Author	No	Subjects	Type/Duration	Exercise	Cluster Protocol	Outcomes
Davies et al. (76)	21	Resistance Trained individuals	Chronic- 8 weeks	Bench Press	4x5 Bench Press at 85% 1-RM, 30 s IRR, 3mins inter-set rest	Both groups significantly increased absolute and relative muscular strength before or after intervention. CLU increasing by 9.90 ± 3.60% ($p < 0.001$, ES = 1.94) and 8.55 ± 4.48% ($p < 0.001$, ES = 1.79). TRAD increasing by 11.06 ± 7.65% ($p < 0.001$, ES = 1.84) and 12.16% ± 7.07% ($p < 0.001$, ES =1.43). CLU was superior compared with the TRAD in MV maintenance in sets 1 ($p = 0.002$), 2 ($p = 0.001$), and 4 ($p = 0.037$). CLU was also superior in maintaining PV compared with the TRAD- in set 1 only (p =0.043) MV throughout the session was greater for the CLU compared with the TRAD ($p = 0.015$),
Denton & Cronin, (77)	9	Healthy males	Acute	Bench Press 6RM =1.01xBM	TS – 4x6 with 302 inter-set rest, CLU1 8x3 with 130 inter-set rest, CLU2-8 sets, 3 repetitions during sets 1,3,5,7 % set to failure 2,4,6,8	CLU1 resulted in similar power output, force, and work compared with TS. CLU2 resulted in a greater number of repetitions, work, and lactate than CLU1 and TS. All variables in CLU2 were significantly different to CLU1 and TS.
Girman et al. (112)	11	Trained males	Acute	Clean Pull & Back Squat	TS: 1 x 6 repetitions clean pull at 75% and 1 x 10 back squat 70% with 120 s inter-set rest; CLU: same as TS, but 15 s intra-set rest and 90 s inter-set rest	CLU resulted in lower lactate and higher jump height, with similar hormone responses ($p < 0.05$)
Hansen et al. (134)	18	Elite Rugby union Players	Chronic- 8 weeks	Squat and pull variations,	80–95% 1-RM; TS: 3–5 sets of 3–8 with 180 s inter-set rest; CLU: same as TS but with 120 s inter-set rest and 10 to 30 s IRR	CLU and TS both increased strength, greater increase after TS; neither protocol had a significant change in JS force, velocity, or power. increase was significantly greater ($p < 0.05$) in the TS (% change = 18.3 ± 10.1, ES = 2.2) vs CLU group (% change = 14.6 ± 18.0, ES = 1.0). CLU had a likely positive effect for PP at 40 kg (% difference between groups = 6.5%) and for PV at 0 and 40 kg (% difference between groups = 3.3 and 4.7%,

						Effect of the CLU on PF at 40 kg was possibly positive (% difference between groups = 1.8%).
Iglesias et al. (160)	13	Males, bench press 1-RM 1.23x BM; bicep curl 1-RM 0.25 x BM	Acute	Bench Press AND Bicep curls	Various loads; TS: repetitions to failure using 70% 1-RM; CLU: repetitions to failure using 90% 1-RM with 30 s IRR	Maximal repetitions at 70%1-RM lower for biceps curl (16.31 ± 2.59 vs. 8.77 ± 3 in bench press and biceps curl, respectively; $p > 0.05$) and at 90% of 1-RM (21.85 ± 11.06 vs. 18.54 ±12.84 in bench press and biceps curl, respectively; $p < 0.05$). CLU resulted in a greater number of repetitions with a heavier load compared with the greatest number of repetitions performed using TS with a lighter load
Iglesias et al. (162)	10	Judo athletes 1-RM=1.58xBM	Acute	Back Squat	4RM Load, TS: 3 sets to failure, 180-s Inter-set rest; CLU: same volume as TS with subject-dependent IRR with same EW:R as TS	CLU resulted in greater movement velocity during the protocol and less lactate after compared with TS.
Iglesias- Soler et al. (161)	9	Judo athletes 1-RM=1.57xBM	Acute	Back Squat	4RM Load, TS: 3 sets to failure, 180-s Inter-set rest; CLU: same volume as TS with subject-dependent IRR with same EW:R as TS	CLU resulted in a greater number of repetitions while and a greater movement velocity than TS.
Iglesias- Soler et al. (163)	13	6 female and 7 male sports science students: strength level not provided for each sex	Chronic 5 weeks	Unilateral Leg Extensions	TS= 4x8 (32 repetitions) 10RM load, 180 s rest inter-set. CLU (32 repetitions), 17.4 s IRR	CLU and TS resulted in similar increases in 1-RM, power output, and muscular endurance. MV of the TS was lower than for CLU (0.48±0.06 vs. 0.54±0.06 ms^{-1}; $p < 0.001$), while perceived exertion was higher (8.3 ± 0.9 and 6.56 ± 1.6 for TS and IRT; $p = 0.002$)
Joy et al. (172)	9	Resistance trained males, 1-RM= 1.76 x BM back squat	Acute	Back Squat	TS: 4 x 10 with 120 s inter-set rest at 75%; CLU: 8 x 4 with 60 s inter-set rest at 75%	CLU resulted in greater power output, but less muscle activity compared with TS. MP output decreased over successive set when collapsed for condition. CLUs resulted in greater MP output during latter repetitions of each set (repetition 4, 6-10; $p < 0.05$).
Lawton et al. (200)	26	Elite junior, male basketball,	Acute	Bench Press	TS: 6 repetitions; CLU 1: 6 x 1 with 20 s IRR; CLU2: 3 x 2 with 50 s inter-set rest.	Significantly ($p \leq 0.02$) greater power outputs during CLU vs TS (21.6–25.1%)

		and soccer players, bench press 6RM= 0.83 x BM			CLU3: 2 x 3 with 100 s inter-set rest	
Lawton et al. (199)	26	Elite junior, male basketball, and soccer players, bench press 6RM= 0.83 x BM	Chronic 6 weeks	Bench Press	80– 105% 6RM load; TS: 4 x 6 with 26 s inter-set rest; CLU: 8 x 3 with similar work-to-rest ratios as TS	Increases in power and strength were present after both CS and TS. Strength increases were greater after TS (9.7 v 4.9%); TUT during training was greater during TS. No significant differences in power
Mayo et al. (216)	8	healthy (7 male, 1 female), moderately trained sport science students	Acute	Bench Press; Parallel Squat	TS: 5 × sets to failure CS: 5×1 until volume equated TS condition. CS rest intervals. Bench press: 24.7 s Squat: 21.9 s Load equal to 10RM (moderate)	Significantly higher values of MPV of bench press ($F_{1, 7}$ = 17.49, p = 0.004), however not squat. Simple effects indicated that RPE was lower during the CS than the Failure session for bench press ($F_{1, 7}$ = 17.79, p = 0.004), but not for parallel squat. Differences between exercises only observed for the CS, with higher values in parallel squat than bench press ($F_{1, 7}$ = 27.32, p < 0.001).
Moir et al. (237)	11	resistance trained males, deadlift 1-RM= 1.95 x BM	Acute	Deadlift	90% 1-RM; TS: 4 repetitions; CLU1: 4 repetitions with 30 s IRR; CLU2: 4 repetitions with 30 s intra-set rest after second rep	Compared to the TS, CLU configurations resulted in greater TUT (p < 0.001) and greater impulse (p < 0.001) during the repetitions. Reductions in power were observed during the CLU compared to the TS (p = 0.001). Force was similar between variations
Mora-Custodia et al. (238)	30	Resistance trained males who were sports science students full squat exercise was 103.1 ± 12.7	Acute	Back squat; 60–80% of 1-RM (moderate and heavy)	TS: 3 × 6, 5, 4 or 3 repetitions CS: rest between each repetition for each set configuration (10 s or 20 s IRR)	significant differences between CR and IRR10 (p < 0.05 – 0.001) and CR and IRR20 (p < 0.05 – 0.001) in MPV of each repetition, mainly in the last two repetitions of each training set. CR group showed significantly (p < 0.01) greater loss of CMJ height than IRR20 in REP 1, and significantly higher loss of MPV against V1 $m \cdot s^{-1}$ load than IRR10 (p < 0.05) and IRR20 (p < 0.01) in REP 1.

		kg (1.45 ± 0.24 normalised per kg of body mass)				For REP 2, REP 3 and REP 4, although there were no significant differences between groups, CR showed a greater percentage of change (16.8 – 22.1%) and ES (1.05 – 2.35) compared to IRR10 (Δ: 12.8 – 18.4%; ES: 1.08 – 2.47) and IRR20 (Δ: 13.5 – 18.1%; ES: 0.91 – 2.64) in these variables
Oliver et al. (254)	22	10 of which were military males; bench press 1-RM= 1.67 x BM; back squat 1-RM= 2.09 x BM	Chronic 12 weeks	Total body	60–75% 1-RM; TS: 4 x 10 with 120 s inter-set rest; CLU: 8 x 5 with 60 s inter-set rest	CLU and TS resulted in similar increases in lean mass, but CLU resulted in greater gains in strength and power. The CLU produced greater power output in bench (p = 0.020), VJ, p = 0.036) with squat power approaching significance (p = 0.053) after post hoc analysis (p < 0.10).
Rial-Vasquez et al. (268)	39	Sports Science students (11females/28 males	Chronic 5 weeks	Back Squat and Bench Press	TS: 4x8 with 300 s rest between sets CS: 16x2 with 60 s IRR, 300 s between sets	TT group produced higher lactate than CT group. Significant differences between groups for the peak values after sessions ($p \leq 0.05$). Greater average MPV in the squat during CT vs TT (p = 0.049; g= 0.823; 95% CI: [0.014, -1.632]).
Rooney et al. (273)	42	18 males/ 24 females	Chronic 6 weeks	Bicep Curl	TS: 6–10 repetitions at 6 RM; CLU: 6–10 repetitions at 6RM with 30 s IRR	TS resulted in greater gains in strength compared with CLU
Tufano et al . (330)	12	Resistance-trained males, back squat 1-RM= 1.93 x BM	Acute	Back Squat	60% 1-RM, TS: 3 x 12 with 120 s inter-set rest; CLU1: 3 x 12 with 120 s inter-set rest and 30 s intra-set rest after every 2 repetitions; CLU2: 3 x 12 with 120 s inter-set rest and 30 s intra-set rest after ever 4 repetitions	CLU1 and CLU2 maintained velocity and power output better than TS; more frequent intra-set rest (CLU1) resulted in greater maintenance of velocity and power output (CLU2). Averaged across all repetitions, PV, MV, PP, MP were greater in CLU1 and CLU2 than in TS (p < 0 .01), with CLU1 also resulting in greater values than CLU (p < 0.02).

Tufano et al. (329)	12	Strength trained males, 1-RM back Squat 1.88xBW	Acute	Back Squat	TS-3x12 at 60% 1-RM with 120 s inter-set rest. CS4- of 3 sets of 12 using 75% 1-RM with 120 seconds of seated inter-set rest and 30 s of intra-set rest after 4 repetitions. CS2 of 3 sets of 12 using 80% 1-RM with 120 s seated inter-set rest and 30 s, intra-set rest every 2 repetitions	Compared with TS and CS4, CS2 resulted in greater MF, TW, and TUT in addition to less MV, PV, and MP. CS4 resulted in greater MF, TW, and TUT in addition to less MV, PV, and MP than TS did.
Valverde-Esteve et al. (336)	16	Physical education males, bench press 1-RM =1.15x BM	Acute	Bench Press	Subject dependent "optimal load" of about 49% 1-RM; TS:1x15 with 15 s IRR; CLU:1x15 with 15 s IRR; CLU2: 1 x 15 with 10 s IRR,	PP output maintained best in CLU2, followed by CLU1, both maintained power output better than TS. Significant decreases were observed from the second repetition in the IRR10 s and IRR5 s
Wetmore et al. (344)	11	Resistance trained males Back Squat 1.84 ± 0.34 x BW	Acute	Back Squat	TS = Back squat 3x5 at 80%, 3 minutes rest between sets CS = Back squat 3x5 at 80%, 3 minutes rest between sets, IRR 30 s	PF (TS) 3002 ± 504 (N). (CS) 3012 ± 465, $p > 0.05$, ES = 0.09 (N) PP (TS) 2518 ± 784 (W) (CS) 2834 ± 982, $p < 0.001$, ES = 0.77 (W) TW (TS) 3036 ± 524 (CS) 3068 ± 575, $p < 0.001$, ES = 0.28 CPV (TS) 1.013 ± 0.175 ($m.s^{-1}$) (CS) 1.106 ± 0.217, $p < 0.001$, ES = 0.77 ($m.s^{-1}$) CMV (TS) 0.489 ± 0.071($m.s^{-1}$) (CS) 0.541 ± 0.072, $p < 0.001$, ES = 0.81 ($m.s^{-1}$) CPA (TS) 4.292 ± 1.503 ($m.s^{-2}$) (CS) 4.421 ± 1.262, $p = 0.03$, ES = 0.17 ($m.s^{-2}$) CMA (TS) -0.006 ± 0.002 (CS) -0.007 ± 0.003, $p = 0.002$, ES = 0.24 TTP (TS) 1.267 ± 0.226 (s) (CS) 1.134 ± 0.178, $p < 0.001$, ES = 0.68 (s) TPV (TS) 1.311 ± 0.225 (s) (CS) 1.178 ± 0.177, p < 0.001, ES = 0.68 (s)

Key: RM = Repetition maximum; PF = Peak Force; PP = Peak Power; MP = Mean Power; PV = Peak Velocity; MV = Mean Velocity; TS = Traditional Set; CLU = Cluster set; BM = Body Mass; CMJ = Countermovement Jump; SLJ = Standing Long Jump; IRR = Inter-repetition rest; TOV = Take-Off velocity; TUT = Time Under Tension; VJ = Vertical Jump; RPE = Rate of Perceived Exertion; $m{\cdot}s^{-1}$ = Meters Per Second; TUT = Time under tension; TW = Total work; BW = bodyweight; Concentric peak velocity = (CPV),; Concentric Mean Velocity = (CMV); Concentric Peak Acceleration = (CPA); Concentric Mean Acceleration = (CMA); Time to Peak Power = TTP; Time to Peak Velocity = TTV; Rep = Repetition

Table 2.7-Summary of acute & training studies using cluster sets during ballistic exercises

Author	No	Subjects	Type/Duration	Exercise	Cluster Protocol	Outcomes
Asadi & Ramirez-Campillo. (7)	13	College Aged males	Chronic -6 weeks	Depth Jumps	Depth Jumps from 45cm Box- TS: 5x20 with 120 s interest rest. CS:5x20 with 90 s interest rest & 30 s intra-set rest	Both groups had similar improvements ($p < 0.05$) in CMJ, SLJ, t-test, 20-m, and 40-m s-print. magnitude of improvement in CMJ, SLJ and t-test was greater for the CS group [ES] = 1.24, 0.81 and 1.38. Magnitude of improvement in 20-m and 40-m sprint test greater for the traditional group (ES = 1.59 and 0.96) compared to the cluster group (ES = 0.94 and 0.75)
Garcia-Ramos et al. (102)	34	College Aged males	Acute	Bench Press Throws 1.02xBM	Bench Press Throws at 30/40/50% 1-RM. TS 15 repetitions CLU1- 15 repetitions with 6 IRR. CLU2- 15 repetitions with 12 IRR	PV decrease was significantly lower for IRR12 compared with CR and IRR6 at least since the repetition 4. No differences between CR and IRR6 protocols until repetition 7 at 30%RM and 40%RM and until repetition 5 at 50%RM. Decrease of PV during the CR protocol was virtually linear for the 3 loads (r2 = 0.99). Linear relationship became weaker for IRR6 (r2 = 0.79–0.95) and IRR12 (r2 = 0.35–0.87).
Girman et al. (112)	11	Trained males	Acute	Clean Pull & Back Squat	TS: 1 x 6 repetitions clean pull at 75% and 1 x 10 back squat 70% with 120 s inter-set rest; CLU: same as TS, but 15 s intra-set rest and 90 s inter-set rest.	CLU resulted in lower lactate and higher jump height, with similar hormone responses ($p < 0.05$).

Haff et al. (126)	13	track and field 5 & 8 Olympic weightlifters 1-RM PC= 1.32xBM	Acute	CP from Floor	Clean pulls at 90 and 120% 1-RM; TS: 5 repetitions; CLU: 5 repetitions with 30 s IRR	CLU exhibited significantly (90%: *p* = 0.007; 120%: *p* = 0.009) higher PV than the TS. PV at 90% was significantly higher than 120%. CLU resulted in significantly higher (*p* = 0.01) barbell displacements when compared with TS at 120%. Difference between the CLU and TS displacements during 90% trial approached statistical significance (*p* = 0.02). CLU resulted in a significantly (*p* = 0.001) higher barbell displacement during the 120% trials.
Hansen et al. (134)	18	Elite Rugby union Players	Chronic -8 weeks	Squat and pull variations,	80–95% 1-RM; TS: 3–5 sets of 3-8 with 180 s inter-set rest; CLU: same as TS but with 120 s inter-set rest and 10 to 30 s IRR	CLU and TS both increased strength, greater increase after TS. Neither protocol had a significant change in JS force, velocity, or power. Increase was significantly greater (*p* < 0.05) in the TS (% change = 18.3 ± 10.1, ES = 2.2) vs CLU group (% change = 14.6 ± 18.0, ES = 1.0). CLU had a likely positive effect for PP at 40 kg (% difference between groups = 6.5%) and for PV at 0 and 40 kg (% difference between groups = 3.3 and 4.7, Effect of the CLU on PF at 40 kg was possibly positive (% difference between groups = 1.8%).
Hansen et al. (135)	20	semi and professional male rugby players, strength level not provided, likely high strength levels	Acute	Loaded JS	TS- 4x6 with 180 s inter-set set, CLU1- 4x6 with 12 IRR rest & 120 s interest, CLU2- 4x6 with 30 s rest after doubles & 120 s interest rest, CLU3- 4x6 with 30 rest after triples & 120 s inter-set	PP was significantly (*p* < 0.05) lower for TS compared with CLU1 and CLU3 for repetition 4, and CLU groups for repetitions 5 and 6. PV was significantly lower (*p* < 0.05) for TS compared with CLU3 at repetition 4, significantly lower compared with CLU2 and CLU3 at repetition 5, and significantly lower compared with all CLU conditions for repetition 5. No significant differences between any of the set configurations at any rep for force.
Hardee et al. (140)	10	Recreational Weightlifters 1-RM = 1.39x BW	Acute	PC at 80% 1-RM	TS-3x6 with 180 s inter-set rest, CLU1, same as TS but with 20 s IRR, CLU2, same as TS but with 40 s IRR	Average RPE for TS and CLU1 (20IRR) were significantly different (*p* ≥ 0.001). from CLU2 (40IRR) (7.43 ± 0.34, 6.46 ± 0.47, and 5.30 ± 0.55). CLU resulted in greater power output and less exertion than TS. CLU with longer rest periods (40IRR) maintained power

						output and decreased exertion more than when CLU rest periods were shorter (20IRR).
Hardee et al. (141)	10	Recreational Weightlifters 1-RM = 1.39x BW	Acute	PC at 80% 1-RM	TS-3x6 with 180 s inter-set rest, CLU1, same as TS but with 20 s IRR, CLU2, same as TS but with 40 s IRR	CLU configurations led to the maintenance of vertical displacement throughout all sets. Significant differences in horizontal displacement were found between repetitions 1 and 6 for the first and second set of TS ($p \geq 0.05$). No differences were found between repetitions 1 and 6 with a cluster set configuration utilising 20IRR
Hardee et al. (142)	10	Recreational Weightlifters 1-RM = 1.39x BW	Acute	PC at 80% 1-RM	TS-3x6 with 180 s inter-set rest, CLU2, same as TS but with 20 s IRR, CLU2, same as TS but with 40 s IRR	TS PP significantly decreased by 15.65 (Rep 1-6), IRR20 PP significantly decreased by 5.50% (Rep 1-6), IRR40 PP significantly decreased by 3.3% (Rep 1-6), PF (TS) significantly decreased by 7.34%, PF (IRR20) significantly decreased by 2.67%, PF (IRR40) significantly decreased by 0.44%. TS PV- significantly decreased by 10.21% (Rep 1-6), IRR 20PV- significantly decreased by 3.67% (Rep 1-6), IRR 40 PV- significantly decreased by 1.70% (Rep 1-6). ($p \geq 0.05$ Force, velocity, and power were better maintained during CLU than TS; CLU with longer IRR periods maintained these variables better than when CLU rest periods were shorter
Jukic and Tufano (174)	15	Strength trained males 1-RM PC = 99.8 ± 10.8 kg, 1-RM/RM = 1.13 ± 0.14.	Acute	Clean Pull from Floor	TS- 3x6 CP at 80, 100, 120% 1-RM PC (180 s IRR) RR/CLU = 9x2 CP at 80, 100, 120% 1-RM PC (45 s inter rep rest)	For MVM, PVM, MVD, and PVD, there were small-to-moderate effect sizes in for RR80 and RR100, but large effects favouring RR120, compared to TS. Number of repetitions within a 20% velocity loss threshold was 17.7 ± 0.6 during RR and 16.5 ± 2.4 during TS (g = 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 (g = 0.66).
Koefoed et al.(189)	10	Recreational males and females	Acute	JS 40% BW	TS: 4 × 6 repetitions CS: 4× (3×2), 20 s IRR`	PF was 141 ± 263 N, (5.2% ± 8.3%), higher in the session with CS compared with TS (p = 0.047). PP output was 178 ± 181 W, (4.1% ± 4.9%), higher in the session with CS compared to TS (p = 0.005).

Morales-Artacho et al. (239)	19	Males	Chronic- 3 weeks	Smith Machine CMJ SJ with 20% 1-RM	CS- 6x3x2 (30 s rest every 2 repetitions, 4.5min inter-set rest) TS – 6x6 (5 min inter-set rest)	After CT, very-likely moderate increments in P_{25} were observed compared to TT (p = 0.011, ES = 0.55), due to a very-likely moderate rise in V_{25} (p = 0.001, ES = 0.71).
Moreno et al. (240)	26	Recreationally trained college males	Acute	BW Plyometric	TS: 2 x 10 with 90 s inter-set rest; CLU1: 4 x 5 with 30 s inter-set rest; CLU2: 10 x 2 with 10 s inter-set rest	CLU1 and CLU2 resulted in similar force, but greater JH, power output, and take off velocity compared with TS. CLU2 appeared to be superior.

Key: RM = Repetition maximum; PF = Peak Force; PP = Peak Power; MP = Mean Power; PV = Peak Velocity; MV = Mean Velocity; TS = Traditional Set; CLU = Cluster set; BM = Body Mass; CMJ = Countermovement Jump; SLJ = Standing Long Jump; IRR = Inter-repetition rest; TOV= Take-Off velocity; TUT = Time Under Tension; VJ = Vertical Jump; RPE = Rate of Perceived Exertion; $m{\cdot}s^{-1}$= Meters Per Second; P_{25} = Power at 75% body mass; V_{25} = Velocity at 75% body mass; MPV = Mean propulsive velocity; MVM = Mean Velocity maintenance; PVM = Peak velocity maintenance; MVD = Mean Velocity Decline; PVD = Peak velocity Decline; CR = Continuous repetitions; JH = Jump height

One method for comparing lower-limb kinetics and kinematics over an entire movement sequence is using statistical parametric mapping (SPM) (262). This method involves random field theory and calculates a critical threshold for each test, considering both the magnitude and shape of the entire data set for each curve, and has been used to assess GRF data and joint kinetics and kinematics in athletic populations (159, 270, 338), and is well established when evaluating human movement (159). Further, SPM regards time series variables as a single observation (342). Moreover, SPM enables a more comprehensive evaluation of movement throughout various tasks and has been used to identify additional limb asymmetries that were not found with traditional discrete analyses alone (159). Whilst most of the previous research on weightlifting movements is via discrete-point analyses (i.e., peak variables), such discrete analysis is only able to inform training decisions or interventions based on targeted peaks or other discrete points of interest (e.g., means across a movement), however, no additional information on movement patterns or performance is provided (159). Although these results provide important information about the peak outputs of the lifter-barbell system, they only offer information about differences at one time point, usually in the propulsive phase, and usually the second pull phase in weightlifting exercises, and fail to address differences within additional phases (185). To overcome these limitations, researchers have utilised curve analysis in jumping movements (61, 62, 223) or weightlifting derivatives (313, 314), which utilises discrete pairwise comparisons of point data. However, advantages of SPM are that one-dimension analysis utilises random field theory (261) instead of performing separate inferential tests at each time point, thereby reducing Type I error. Additionally, one-dimensional analysis allows for non-directed hypotheses on the portion of the curve where changes may occur (261).

Discrete analysis assumes that discrete points are independent of adjacent points in the overall time series, whereas SPM does not make this assumption. With reference to biomechanical time series data, this assumption is invalid because adjacent points are inherently related in continuous time series data (159). To date, only one study has investigated continuous time series data in weightlifting derivatives utilising SPM (185), with findings demonstrating curve analysis data was more probable to show statistically significant differences between the exercises when compared with data from the SPM procedure. This highlights that previous research using discrete variables may have inflated type I errors. Consequently, it would be beneficial for practitioners to have a greater and more accurate understanding of the effect of different loads used during weightlifting derivatives to help inform practice, including consideration of the different phases of the exercise.

2.4.3. The Use of Cluster Sets in Training Studies

Whilst the use of CLU in an acute setting has been widely investigated, the use of training studies investigating CLU has received significantly less attention, which is surprising given the positive results of CLU structure in an acute setting. One of the first studies to investigate the use of CLU in an training setting was undertaken by Lawton et al. (199). In this study, Lawton and colleagues compared a TS structure and CLU structure at 6-RM smith machine bench press loads in 26 junior elite male basketball players and 14 soccer players, all with a relatively low training experience of minimum 6 months. The subjects performed either a TS of 4 x 6 repetitions or 8 x 3 CLU in the same amount of time to equalise the work-to-rest ratio between groups (113 vs 260 s, total time 13minutes, 20 s). Interestingly, the concentric time was significantly greater during TS group (36.03 ± 4.03s versus 31.74 ± 4.71 s), despite equalising work in both conditions. After the 6 weeks, TS group displayed significantly greater increases (% change = 9.7% versus 4.9%) in 6-RM strength than the CLU, however there were no significant differences in power outputs in the bench press throw at 20 kg, 30 kg, and 40 kg loads between the two training groups, however power did improve between 5.8 to 10.9%. The authors concluded that the greater TUT TS resulted in greater total forces and therefore greater increases in maximal strength (as indicated by the significantly greater increases in 6-RM). However, it could be argued that the use of CLU may have resulted in an ability to lift a greater load. Further, as the subjects were instructed to throw the bar as ‘fast and high’ as possible and given the fact that the CLU showed improvements in power due to the fact that the CLU had a lower TUT and therefore a greater concentric velocity than the TS. Additionally, as both groups lifted the same relative intensity throughout the programme, this may have resulted in a reported RPE which is theoretically lower that during the TS and it should be noted that a purpose of CLU loading is to allow for a greater intensity and volume lifted (160).

Similar trends to the study by Lawton et al. (199) were observed in a 8 week study by Hansen, Cronin, Pickering and Newton (134) who investigated whether CLU led to improved power training adaptations in the preseason preparation of elite level rugby union players. Eighteen highly trained rugby union players were divided into 2 training groups, a TS (n = 9) group and a CLU (n = 9) group prior to undertaking 8 weeks of lower body resistance training consisting of clean and squat variations, with both groups completing other training such as upper body, conditioning, and speed sessions twice per week. The authors showed that there were significantly ($p < 0.05$) greater improvements in back squat 1-RM strength when compared with CLU (an 18.3% increase and a 14.6% increase for TS and CLU, respectively); however, PP or PV velocity assessed via loaded JS did not significantly improve. It should be noted that effect sizes ranged from small to large (Cohen's d = 0.2-0.9) at 20-40 Kg for power assessed in the loaded JS, indicating a likely positive effect practically. The greater increase in strength in the TS group shows that CLU protocols may not be ideal when both groups perform the same training loads, training volumes, and total rest time, which is also shown previously (199) and a greater volume and intensity may be possible with a CLU structure.

The use of TS vs CLU has also been measured over a longer duration of 12 weeks (254). The authors investigated the effect of CLU and TS over 12-week total-body hypertrophy focused training program in 22 resistance-trained males. Briefly, the TS group trained with 4 x 10 repetitions for all compound lifts, consisting of a variety of bilateral and unilateral exercises with 120 s of inter-set rest, whilst the CLU group performed 8 x 5 repetitions with 60 s of inter-set rest, resulting in the total rest time equal between groups. The authors demonstrated that after 12 weeks, both the TS group and CLU had a significant improvement in 1-RM Bench press, 1-RM back squat, back squat power and jump power ($p \geq 0.05$), whilst CLU group experienced greater increases in bench press and vertical jump power compared with TS. However, in contrast to other studies (134, 199), the CLU resulted in a greater increase in strength when compared to TS structure. This may be partly explained by the 1-RM strength testing that occurred at 4 and 8 weeks, which then allowed for a recalculation of improved 1-RM scores, and the block repeated with the same intensities in a periodised manner, therefore the increases in strength be a contributing factor.

The effects of CLU vs TS set have also been investigated in single joint training over a five-week mesocycle. Iglesias-Soler, Mayo, Rio-Rodriguez, Carballeira, Farinas and Fernandez-Del-Olmo (163) investigated the effects of a TS and an CLU protocol over a five-week period using unilateral knee extensions in mixed gender untrained sports science students. Subjects were assigned to either the TS group (4 x 8, 10 RM load, 180 s of inter-set rest) or CLU group (32 repetitions, 10RM load, 17.4 s of IRR), in which the work to rest ratio was identical. Results showed that TS resulted in slower mean propulsive velocities (0.48 vs. 0.54 $m.s^{-1}$) and a higher RPE score (8.3 vs. 6.6) than CLU, whilst both groups had a similar increase in isometric strength measured via isometric leg extension. The results of this study suggest that the CLU set protocol could increase the overall intensity due to the short rest periods throughout the set, which is evident in the RPE scores.

Further evidence for the effect of chronic response to CLU loading in plyometric training is shown previously (7). The authors compared the effects of six-week CLU versus TS plyometric training on jumping ability (CMJ and standing long jump), sprint (20 m and 40 m) and agility performance (t-test) in 13 college-aged students who had not undertaken plyometric training for six months but were familiar with this training modality. The TS group performed 5 x 20 maximal depth jumps from a 45 cm box with 120 s of inter-set rest, whilst the CLU group completed 5 x 20 but with 30 s of intra-set rest after 10 repetitions of each set and 90 s of inter-set rest, twice per week for six weeks. Results showed that there was a significant improvement ($p \geq 0.05$) in both groups for all tests, and that after six weeks of depth jumping, both groups had similar maximal intensity performance adaptations in the CMJ (ES = 1.24 and 0.84), standing long jump (ES = 0.81 and 0.60), t-test (ES = 1.38 and 9), 20 m (ES = 0.94 and 1.59) and 40 m sprint times (ES = 0.75 and 0.96). Further, although there were no significant interactions between groups, the ES were greater in the CLU group for CMJ, long jump distance, and t-test time, whereas the effect sizes were greater for the TS group for 20 and 40 m sprint times, highlighting the optimal method for improving desired variables.

The use of CLU has been widely implemented and has been shown to have positive effects on kinetic and kinematic performance, however further research is needed to investigate the use of CLU in weightlifting derivatives at lower loads. Currently, the plethora of CLU research during weightlifting exercises ranges from 75-120% (112, 126, 140-142), with the later research utilising 80% 1-RM based of the optimal load for PC. However, the optimal load to elicit PP for the PC has been shown to range between 60-80% 1-RM (49, 53, 183), with no statistical differences between 60-80% 1-RM (49) or 50-90% 1-RM (64, 179, 183) and weightlifting derivatives excluding the catch phase to be between 30-45% 1-RM (316). Therefore, it is plausible that the current research on CLU repetitions may not appropriate as more repetitions may be possible at lower loads and in exercises with a reduced ROM like the JShrug or mid-thigh variations before fatigue affects performance. Additionally, another issue with CLU is in exercises such as back squat and bench press where the subjects is required to un-rack and re-rack the bar between repetitions as this may result is a reduced/increased rest that could affect the overall reliability and consistency. Finally, it could be argued that the loads and exercise performed would affect the outcome of power and velocity measures. As previously stated, whilst TS result in greater fatigue and therefore metabolite accumulation (113), CLU sets allow for greater short term energy stores (328, 332). The majority of studies used submaximal loads and/or exercises for the CLU sets, which are not typically used to develop maximal strength (i.e., JS at 40 kg or back squats at 75% 1-RM, it is not surprising that force does not change considerably and therefore, power likely remains greater in CLU sets due to the result of greater velocities observed (328).

2.5. SUMMARY AND IMPLICATIONS

Within the literature review, a series of gaps were highlighted that require further investigation. Briefly, chapter 2.3.8 highlighted that many different derivatives and loading paradigms have been previously investigated, researchers have not investigated kinetics or kinematics during the CMS or HP across a spectrum of loads. Moreover, whilst acute peak and mean variables have been assessed during the MTP, it would be worth identifying if a CMS (i.e., a MTP initiated with a prior countermovement) or a HP (i.e., a clean pull from the knee initiated with a prior countermovement) elicited greater kinetics or kinematics than the MTP or PFK. In addition, although previous studies have investigated only the differences in force- velocity-, and power-time curves during weightlifting derivatives (185, 313, 314), none have investigated these differences in the CMS, HP or across a spectrum of loads. Therefore, investigating differences in these loads and exercises may provide a greater understanding of any technical and biomechanical differences. Lastly, whilst the effect of RR on weightlifting derivatives at supramaximal loads from the floor (i.e., clean pull) has been previously examined (174, 176), researchers are yet to examine this in derivatives with a shorter range of motion (i.e., CMS/HP), which may yield different findings.

The chapter below has been published in the Journal of Strength and Conditioning Research and the reference numbers in this thesis will differ from the published manuscript. Any typos and grammatical errors from the published manuscript have been amended in this version, with the reference numbers in line with the references throughout the thesis. The figures have been amended for this thesis.

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Chapter 3: Study 1- A Comparison of Kinetic and Kinematic Variables during the Midthigh Pull and Countermovement Shrug, Across Loads

3.1. ABSTRACT

This study compared kinetic and kinematic variables during the midthigh pull (MTP) and countermovement shrug (CMS). Eighteen males (age: 29.43 ± 3.95 years, height: 1.77 ± 0.08 m, body mass: 84.65 ± 18.79 kg, and 1 repetition maximum [1-RM] power clean: 1.02 ± 0.18 $kg \cdot kg^{-1}$) performed the MTP and CMS at intensities of 40, 60, 80, 100, 120, and 140% 1-RM, in a progressive manner. Peak force (PF), mean force (MF), peak velocity, peak barbell velocity (BV), peak power, (PP), mean power (MP), and net impulse were calculated from force-time data during the propulsion phase. During the CMS, PF and MF were maximised at 140% 1-RM and was significantly greater than the MTP at all loads ($p \leq 0.001$, Hedges $g = 0.66–0.90$); $p < 0.001$, $g = 0.74–0.99$, respectively). Peak velocity and BV were significantly and meaningfully greater during the CMS compared with the MTP across all loads ($p < 0.001$, $g = 1.83–2.85$; $p < 0.001$, $g = 1.73–2.30$, respectively). Similarly, there was a significantly and meaningfully greater PP and MP during the CMS, across all loads, compared with the MTP ($p < 0.001$, $g = 1.45–2.22$; $p < 0.001$, $g = 1.52–1.92$). Impulse during the CMS was also significantly greater across all loads ($p < 0.001$, $g = 1.20–1.66$) compared with the MTP. The results of this study demonstrate that the CMS may be a more advantageous exercise to perform to enhance force-time characteristics when compared with the MTP, due to the greater kinetics and kinematic values observed.

3.2. INTRODUCTION

Weightlifting exercises (snatch and clean and jerk) and their derivatives are commonly performed by athletes to develop rapid triple extension of the hips, knees, and ankles (plantar flexion). These movements are required by a vast majority of sports (301, 302) as they relate to both sprint and jump performance (37, 154). These exercises are implemented because of the similarities in sport-specific movements (i.e., rapid extension of hips, knees, and ankles) (36), while concurrently developing rapid force production and power (291).

Research on weightlifting biomechanics demonstrated that the second pull phase produces the greatest force and power applied to the barbell, in experienced weightlifters during the clean and power clean (PC) (91, 286). Interestingly, recent research on weightlifting pulling derivatives (i.e., those that exclude the catch phase) indicate that such exercises may provide a comparable (46) or greater (301, 302, 316) training stimulus compared with catch derivatives. Moreover, pulling derivatives permit supramaximal loads (>100% 1 repetition maximum [RM] of a catching derivative) to be performed (52, 55, 181) which has shown to elicit greater peak force (PF), rate of force development, and impulse than loads <1-RM PC (52, 55). This provides an overload stimulus of the triple extension movement, potentially producing superior strength- power characteristics (23, 301, 302).

During the midthigh pull (MTP) from training blocks, Haff et al. (124) demonstrated that system peak power (PP) occurred at 80% 1-RM; however, lighter loads were not assessed. By contrast, Kawamori et al. (181) found that system PP was the highest with 60% 1-RM, in male collegiate weightlifters, compared with 30, 60, 90, and 120% of 1-RM PC. However, 2 studies by Comfort et al. (52, 55) demonstrated that system PP was maximised at 40% in collegiate subjects, with Comfort et al. (52) demonstrating no significant differences between 40 and 60%. It should be noted that the subjects in the aforementioned studies by Comfort et al. (52, 55) did not start from the blocks, which has been performed in previous studies (124, 181). Research into weightlifting derivatives has shown that an increase in load resulted in a decrease in velocity during the MTP performed from a static position (52, 55), and when initiated with a countermovement during the hang high pull (HHP) and jump shrug (JS) (298, 316), the greatest loads maximise PF, and the lowest loads maximise velocity.

To date, no study has investigated the kinetic and kinematic differences between the MTP and countermovement shrug (CMS); a MTP initiated with a countermovement. The CMS has been described as a dynamic exercise that allows for greater overload during the top of the second pull by an ability to produce greater force at a higher velocity through the stimulation of the SSC (79). It would be useful to determine whether the addition or exclusion of the countermovement affects kinetic and kinematic variables during such exercises and to determine which variation may be the most beneficial for enhancing force-time characteristics. Any differences between these movements are likely a result of the performance-enhancing effect of the SSC (333). The SSC muscle action produces a more powerful muscle action than that which would result from a concentric action alone and has been viewed as essential for many sporting activities (96), as a result of the summation of elastic energy and neurological potentiation through stimulation of the muscle spindle (333).

The purpose of this study was to compare kinetic and kinematic variables attained within and between the MTP and CMS, across loads of 40–140% 1-RM PC. It was hypothesised that the CMS would result in higher values at each load across all kinetic and kinematic variables. It was further hypothesised that mean and PF and net impulse would increase with load, whereas mean power (MP) and PP, peak system velocity (PV), and peak barbell velocity (BV) would decrease with an increase in load, in line with previous research (52, 55).

3.3. METHODS

3.3.1. Experimental Approach to the Problem

This study used a within-subject repeated-measures research design; whereby kinematic (peak system velocity and peak BV) and kinetic (PF and mean force (MF) and power, and net impulse) variables were determined during the MTP and CMS. The aforementioned variables were measured by the subject per- forming all lifts on a force plate, and BV was assessed with a linear position transducer (LPT), using progressive loads of 40, 60, 80, 100, 120, and 140% 1-RM PC, to determine differences in kinematic and kinetic variables within and between variations across loads. Progressive loads were used to ensure ecological validity and to minimise risk of injury during the heavier loads. Before the experimental trials, subjects visited the S&C facility on 2 occasions, at the same time of day (5–7 days apart), to establish 1-RM PC reliability following the protocol previously used in a similar research (52, 55), and all lifts were increased with a minimum of 2.5 kg increments. The MTP and CMS were performed on 2 separate days (5–7 days apart) in a randomised order to minimise fatigue. The subjects returned 5–7 days later to perform the other variation following the aforementioned protocol.

3.3.2. Subjects

Eighteen male subjects from various national teams and individual sports such as rugby, soccer, martial arts, athletics, and fencing (age 29.43 ± 3.95 years, height 1.77 ± 0.08 m, body mass 84.65 ± 18.79 kg, relative 1-RM PC 1.02 ± 0.18 kg·kg21, resistance training experience 5.9 ± 1.4 years), who participated in regular resistance training, including some experience with weightlifting derivatives, volunteered to participate in this study. Subjects were free from injury and provided written informed consent before the commencement of testing. Subjects were requested to perform no strenuous activity during the 48 hours before testing, maintain-their normal dietary intake before each session, and to attend testing sessions in a hydrated state. This investigation received previous ethical approval from the University of Salford's ethics committee and conformed to the principles of the World Medical Association's Declaration of Helsinki.

3.3.3. Procedures

One Repetition Maximum Power Clean Testing

Subjects performed a dynamic warm-up that consisted of body weight squats, lunges, and dynamic stretching. Three submaximal PC efforts performed with decreasing volume (6–2 repetitions) and increasing loads (matched to the volume) before commencing their first 1-RM attempt. The 1-RM for each subject was then determined within 5 attempts (interspersed by 2–4 minutes of rest) by gradually increasing the load until an incomplete attempt occurred. All PC attempts began with the barbell on the lifting platform and ended with the barbell caught on the anterior deltoids in a semi squat position above parallel (visually monitored and any attempt caught below this was disallowed). Testing was performed using a lifting platform (Hammer Strength, Ohio, USA); the International Weightlifting Federation approved weightlifting barbell and bumper plates (Eleiko, Halmsted, Sweden). The greatest load achieved across the 2 sessions was used to calculate the loads used during the MTP and CMS. An accredited S&C coach supervised all sessions. For clarity and brevity, from this point on, all 1-RM PC testing in the experimental chapters followed the above protocol and are referred to this description.

Power Testing

Each subject completed a standardised warm-up, low intensity cycling for 5 minutes, followed by 1 set of 3 repetitions of the variation at 40% 1-RM PC. The subjects were then required to complete 1 randomly assigned variation (either MTP or CMS) at intensities of 40, 60, 80, 100, 120, and 140% of their predetermined 1-RM in a progressive order (40–140%) to replicate the progression of loads that occur in training sessions. Three repetitions were performed at each load with 30–60 seconds of rest between repetitions and 3–4 minutes rest between loads to minimise fatigue (18 repetitions total) in line with Comfort et al. (6,7). The barbell was placed on the safety bars of the power cage in between all repetitions to prevent fatigue in both variations. Once the body was stabilised (verified by observing the subject and force-time data), the lift was initiated with the countdown "3, 2, 1, go," and all subjects were instructed to exert maximal intent during each repetition. All lifts were performed in a power cage (Fitness Technology, Adelaide, Australia) on the Fitness Technology 700 ballistic measurement system with an integrated force plate (400 Series) sampling at 600 Hz, interfaced with a desktop computer and ballistic measurement software. Verbal encouragement was provided throughout testing. During all repetitions, subjects were required to use lifting straps for standardisation and to reduce technique breakdown due to loss of grip at higher loads.

For the MTP (Figure 3.1), the subjects lowered the barbell to midthigh, paused for 3 seconds to minimise the effect of the SSC, and then performed the exercise, ensuring a triple extension of the hips, knees, and ankles (plantar flexion) and a shrug that moved the barbell in a vertical plane while maintaining elbow extension (52, 55). Any repetitions that were initiated with a countermovement (identified by visual inspection of the force-time data) were disallowed and repeated after a further 30–60 seconds rest period. Testing was finished on successful completion of all the repetitions across all loads (18 repetitions).

For the CMS (Figure 3.2), the subjects stood completely vertical with knees extended for 3 seconds and then transitioned to the midthigh position by flexing at the knees before immediately performing a rapid triple extension of the hips, knees, and ankles and a shrug that moved the barbell in a vertical plane while maintaining elbow extension (i.e., second pull) in 1 continuous movement (79).

Figure 3.1-Sequence of mid-thigh pull

Figure 3.2-Sequence of countermovement shrug

Force-Time Data Collection

Raw vertical force-time data for each trial was exported as text files and analysed using a customised Excel spreadsheet (version 2016; Microsoft Corp., Redmond, WA, USA). Before the onset of the pull, subjects were instructed to remain stationary on the force platform for 1 second to allow for subsequent determination of the system weight (body mass + barbell weight) (259). For both pulls, vertical ground reaction force (VGRF) data were averaged across the first second while the subjects stood still (this average value represented the system weight), and a force threshold was calculated from the VGRF during this same time period. Specifically, the standard deviation of the VGRF across the first second was calculated and then multiplied by 5, and the resultant value represented the force threshold used to determine the onset of the pull (259). During the MTP and CMS, the onset of movement was deemed to have occurred 30 ms before the VGRF was exceeded and reduced by the force threshold, respectively (259). Velocity of the system (barbell + body) was calculated from VGRF force-time data. Specifically, the acceleration-time record (subtracting system weight from VGRF and then dividing this by system mass on a sample-by-sample basis) was numerically integrated using the trapezoid rule to yield the velocity-time record (259). Power applied to the system was calculated from product of system velocity and VGRF at each time point (52, 55). Net VGRF was integrated with respect to time (also using the trapezoid rule) to obtain the net impulse. As an unweighting and braking phase precedes the propulsion (triple extension) phase during the CMS, but is not included during the MTP, all force-time variables were further analysed in the propulsion phase only. The propulsion phase of both pulls was deemed to have started when the velocity exceeded 0.01 $m.s^{-1}$ and finished at peak velocity, which coincided with the end of the pull (223, 225, 226). Net PF, net MF, PV, PP, MP were defined as the maximum (for peaks) and average (for means) values attained during the propulsion phase (223, 225, 226).

Peak BV was measured through an LPT and was determined as the greatest velocity during the pull (GymAware Power Tool; Kinetic Performance Technologies, Canberra, Australia) with data transmitted through Bluetooth to a tablet (iPad; Apple Inc., California, USA). The LPT recorded the displacement-time curve by determining changes in the position of the barbell (18), which sampled and time-stamped the changes in a barbell position in 20 ms time points. Velocity and acceleration data were then calculated from the first and second derivative of the change in the barbell position with respect to time.

3.4. STATISTICAL ANALYSES

Statistical analyses were performed using SPSS version 24 (SPSS, Chicago, IL, USA). For each variable, the mean output of the 3 pull trials was taken forward for statistical analysis. A 2-way fixed-effect model intraclass correlation coefficients (ICCs) and coefficients of variation (CV), calculated as the standard deviation/mean multiplied by 100 and 95% confidence intervals (CIs), were used to determine reliability and variability of performance measures. Minimal acceptable reliability was determined with an ICC ≥ 0.70 and CV of $\leq 10\%$ (57) (Table 1). Distribution of data was analysed by using the Shapiro-Wilks test of normality, with differences between exercises determined using paired samples t-tests or the Wilcoxon test, at each load. Subsequently, the effect of load was determined by using repeated-measures analysis of variance with Bonferroni post hoc analysis. Sphericity could not be assumed by the Mauchly test ($p > 0.05$) for all variables, and therefore, Greenhouse-Geisser adjustment was used. Standardised differences were calculated using Hedges' g effect sizes, as previously described (148) and interpreted according to Hopkins et al. (152), which defined values as trivial (≤ 0.19), small (0.20–0.59), moderate (0.60-1.19), large (1.20-1.99), and very large (2.0-4.0). An a priori alpha level was set at $p < 0.05$.

3.5. RESULTS

Power clean 1-RM performances were highly reliable (ICC = 0.99, [95% CI = 0.98–1.00], %CV = 1.8% [0.8–2.9%]) between sessions 1 (84.17 ± 21.64 kg) and 2 (85.28 ± 20.09 kg). All MTP variables showed an acceptable level of variability except PP at 40 and 60% (CV ± 10.7–13%) with an acceptable reliability for all variables except mean velocity (MV) at 60% (ICC = 0.67) and 100–140% (ICC = 0.65-0.68). All CMS variables demonstrated an acceptable reliability and variability with the exception MV at 40% (ICC = 0.65) (Table 3.1). Descriptive statistics (mean ± SD), 95% CIs, and effect sizes for the MTP and CMS are shown in Table 3.2;Table 3.3;Table 3.4;Table 3.5. As MV was deemed unreliable, this was removed from further analysis. It is likely that the lower reliability was observed in system velocity due to the small movements during the quiet standing phase, which may vary across subjects.

Table 3.1-Reliability (ICC [95% confidence intervals) and variability (%CV) [95% confidence intervals) of kinetic and kinematic variables during the countermovement shrug and mid-thigh pull

	Intensity	40%		60%		80%	
Variable	**Exercise**	**ICC**	**%CV**	**ICC**	**%CV**	**ICC**	**%CV**
Peak Force	MTP	0.88 (0.70-0.95)	5.5% (3.1-8.0)	0.84 (0.54-0.94)	5.5% (3.1-8.0)	0.93 (0.83-0.97)	3.4% (2.2-4.5)
	CMS	0.95 (0.87-0.98)	4.0% (2.7-7.0)	0.95 (0.87-0.98)	4.0% (2.5-5.2)	0.97 (0.91-0.99)	3.0% (1.5-3.5)
Mean Force	MTP	0.88 (0.71-0.95)	4.9% (2.9-7)	0.83 (0.61-0.93)	5.9% (3.2-8.6)	0.93 (0.82-0.97)	4.0% (2.4-5.6)
	CMS	0.98 (0.94-0.99)	3.0% (1.7-3.4)	0.96 (0.89-0.98)	3.0% (1.0-4.0)	0.98 (0.93-0.99)	2.0% (1.3-2.9)
Peak Velocity	MTP	0.72 (0.38-0.89)	9.0% (4.2-13.9)	0.74 (0.44-0.89)	7.7% (3.8-11.7)	0.90 (0.75-0.96)	4.4% (2.5-6.3)
	CMS	0.70 (0.34-0.86)	4.0% (2.9-5.4)	0.71 (0.38-0.88)	4.0% (2.5-5.7)	0.76 (0.45-0.90)	3.0% (1.8-5.1)
Mean Velocity	MTP	0.71 (0.39-0.88)	9.7% (4.9-14.5)	0.67 (0.33-0.86)	10% (4.5-15.6)	0.76 (0.47-0.90)	7.7% (4.6-10.8)
	CMS	0.65 (0.27-0.85)	5.0% (3.5-6.1)	0.54 (0.13-0.79)	4.0% (1.7-6.4)	0.69 (0.35-0.87)	4.0% (1.0-6.4)
Peak Power	MTP	0.76 (0.47-0.91)	13.0% (7.1-18.8)	0.77 (0.50-0.91)	10.7% (5.8-15.6)	0.91 (0.78-0.97)	5.9% (3.9-7.9)
	CMS	0.94 (0.84-0.98)	5.0% (4.1-6.8)	0.89 (0.73-0.96)	6.0% (3.6-8.0)	0.93 (0.84-0.98)	4.0% (2.7-5.8)
Mean Power	MTP	0.76 (0.46-0.94)	9.9% (5.9-13.9)	0.80 (0.60-0.92)	8.4% (4.2-12.6)	0.90 (0.75-0.96)	5.9% (3.6-8.1)
	CMS	0.96 (0.90-0.99)	4.0% (2.9-5.4)	0.93 (0.82-0.97)	5.0% (2.2-6.9)	0.90 (0.75-0.96)	3.0% (0.9-5.8)
Impulse	MTP	0.81 (0.56-0.93)	8.9% (4.5-13.5)	0.80 (0.55-0.92)	7.9% (4.0-11.8)	0.92 (0.80-0.97)	4.5% (2.6-6.5)
	CMS	0.96 (0.89-0.98)	4.0% (2.8-5.4)	0.96 (0.89-0.98)	4.0% (2.7-5.7)	0.95 (0.86-0.98)	3.0% (1.6-4.8)
Barbell Velocity	MTP	0.94 (0.84-0.98)	3.6% (2.2-4.9)	0.89 (0.73-0.96)	3.5% (1.9-5.0)	0.96 (0.89-0.98)	2.6% (1.7-3.6)
	CMS	0.95 (0.88-0.98)	2.0% (0.9-2.2)	0.91 (0.78-0.97)	2.0% (1.3-2.9)	0.79 (0.52-0.92)	2.0% (1.0-3.6)

	Intensity	100%		120%		140%	
Variable	**Exercise**	**ICC**	**%CV**	**ICC**	**%CV**	**ICC**	**%CV**
Peak Force	MTP	0.93 (0.81-0.97)	3.8% (2.5-5.1)	0.89 (0.73-0.96)	3.4% (1.5-5.3)	0.94 (0.85-0.98)	4.1% (2.7-5.5)
	CMS	0.99 (0.96-0.99)	2.0% (1.4-3.3)	0.96 (0.91-0.99)	3.0% (1.5-4.2)	0.97 (0.91-0.99)	3.0% (2.2-4.6)
Mean Force	MTP	0.96 (0.90-0.99)	3.3% (2.4-4.1)	0.94 (0.85-0.98)	3.6% (2.1-5.0)	0.98 (0.93-0.99)	3.1% (2.3-3.9)
	CMS	0.99 (0.97-0.99)	2.0% (1.5-2.3)	0.99 (0.97-0.99)	1.0% (0.7-2.7)	0.98 (0.95-0.99)	2.0% (1.3-3.0)
Peak Velocity	MTP	0.79 (0.44-0.92)	6.1% (3.8-8.4)	0.92 (0.81-0.97)	3.3% (2.0-4.6)	0.87 (0.69-0.95)	4.9% (3.5-6.3)
	CMS	0.94 (0.85-0.98)	3.0% (1.7-3.5)	0.89 (0.72-0.96)	3.0% (2.1-4.1)	0.87 (0.69-0.95)	3.0% (1.7-4.8)
Mean Velocity	MTP	0.65 (0.17-0.87)	8.9% (6.2-11.6)	0.64 (0.25-0.85)	7.7% (5.3-10.2)	0.68 (0.32-0.87)	7.0% (4.1-10)
	CMS	0.90 (0.74-0.96)	3.0% (2.0-4.7)	0.87 (0.69-0.95)	3.0% (1.5-4.7)	0.93 (0.83-0.97)	3.0% (1.9-5.0)
Peak Power	MTP	0.75 (0.39-0.94)	7.8% (4.5-11.0)	0.86 (0.67-0.94)	4.2% (2.0-6.5)	0.85 (0.64-0.94)	6.4% (4.6-8.3)
	CMS	0.98 (0.92-0.99)	4.0% (2.4-5.1)	0.95 (0.87-0.98)	4.0% (2.6-5.1)	0.95 (0.86-0.98)	4.0% (2.4-6.2)
Mean Power	MTP	0.84 (0.33-0.95)	7.1% (5.1-9.1)	0.81 (0.50-0.93)	5.8% (3.5-8.1)	0.89 (0.74-0.96)	5.8% (3.6-8.1)
	CMS	0.97 (0.89-0.99)	3.0% (1.5-4.3)	0.95 (0.87-0.98)	3.0% (1.4-4.8)	0.96 (0.88-0.98)	3.0% (1.7-5.0)
Impulse	MTP	0.84 (0.60-0.94)	6.2% (3.8-8.5)	0.86 (0.67-0.95)	4.0% (1.1-6.9)	0.90 (0.76-0.96)	5.1% (3.7-6.5)
	CMS	0.99 (0.95-0.99)	3.0% (1.7-3.4)	0.96 (0.91-0.97)	3.0% (2.2-4.3)	0.96 (0.90-0.99)	4.0% (2.2-6.0)
Barbell Velocity	MTP	0.96 (0.89-0.98)	2.5% (1.3-3.6)	0.90 (0.75-0.96)	3.0% (1.0-5.0)	0.93 (0.81-0.97)	2.6% (1.3-4.0)
	CMS	0.94 (0.86-0.98)	2.0% (1.2-2.8)	0.81 (0.55-0.92)	3.0% (1.6-4.0)	0.91 (0.79-0.97	3.0% (1.7-3.5)

MTP = mid-thigh pull; CMS = countermovement shrug; ICC = interclass correlation coefficient; %CV = percentage coefficient of variation

Table 3.2-Descriptive statistics (mean, standard deviation and 95% confidence intervals) for the mid-thigh pull

Intensity	Peak Force (N)	Mean Force (N)	Peak Velocity (m.s^{-1})	Peak Power (W)	Mean Power (W)	Impulse (N.s^{-1})	Barbell Velocity (m.s^{-1})
40%	2411 ± 424 (2200-2622)	1851 ± 311 (1696-2006)	1.03 ± 0.22 (0.93-0.14)	1789 ± 537 (1522-2056)	651 ± 144 (581-725)	120 ± 29 (106-134)	**1.53 ± 0.25*** (1.40-1.65)
60%	2630 ± 434 (2414-2846)	2064 ± 368 (1881-2247)	**1.05 ± 0.21*** (0.94-1.15)	2005 ± 574 (1719-2290)	740 ± 180 (652-828)	137 ± 32 (121-153)	1.47 ± 0.20 (1.37-1.57)
80%	2835 ± 451 (2611-3060)	2255 ± 387 (2702-3208)	1.00 ± 0.12 (0.91-1.08)	**2063 ± 491*** (1819-2308)	799 ± 167 (715-882)	147 ± 30 (132-162)	1.34 ± 0.19 (1.24-1.43)
100%	2955 ± 509 (2702-3208)	2354 ± 446 (2132-2576)	0.89 ± 0.14 (0.82-0.96)	1929 ± 365 (1748-2110)	797 ± 158 (717-874)	147 ± 28 (133-161)	1.15 ± 0.17 (1.07-1.23)
120%	3065 ± 514 (2809-3320)	2512 ± 465 (2280-2743)	0.86 ± 0.13 (0.80-0.93)	1973 ± 347 (1800-2146)	**849 ± 144*** (777-919)	**152 ± 26*** (139-166)	1.07 ± 0.15 (0.99-1.14)
140%	**3135 ± 622*** (2826-3445)	**2646 ± 543*** (2376-2916)	0.77 ± 0.12 (0.71-0.82)	1839 ± 375 (1669-2009)	835 ± 174 (749-921)	151 ± 28 (137-165)	0.97 ± 0.14 (0.89-1.03)
* **Bold** denotes peak performance in each variable							

Table 3.3-Comparisons of kinetic and kinematic variables between loads during the mid-thigh pull using Hedges' *g* effect size

Intensity	Peak Force (N)	Mean Force (N)	Peak Velocity (m.s^{-1})	Peak Power (W)	Mean Power (W)	Impulse (N.s^{-1})	Barbell Velocity (m.s^{-1})
40 vs. 60	0.50*	0.61*	0.09	0.38*	0.53	0.54*	0.26
40 vs. 80	0.95*	1.13*	0.17	0.52*	0.93*	0.89*	0.84*
40 vs. 100	1.14*	1.28*	0.74*	0.30*	0.94	0.93*	1.74*
40 vs. 120	1.36*	1.63*	0.92*	0.40*	1.34	1.14*	2.18*
40 vs. 140	1.33*	1.76*	1.43*	0.11*	1.13	1.06*	2.70*
60 vs. 80	0.45*	0.49*	0.29	0.11	0.32	0.32	0.65*
60 vs. 100	0.67*	0.69*	0.88*	0.15*	0.33	0.33	1.69*
60 vs. 120	0.89*	1.04*	1.06*	0.07	0.65	0.50	2.21*
60 vs. 140	0.92*	1.23*	1.60*	0.33	0.52	0.46	2.83*
80 vs. 100	0.24*	0.23*	0.82*	0.30	0.01	0.00	1.03*
80 vs. 120	0.47*	0.59*	1.09*	0.21	0.31	0.17	1.54*
80 vs. 140	0.54*	0.81*	1.87*	0.50	0.21	0.13	2.17*
100 vs. 120	0.21*	0.34*	0.22	0.12	0.34	0.18	0.49*
100 vs. 140	0.31*	0.57*	0.90*	0.24	0.22	0.14	1.13*
120 vs. 140	0.12	0.26*	0.70*	0.36	0.09	0.04	0.67*
* Denotes significant differences between loads ($p \leq 0.036$)							

Table 3.4-Descriptive statistics (mean, standard deviation and 95% confidence intervals) for the countermovement shrug

Intensity	**Peak Force (N)**	**Mean Force (N)**	**Peak Velocity ($m.s^{-1}$)**	**Peak Power (W)**	**Mean Power (W)**	**Impulse ($N.s^{-1}$)**	**Barbell Velocity ($m.s^{-1}$)**
40%	2891 ± 603 (2591- 3191)	2334 ± 853 (2109-2559)	***1.39 ± 0.12** (1.33-1.45)	2738 ± 697 (2391-3085)	1010 ± 260 (881-1139)	168 ± 43 (146-189)	**1.96 ±0.18*** (1.87-2.05)
60%	3048 ± 648 (2726-3370)	2512 ± 510 (2259-2766)	1.37 ± 0.12 (1.31-1.43)	2910 ± 643 (2590-3230)	1113 ± 276 (946-1250)	185 ± 45 (163-208)	1.79 ± 0.16 (1.72-1.81)
80%	3236 ± 704 (2886-3586)	2706 ± 553 (2431-2981)	1.34 ± 0.12 (1.28-1.40)	3093 ±736 (2727-3460)	1208 ± 332 (1043-1374)	204 ± 52 (178-230)	1.64 ± 0.12 (1.58-1.70)
100%	3413 ± 821 3004-3821)	2783 ± 641 (2554-3192)	1.29 ± 0.17 (1.21-1.38)	3151 ± 877 (2715-3587	1297 ± 384 (1106-1488)	217 ± 59 (188-247)	1.50 ± 0.16 (1.42-1.58)
120%	3550 ± 845 (3130-3971)	3022 ± 665 (2691-2988)	1.22 ± 0.13 (1.16-1.29)	**3160 ± 796*** (2764-3556)	1322 ± 344 (1151-1493)	**226 ± 56*** (198-254)	1.38 ± 0.11 (1.33-1.44)
140%	**3640 ± 814*** (3235-4045)	**3143 ± 632*** (2829-3457)	1.15 ± 0.14 (1.07-1.22)	3100 ± 692 (2756-3444)	**1353 ± 331*** (1188-1517)	225 ± 56 (197-253)	1.27 ± 0.14 (1.20-1.34)

* **Bold** denotes peak performance in each variable

Table 3.5-Comparison of kinetic and kinematic variables between loads during the countermovement shrug using Hedges' *g* effect sizes

Intensity	**Peak Force (N)**	**Mean Force (N)**	**Peak Velocity ($m.s^{-1}$)**	**Peak Power (W)**	**Mean Power (W)**	**Impulse ($N.s^{-1}$)**	**Barbell Velocity ($m.s^{-1}$)**
40 vs. 60	0.25*	0.25*	0.16	0.25*	0.38	0.38*	0.98
40 vs. 80	0.51*	0.51*	0.41	0.48*	0.65*	0.74*	2.05*
40 vs. 100	0.71*	0.58*	0.67*	0.51*	0.86	0.93*	2.64*
40 vs. 120	0.88*	0.88*	1.33*	0.55*	1.00	1.14*	3.88*
40 vs. 140	1.02*	1.05*	1.80*	0.51*	1.12	1.12*	4.18*
60 vs. 80	0.27*	0.36*	0.24	0.26*	0.30	0.38	1.04*
60 vs. 100	0.48*	0.46*	0.53*	0.31	0.54	0.60	1.77*
60 vs. 120	0.65*	0.84*	1.17*	0.34*	0.66	0.79	2.92*
60 vs. 140	0.79*	1.07*	1.65*	0.28	0.77	0.77	3.38*
80 vs. 100	0.23*	0.13*	0.33*	0.07	0.24	0.23	0.97*
80 vs. 120	0.39*	0.51*	0.94*	0.09	0.33	0.40	2.21*
80 vs. 140	0.52*	0.72*	1.42*	0.01	0.43	0.38	2.77*
100 vs. 120	0.16*	0.36*	0.45	0.01	0.07	0.15	0.85*
100 vs. 140	0.27*	0.55*	0.88*	0.06	0.15	0.14	1.50*
120 vs. 140	0.11	0.18*	0.51*	0.08	0.09	0.02	0.85*

* Denotes significant differences between loads ($p \leq 0.036$)

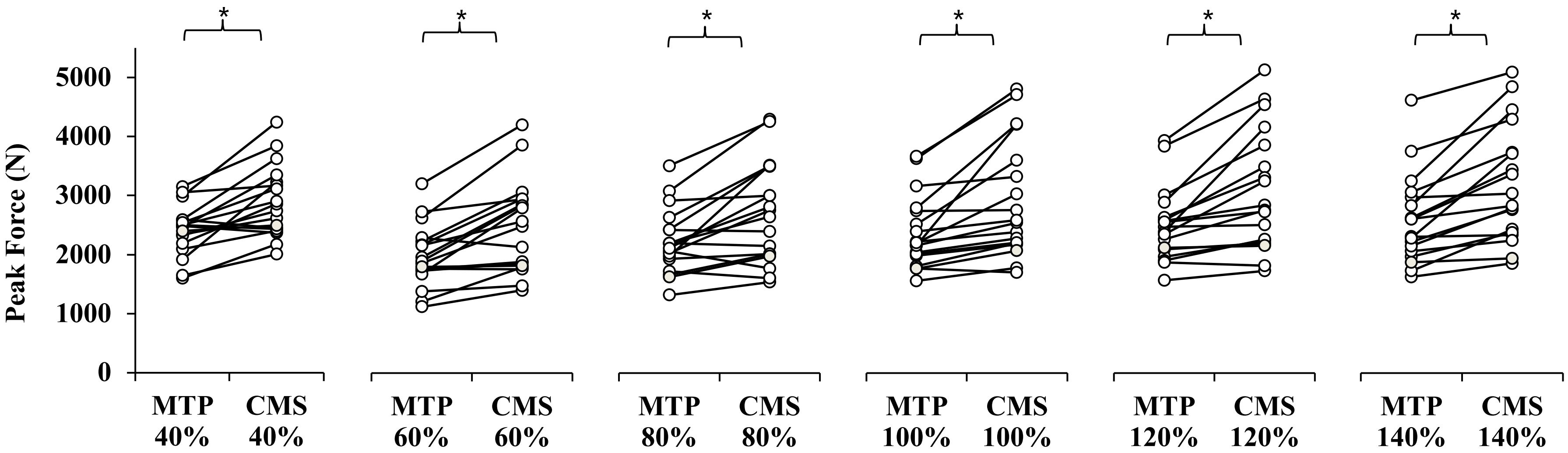


Figure 3.3- Comparison of individual differences in Peak Force between CMS and MTP across loads. *Significantly greater than MTP ($p \leq 0.001$)

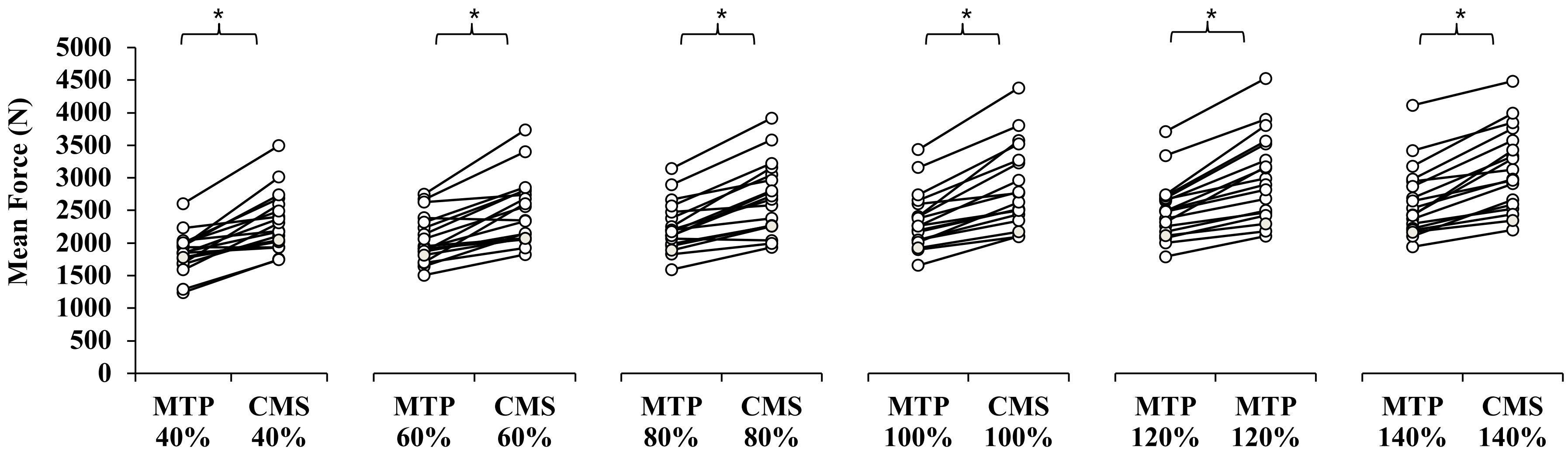


Figure 3.4- Comparison of individual differences in Mean Force between CMS and MTP across loads* Significantly greater than MTP ($p < 0.001$)

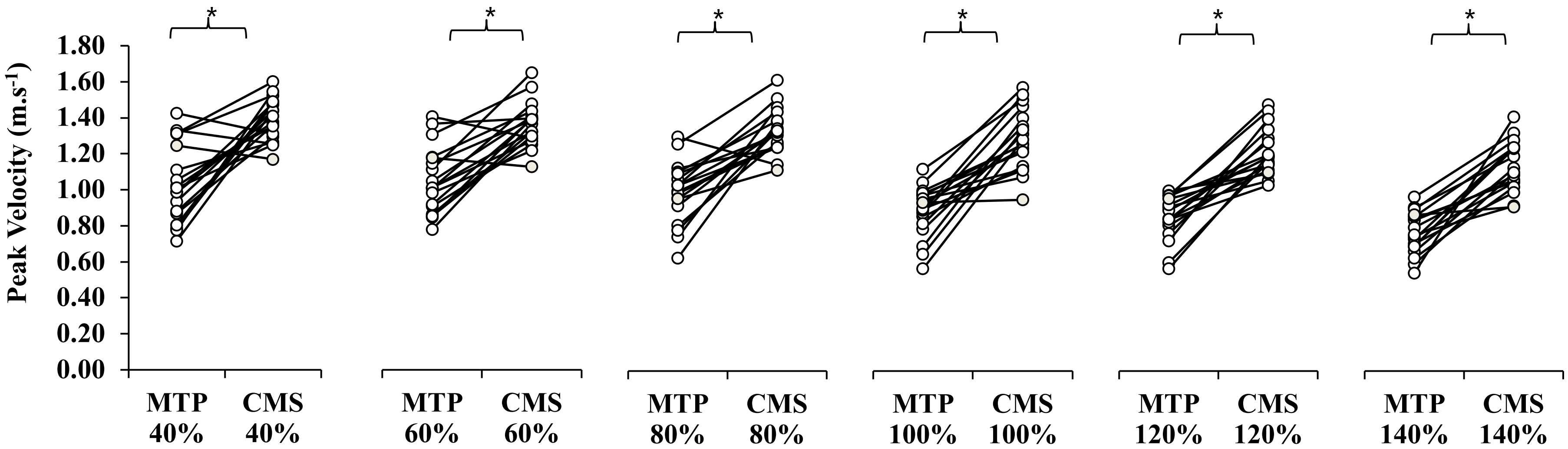


Figure 3.5- Comparison of individual differences in Peak Velocity between CMS and MTP across loads. *Significantly greater than MTP ($p < 0.001$)

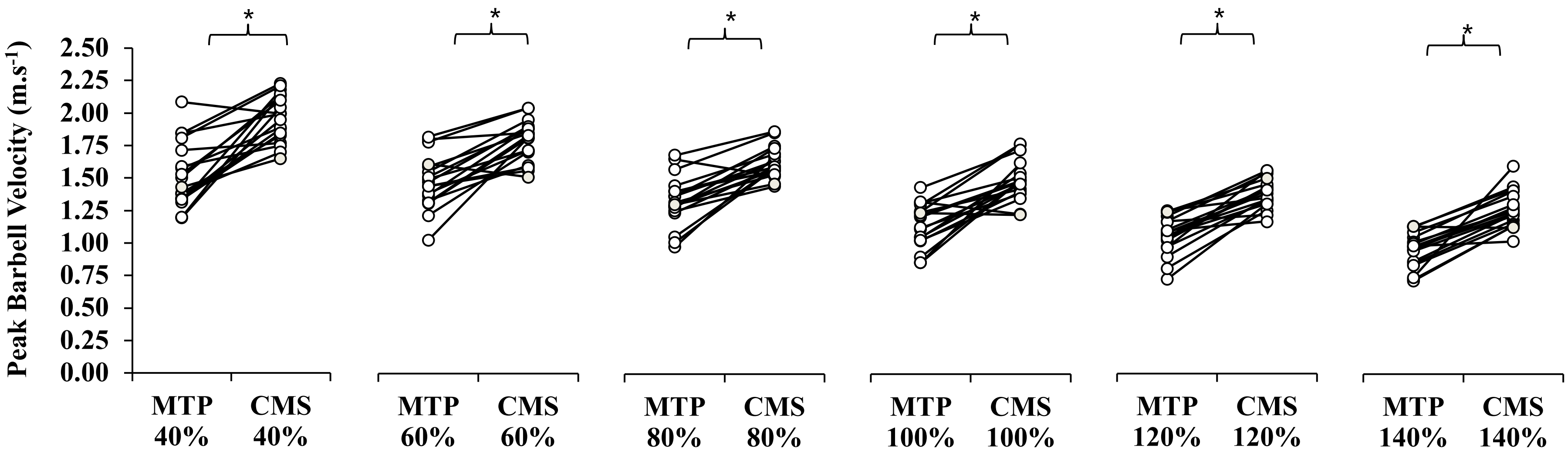


Figure 3.6- Comparison of individual differences in Peak Barbell Velocity between CMS and MTP across loads. *Significantly greater than MTP ($p < 0.001$)

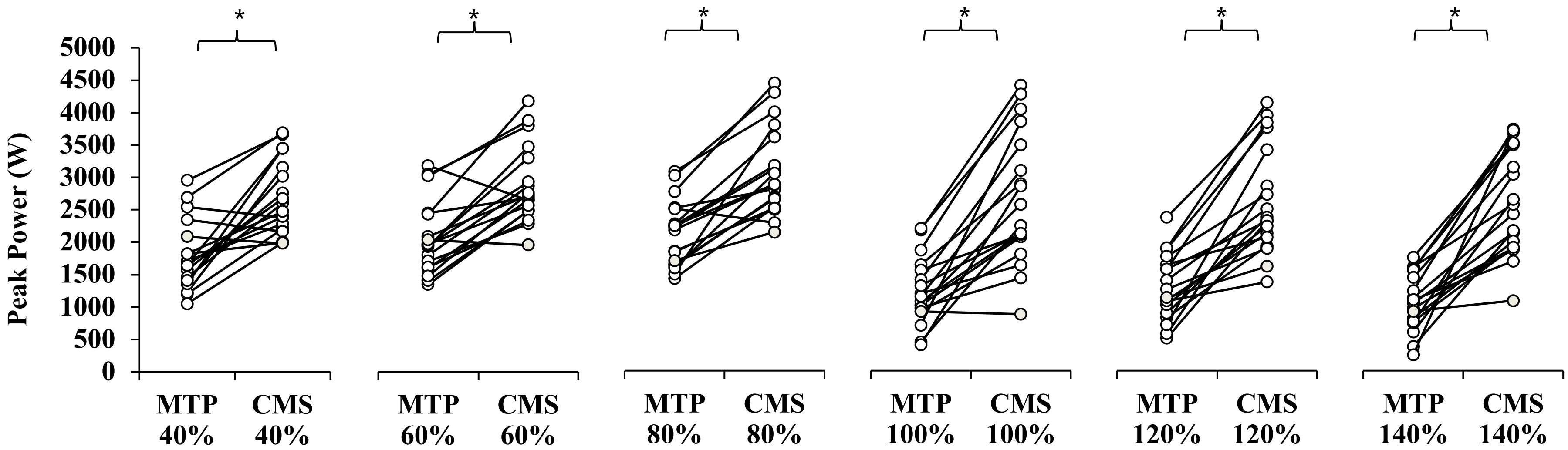


Figure 3.7- Comparison of individual differences in Peak Power between CMS and MTP across loads. *Significantly greater than MTP ($p <$ 0.001)

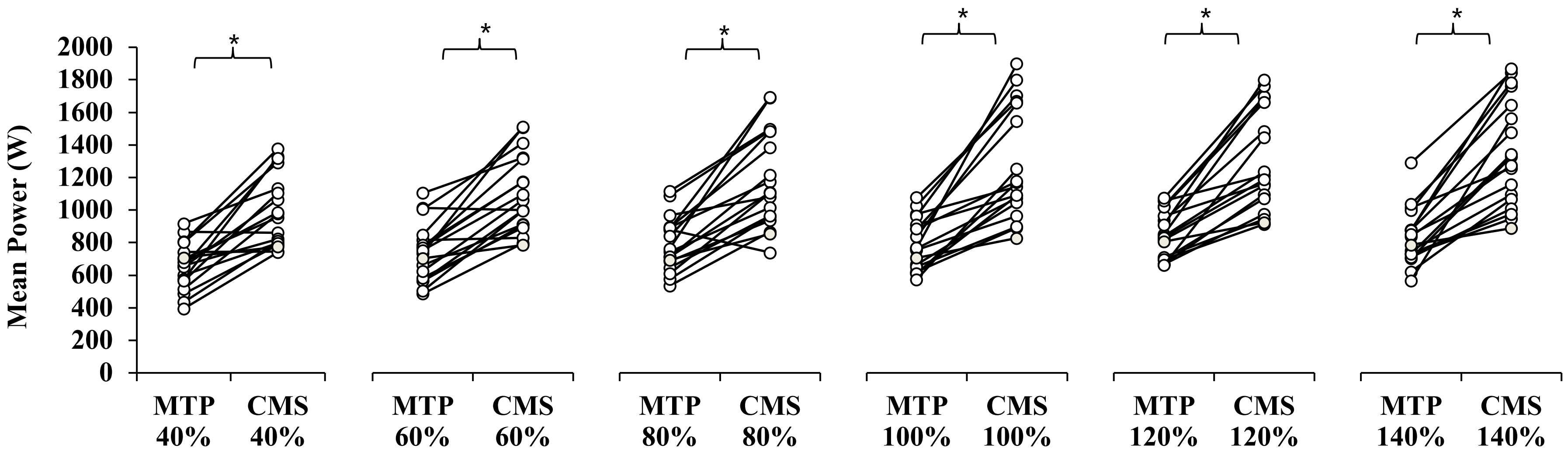


Figure 3.8- Comparison of individual differences in Mean Power between CMS and MTP across loads. *Significantly greater than MTP ($p <$ 0.001)

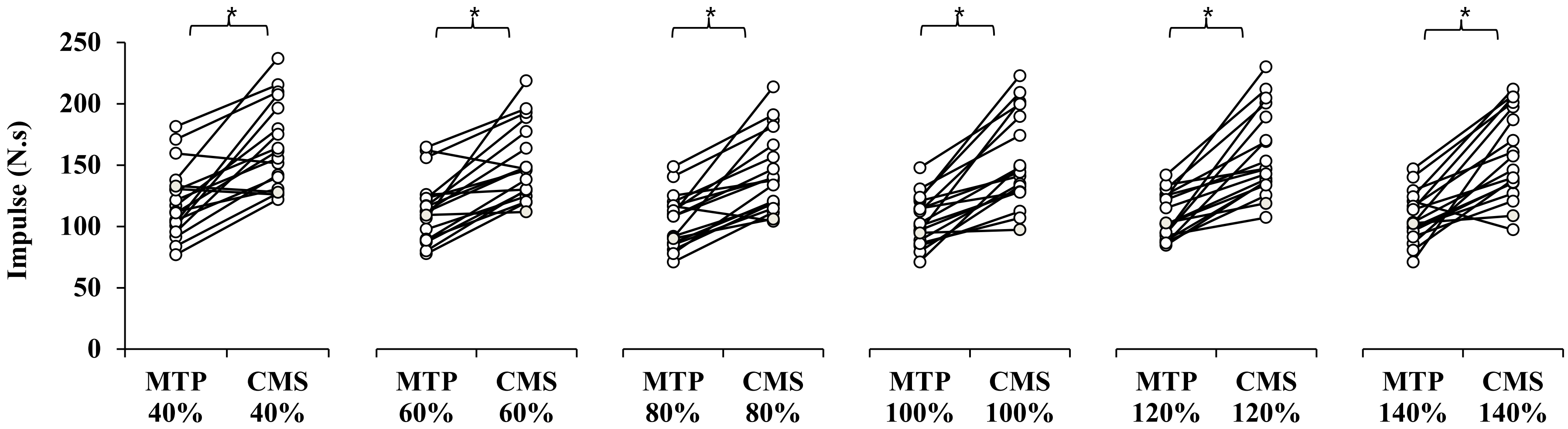


Figure 3.9- Comparison of individual differences in Impulse between CMS and MTP across loads. *Significantly greater than MTP ($p < 0.001$)

Comparison Between Exercise Variations

There was a moderately and significantly greater PF during the CMS when compared with the MTP across all loads ($p \leq 0.001$, $g = 0.66$-0.90) (Figure 3.3). Similarly, MF in the CMS was moderately and significantly greater across all loads ($p < 0.001$, $g = 0.74$-0.99) (Figure 3.4). Peak velocity during the CMS was significantly greater and of a large to very large magnitude, across all loads ($p < 0.001$, $g = 1.83$-2.85) compared with the MTP (Figure 3.5). Peak BV in the CMS demonstrated large to very large significant differences across all loads ($p < 0.001$, $g = 1.73$-2.30) (Figure 3.6). There was a very large and significant difference in PP during the CMS across all loads when compared with the MTP ($p < 0.001$, $g = 1.45$-2.22) (Figure 3.7). Mean power demonstrated a large and significant difference during the CMS across all loads when compared with the MTP ($p < 0.001$, $g = 1.52$-1.92) (Figure 3.8). Net impulse during CMS was significantly greater across all loads ($p < 0.001$, $g = 1.20$-1.66) with a large magnitude (Figure 3.9).

Effect of Load on Midthigh Pull Kinetics and Kinematics

Peak force progressively increased with load with the greatest load occurring at 140% 1-RM (Table 3.2), although this was not significantly greater than PF at 120% 1-RM, with small to large significant differences between all loads. Similarly, MF progressively increased as load increased, with the greatest MF achieved at 140% 1-RM, with small to large and significant differences between all loads (Table 3.3).

Peak velocity was greatest at 60% 1-RM and showed a progressive decrease across loads (Table 3.2). Peak velocity at 60% 1-RM was moderately and significant greater compared with 100 and 120% 1-RM, with a large significant difference compared with 140% 1-RM. There was no meaningful or significant difference in PV achieved across loads of 40–80% 1-RM. Peak BV was greatest at 40% 1-RM and showed a progressive decrease across loads, which was moderately and significantly greater than 80% 1-RM, with large to very large significant differences compared with 100, 120, and 140% 1-RM. Peak BV at 60% 1-RM demonstrated a small yet nonsignificant decrease compared with 40% 1-RM (Table 3.3).

Peak power demonstrated progressive increase with an increase in load from 40 to 80% with the highest PP occurring at 80%1-RM (Table 3.2). Peak power at 80% demonstrated moderate significant differences with 40%. Mean power demonstrated a progressive increase from 40 to 80% with the highest MP occurring at 120% 1-RM, which was not significantly greater than any other load (Table 3.3). Net impulse demonstrated a progressive increase with load with the greatest impulse occurring at 120% 1-RM (Table 3.2), which demonstrated moderate to large significant differences than 40% only (Table 3.3).

Effect of Load on Countermovement Shrug Kinetics and Kinematics

Peak force progressively increased with load, with the greatest load occurring at 140% 1-RM (Table 3.4). Small to large significant differences occurred between all loads, other than 120-140% 1-RM, where there was only a trivial and nonsignificant difference (Table 3.5). Similarly, MF progressively increased as load increased, with the greatest MF achieved at 140% 1-RM (Table 3.4), with small to large and significant differences between all loads (Table 3.5).

Peak velocity was greatest at 40% 1-RM and showed a progressive decrease across loads (Table 3.4). Peak velocity at 40% was moderately and significantly greater compared with 100 and 120%, with a large significant difference compared with 140% 1-RM. There was no meaningful or significant difference in PV achieved across loads of 60–80% 1-RM (Table 3.5).

Peak BV was greatest at 40% 1-RM and showed a progressive decrease across loads, with large to very large significant differences compared with 80-140% 1-RM. Peak BV at 60% 1-RM demonstrated a small yet nonsignificant decrease compared with 40%1-RM (Table 3.5).

Peak power showed a progressive increase from 40 to 120% and was maximised at 120%. Peak power at 120% showed moderate to large significant differences with 40-60% and trivial to small nonsignificant differences with all other loads (Table 3.5). Similarly, MP showed a progressive increase with load, with 140% resulting in the greatest power (Table 3.4). Mean power at 140% showed trivial to small nonsignificant differences with all loads (Table 3.5). Net impulse showed a progressive increase with the load with maximal impulse occurring at 120%. Net impulse at 120% showed a moderate significant difference to 40% and trivial to small nonsignificant differences with all other loads (Table 3.5).

3.6. DISCUSSION

The primary aim of this study was to investigate the effect of the inclusion of a countermovement on kinetic and kinematic variables during the MTP (CMS vs. MTP). The results reveal that the inclusion of the countermovement results in a large and significantly greater performance in all dependent variables when compared with the MTP, in line with our hypothesis. To the best of the authors' knowledge, this was the first study to compare the effects of the inclusion of a countermovement in weightlifting pulling derivatives. In line with our other hypotheses, an increase in load resulted in a decrease in velocity and an increase in force and impulse.

Meaningful significantly greater PF was observed during the CMS compared with the MTP, across all loads, and was maximised at 140% in both variations (Figure 3.3), in agreement with previous studies (52, 55). The PF reported in this study was lower than 1 study (52) but greater than another (55), which may be a result of lifting competence and body mass differences, considering the 1-RM PC values were similar between the current and previous studies. In addition, the previous studies demonstrated that PF increased by 8.8% (52) and 10.6% (55) across loads respectively, which is much lower than the 23% increase in this study.

Similarly, MF was greater during the CMS compared with the MTP, at all loads, and progressively increased with an increase in load and was maximised at 140% 1-RM, with moderate to large differences between variations (Figure 3.4). The use of MF as a kinetic measure in weightlifting derivatives has not been fully investigated. Although valuable performance characteristics, peak variables only represent instantaneous points during a given movement. During sporting movements, force is applied over time and not instantaneously; therefore, further research is needed to support the use of MF as a kinetic measure. However, as both PF and MF showed a progressive increase with load and maximised at the greatest load in both the variations, practitioners can use either kinetic variable as their choice of force measurement.

Peak velocity during the CMS showed significantly and meaningfully greater velocity compared with the MTP across loads (Figure 3.5). The greatest PV in the MTP occurred at 60% 1-RM, (Table 3.2) and decreased from 27% from 60 to 140% 1-RM. During the CMS, PV was maximised at 40% 1-RM (Table 3.4) and decreased by 17% from 40 to 140% 1-RM. These results indicate that practitioners seeking to improve the velocity of a loaded triple extension movement should prescribe loads of 40–80% of 1-RM PC during the MTP and CMS, but that the CMS is superior in terms of the actual velocities achieved (Figure 3.5).

The peak velocities in this study are lower than the hang PC (HPC), HHP, and JS peak, centre of mass (COM) velocities across loads of 30, 45, 65, and 80% 1-RM PC, as previously reported (316). Load PV main effect sizes showed that at 45% (>1.6$m \cdot s^{-1}$), 65% (>1.6$m \cdot s^{-1}$), 80% (>1.5$m \cdot s^{-1}$) 1-RM HPC, greater PV was produced during the HPC, HHP, and JS when compared with this study at similar loads; however, loads of >80% were not assessed. However, careful consideration must be made when directly comparing these findings to the aforementioned study as there are large differences in strength levels, assessed by 1-RM PC. In addition, the HPC, HHP, and JS started in the midthigh position and used a countermovement to the knee as opposed to the midthigh position in this study and, therefore, had a greater distance and duration to accelerate the barbell.

Furthermore, the JS is a weightlifting pulling derivative where the subject leaves the ground and therefore accelerates through a full range of motion through to take off (302). However, during the MTP and CMS and particularly at lower loads, there is likely a deceleration phase during the concentric phase as the subjects were encouraged not to jump off the platform. The PV values reported in this study are lower than the values reported previously, which investigated kinematics and kinetics of the JS (298, 316). Therefore, at lower loads, the JS may be a better exercise to develop greater velocities than the MTP and CMS.

Peak BV in the CMS demonstrated large to very large significant differences across all loads compared with the MTP (Figure 3.6). The greatest peak BV during the MTP occurred at 40% and was significantly greater than all loads except 60%. During the CMS, peak PV was maximised at 40% 1-RM, which showed a very large significant difference than all loads except than 60% 1-RM (Table 3.5).

The peak BV results are lower than the peak BV reported previously (52, 55), with Comfort et al. (52, 55) reporting a decrease in MTP peak BV of 69 and 49% from 40% 1-RM to 140% 1-RM, respectively, whereas this study showed a decrease of 37% for MTP (Table 3.2) and 35% for CMS (Table 3.4); which may be a result of lifting competency between subjects. Although 1-RM PC measurements are similar between studies, at the lower loads, it may be plausible that the subjects found it difficult in performing and coordinating weightlifting derivatives at loads that could be considered warm-up loads (40-60%), which ultimately resulted in lower peak BV than previously reported. It is also worth considering the ability of subjects to perform maximal effort pulling derivatives with loads as light as 40% 1-RM the same way they would perform at supramaximal loads.

Measurement of velocity in weightlifting derivatives are generally performed with a force plate or LPT (52, 55, 298, 299, 316). Moreover, devices that measure BV (i.e., LPT and accelerometers) are generally cheaper, easier to transport, and much more accessible to practitioners. The findings of this study showed that both system velocity and BV generally showed a progressive decrease with load, therefore, showing a similar trend. Although the peak BV resulted in greater velocities than PV, this may give an insight into the change in system velocity overloads. From a practical standpoint, as the system and bar velocities are different, practitioners should not use the devices interchangeably (198). It is likely that the lower reliability observed in system velocity compared with BV is likely because system velocity is calculated from force-time data, which assumes that velocity is zero during the period of quiet standing, which can vary, therefore, reducing reliability. This is more sensitive than the displacement-time data, where subtle changes in posture are unlikely to be sufficient for the LPT to identify movement and, therefore, a change in velocity.

There was significantly greater PP observed during the CMS compared with the MTP across all loads with large to very large effect sizes, highlighting the stimulation of the SSC allows for greater power to be produced as the athlete can overcome a greater force at a greater velocity (79). Therefore, it is recommended that S&C coaches should use the CMS when targeting power development as it may be preferred to the MTP.

Peak power during the MTP was maximised at 80% (2063 ± 491 W) 1-RM (Tables 3.2 and 3.3). This contrasts with the studies by Comfort et al. (52, 55) who reported that PP was maximised at 40% in both studies, with considerably higher PP values reported 3712.82 ± 254.38 W and 5451 ± 1552.3 W, respectively. Surprisingly, during the CMS, PP was maximised at 120% 1-RM, (Table 3.4 and Table 3.5). These findings suggest that higher loads are required to generate maximal power in the MTP and CMS. Given that PP was maximised at different loads in the both exercises, these findings agree with Soriano et al. (283) who suggests that the optimal load for power development may be exercise-specific.

These findings are not in agreement with Kawamori et al. (181) who reported system PP (2228.9 ± 192.3 W) was greatest at 60% of 1-RM when comparing loads of 30, 60, 90, 120% of 1-RM; however, no significant difference between loads was reported. Furthermore, Kawamori et al. (181) used collegiate weightlifters, which may partially explain power at the higher loads due to an increase competency in weightlifting derivatives. However, although this study did not use weightlifters, PP was maximised at higher loads (80-120%) (Figure 3.7), which may be partly explained by the inexperience of the subjects performing these movements at such high loads, with lower percentages typically observed when training the PC (141).

The optimal load for PP achieved in this study for the MTP is in line with PP achieved during the HPC and PC exercises (59, 64, 183, 299). However, several studies indicated that no statistical differences existed between the loads that produced the greatest PP at 60-80% 1-RM (49), 50-90% (64, 179, 183), and 30-80% (299).

It has been suggested that strength levels may influence the load that PP is obtained (292). Stone et al. (292) demonstrated that stronger athletes produced PP at 40% 1-RM when compared with weaker athletes (10% 1-RM) in the JS, when power was assessed through inverse dynamics. In this study, the average 1-RM PC 85.8 ± 21.7 kg is similar 87.6 ± 8.5 kg when compared with previous research (52), which would suggest no strength differences between studies. However, within this study, individual 1-RM PC ranged from 55 to 140 kg which shows a large variance in strength levels which may help to explain the similar values in PP across loads (1789 ± 537 W & 2063 ± 491 W) and PP attained at higher load. These findings highlight that PP may occur over a spectrum of loads, as previously reported (49, 179, 183). Therefore, as an athlete gets stronger, S&C coaches may be able to prescribe greater loads that will maximise power production. It should be noted that although reliable measures, there was high variability in MTP PP at 40 and 60% (Table 3.1).

During the CMS, MP was meaningfully and significantly greater than compared with the MTP at all loads (Figure 3.8). Surprisingly, during the CMS, MP showed a progressive increase with load, with 140% resulting in the greatest power (Table 3.4). This is likely explained by the fact that MF increased by 25.7%, whereas velocity decreased by 22.4% across loads (Table 3.4). Similarly, during the MTP, the greatest MP occurred at 120% 1-RM (Table 3.2 and Table 3.3). Mean force increased by 30% from 40 to 140%, whereas velocity decreased by 26.4% (Table 3.2). The subjects in this study appeared to accelerate loads faster, due to the relatively proportionate increases in forces and decrease in velocities, MP may be improved over a spectrum of loads. Moreover, the fact that there was not a large decrement in velocity at the heavier loads may suggest that the subjects are capable of a higher 1-RM PC; however, they may be limited by their ability to catch the barbell proficiently.

The CMS resulted in a large and significantly greater net impulse compared with the MTP across all loading conditions (Figure 3.9) and is likely due to the greater magnitudes of forces produced over greater duration through the inclusion of the countermovement. In this study, MTP net impulse showed a progressive increase with load and was maximised at 120% (Table 3.2), which was not statistically different to 60-100 and 140% (Table 3.3) which is in agreement with Comfort et al. (52, 55) who also demonstrated that impulse was maximised at higher loads (140%). This is expected, given that PF and MF were maximised at the greatest loads. In agreement with this study, Comfort et al. (52) demonstrated that although impulse was maximised at 140%, and it was not significantly different to 80-120%. Similarly, during the CMS, impulse increased with load and was maximised at 120% 1-RM (Table 3.4). As impulse has been shown to have a perfect correlation to jump height and is strongly related to change of direction and agility tasks (349), the use of the CMS may be preferred to the MTP when the focus is improving the aforementioned athletic tasks due to the greater impulse achieved at the same loads.

The findings of this study are not without their limitations. This study and previous studies calculated percentages based off the 1-RM PC, which includes the catch phase (52, 55). The MTP and CMS exercises theoretically have a greater 1-RM based on the decreased displacement and range of motion (301), and therefore there may be discrepancies in the effort that is produced. As loads of true maximal effort during pulling variations have not yet been investigated, the load percentages may not be a true reflection of weightlifting pulling ability and may in fact result in a greater 1-RM, and therefore greater loads during testing. The authors acknowledge that it may be impractical to perform 1-RM tests for certain movements due to the absence of criteria for what determines a successful repetition. Finally, future research should focus on investigating force-time characteristics with trained weightlifters to observe if similar results are produced during the CMS.

3.7. PRACTICAL APPLICATIONS

It is imperative for S&C practitioners to select exercises that maximises their athletes' capabilities and identify which strength quality is the primary focus. The CMS results in consistently higher kinetic and kinematic variables compared with the MTP across all loads. The results of this study demonstrate that the greatest peak velocities range from 40 to 60% 1-RM PC during both the MTP and CMS. By contrast, force and impulse are maximised at the higher loads of 120-140% 1-RM. In addition, if the goal is to maximise PP output, loads of 80–120% 1-RM PC are recommended during the MTP and CMS, while MP production was maximised at 120-140%. Furthermore, it is important to note that to train the entire force velocity continuum, a range of loads should be prescribed, in a periodised manner, incorporating a variety of exercises, as it seems that the optimal load for power production is exercise-specific (283, 301).

3.8. APPLIED RESEARCH PERSPECTIVE

Based upon the results of the above study, the CMS appears to be a preferential exercise to acutely maximise kinetics and kinematics compared to the MTP, likely due to the benefits of the SCC. As the displacement of the barbell is small (barbell at mid-thigh), these exercises are easy to perform. Future research should consider whether the differences are evident in weightlifting derivatives where barbell displacement is larger, and a greater ROM is performed, for example the clean pull from the knee and the hang pull.

The chapter below has been published in the Journal of Strength and Conditioning Research and the reference numbers in this thesis will differ from the published manuscript. Any typos and grammatical errors from the published manuscript have been amended in this version. The reference numbers have also been updated to reflect the references throughout the entire thesis.

Meechan, D, McMahon, JJ, Suchomel, TJ, and Comfort P. A comparison of kinetic and kinematic variables during the pull from the knee and hang pull, across loads. J Strength Cond Res 34 (7): 1819–1829, 2020

Chapter 4: Study 2- A Comparison of Kinetic and Kinematic Variables during the Pull from the Knee and Hang Pull, Across Loads

4.1. ABSTRACT

Kinetic and kinematic variables during the pull from the knee (PFK) and hang pull (HP) were compared in this study. Eighteen males (age = 29.43 ± 3.95 years; height 1.77 ± 0.08 m; body mass 84.65 ± 18.79 kg) performed the PFK and HP with 40, 60, 80, 100, 120, and 140% of 1-repetition maximum (1-RM) power clean, in a progressive manner. Peak force (PF), mean force (MF), peak system velocity (PSV), mean system velocity (MSV), peak power (PP), mean power (MP), and net impulse were calculated from force-time data during the propulsion phase. During the HP, small-to-moderate yet significantly greater MF was observed compared with the PFK, across all loads ($p \leq 0.001$; Hedges $g = 0.47$-0.73). Hang pull PSV was moderately and significantly greater at 100–140% 1-RM ($p = 0.001$; $g = 0.64$-0.94), whereas MSV was significantly greater and of a large-to-very large magnitude compared with PFK, across all loads ($p < 0.001$; $g = 1.36$-2.18). Hang pull exhibited small to moderate and significantly greater ($p \leq 0.011$, $g = 0.44$-0.78) PP at 100-140%, with moderately and significantly greater ($p \leq 0.001$, $g = 0.64$-0.98) MP across all loads, compared with the PFK. Hang pull resulted in a small to moderate and significantly greater net impulse between 100 and 140% 1-RM ($p = 0.001$, $g = 0.36$-0.66), compared with PFK. The results of this study demonstrate that compared with the PFK, the HP may be a more beneficial exercise to enhance force-time characteristics, especially at loads of ≥1-RM.

4.2. INTRODUCTION

The implementation of weightlifting movements and their derivatives are commonly included in training programs in an attempt to improve athletic performance characteristics such as power and force (307), because of their ability to develop the rapid triple extension movement of the hips, knees, and ankles (plantar flexion), which are performed in a multitude of sporting tasks (36, 301, 302). Hence, performance during weightlifting movements has been shown to be correlated with sprint, jump, and change of direction performance (154).

Weightlifting exercises and their derivatives are frequently implemented because of their similarities with sport-specific movements (36), as they allow for the expression of moderate to high loads, with minimal, if any, deceleration during the concentric/propulsion phase. Previous cross-sectional research indicated that weightlifting pulling derivatives (i.e., those that exclude the catch phase) may provide a comparable (45, 46) or greater (56, 301, 302, 307, 313, 314, 316) training stimulus compared with catching derivatives. Furthermore, the results of a recent training study demonstrated that no differences existed in force-time variables, assessed during dynamic and isometric assessments, when either catching or pulling derivatives were used (47).

A plethora of the literature examining weightlifting derivatives has investigated the kinetic and kinematic characteristics of the second pull, described by DeWeese and Scruggs (79) as the phase commencing from the midthigh position, with research demonstrating that the second pull phase produces the greatest vertical force and power applied to the barbell, in experienced weight- lifters during the clean, snatch, and power clean (91, 286).

When investigating the kinetic differences between the power clean, power clean from the knee, midthigh power clean, and mid- thigh pull (MTP), investigators concluded that greater system power and force occurred with the midthigh variations, with no significant difference between these variations (45, 46). Additionally, weightlifting pulling derivatives have been shown to produce greater peak power (PP), peak force (PF), peak velocity (PV), rate of force development, impulse, and work when compared with the hang power clean (188, 313, 314, 316). Furthermore, pulling derivatives permit the use of supramaximal loads (>100% 1-repetition maximum [1-RM] of a catching derivative), which have been shown to elicit greater force and impulse than loads ≥100% 1-RM power clean (52, 55, 181, 232), with an increase in load resulting in a greater force and impulse (52, 55, 232), and a decrease in velocity and power (52, 55), as would be expected.

Although researchers have previously investigated the force- time characteristics of weightlifting derivatives, no one has investigated the kinetic and kinematic differences between the pull from the knee (PFK) and hang pull (HP). It would be useful to identify if the addition or exclusion of the countermovement affects kinetic and kinematic variables during such exercises to determine if commencing from a static position (e.g., PFK) or stimulating the stretch shortening cycle (SSC) via starting with a countermovement (e.g., HP) is most beneficial for enhancing force-time characteristics. It should be noted that if athletes perform certain variations of a derivative, then this may place different physiological demands throughout a periodised training cycle. Depending upon the starting position and whether a countermovement or static start is used, a different stimulus may occur (302). Therefore, it is important for practitioner's to apply the most appropriate training stimulus at the correct time, based upon biomechanical and physiological characteristics (301). The way these movements are performed (i.e., one from a static position (PFK) and the other initiated with a countermovement [HP]) may allow athletes to develop greater concentric force-time characteristics (force, impulse, power) when initiated with a counter- movement. A recent study demonstrated that initiating a pulling derivative with a prior countermovement (countermovement shrug) resulted in greater kinetic (force, impulse, and power) and kinematic (system and barbell velocity [BV]) values when compared with a static start (MTP) during the propulsive phase (232), which is likely because of the stimulation and utilisation of the SCC (79, 333). Briefly, the SSC is a naturally occurring muscle function whereby the muscle is immediately lengthened before shortening. This produces a more powerful muscle action than that which would result from a concentric action alone (96), via the storage and release of elastic energy and the neurological potentiation via the stimulation of the muscle spindle (333).

The purpose of this study was to investigate the inclusion of a countermovement on kinetic and kinematic variables during the PFK, across loads of 40-140% 1-RM. A secondary aim was to determine the influence of load on the kinetic and kinematic variables during the PFK and the HP. It was hypothesised that the inclusion of the countermovement, during the HP, would result in higher kinetic and kinematic values across all variables. It was further assumed that force and impulse would increase with load, whereas system power and velocity would decrease with an increase in load, in line with previous research (52, 55). The results of this study should help to inform S&C coaches regarding programming options for the HP and PFK, to optimise kinetic and kinematic outputs.

4.3. METHODS

4.3.1. Experimental Approach to the Problem

A within-subject repeated-measures research design was used to compare the kinetic (peak and mean force [MF] and power, and net impulse) and kinematic (peak and mean system velocity

[MSV], peak BV) variables of the PFK and HP. The above- mentioned variables were measured by the subject performing all lifts on a force plate, and BV assessed with a linear position transducer (LPT), using progressive loads of 40, 60, 80, 100, 120, and 140% 1-RM power clean (PC), to determine differences in kinematic and kinetic variables within and between variations across loads. Progressive loads were used to ensure ecological validity and to minimise risk of injury during the heavier loads. Before the experimental trials, subjects visited the S&C facility on 2 occasions (5–7 days apart), at the same time of day, to establish 1-RM PC reliability, following the protocol previously used in similar research (52, 55). The PFK and HP testing sessions were performed on 2 separate days (5-7 days apart) in a randomised order to minimise fatigue and prevent an order effect.

4.3.2. Subjects

Eighteen male subjects from various level sports (mean ± SD age, 29.43 ± 3.95 years; height, 1.77 ± 0.08 m; body mass, 84.65 ± 18.79 kg; resistance training experience, 5.94 ± 1.43 years; experience in weightlifting exercises, 3.50 ± 1.34 years; 1-RM PC, 85.83 ± 21.70 kg) who participated in regular resistance training, volunteered to participate in this study. Subjects were free from injury and provided written informed consent before the commencement of testing. Subjects were requested to perform no strenuous activity during the 48 hours before testing, maintain their normal dietary intake before each session, and attend testing sessions in a hydrated state. This investigation received prior ethical approval from the University of Salford Institutional Ethics Committee and conformed to the principles of the World Medical Association's Declaration of Helsinki.

4.3.3. Procedures

One-Repetition Maximum Power Clean Testing

Each subject's 1-RM PC was assessed following a standardised protocol (8). For a detailed description of the protocol, see additional detail in study 1, (Section 3.3.3 page 107).

Hang Pull vs. Pull from the Knee Testing

Each subject completed a standardised warm-up, low intensity cycling for 5 minutes, followed by 1 set of 3 repetitions of a randomly assigned variation (either PFK or HP) at 40% 1-RM PC. The subjects were then required to complete the assigned variation at intensities of 40, 60, 80, 100, 120, and 140% of their predetermined 1-RM in a progressive order (40-140%) to replicate the progression of loads that occur in training sessions. Three repetitions were performed at each load with 30-60 seconds of rest between repetitions and 3-4 minutes of rest between loads to minimise fatigue (18 repetitions total) in line with the previous literature (52, 55). The barbell was placed on the safety bars of the power cage in between all repetitions to prevent fatigue in both variations. Once the body was stabilised (verified by observing the subject and force-time data), the lift was initiated with the countdown "3, 2, 1 go," and all subjects were instructed to exert maximal intent during each repetition. All lifts were performed in a power cage (Fitness Technology, Adelaide, Australia) on the Fitness Technology 700 ballistic measurement system with integrated force plate (400 Series) sampling at 600 Hz, interfaced with a desktop computer and ballistic measurement software. Verbal encouragement was provided throughout testing. During all repetitions, subjects were required to use lifting straps for standardisation and to reduce technique breakdown because of loss of grip at higher loads.

During both variations, the subjects had to perform the transition (knee to midthigh position), second pull, and then control and decelerate the barbell as it descended from its maximum displacement. Any repetitions that were initiated with a countermovement (identified by visual inspection of the force-time data) were disallowed and repeated after a further 30-60 seconds of rest period. Testing was finished upon successful completion of all the repetitions across all loads (18 repetitions).

For the PFK (Figure 4.1), the subjects lowered the barbell to just above the patella, paused for 3 seconds to minimise the effect of the SSC, and then performed the exercise, ensuring a triple extension of the hips, knees, and ankles (plantar flexion) and a shrug that moved the barbell in a vertical plane, while maintaining elbow extension (56). For the HP (Figure 4.2), the subjects started each movement in a standing position, with their knees slightly bent and the barbell positioned at the midthigh (52, 55). The subjects then performed a countermovement by flexing at the hip, while maintaining their knee angle and lowering the barbell to a position just above their patella. Upon reaching this position, the subjects immediately transitioned back to the midthigh position by flexing their knees and extending their hips to bring their torso to an upright position followed immediately by a rapid triple extension of the hip, knee, and ankle (plantar flexion) and a shrug that moved the barbell in a vertical plane while maintaining elbow extension (i.e., second pull) in 1 continuous movement. Blocks were not used as the system mass would change on the force plate (from body weight + bar mass) once the bar was lifted from the blocks, which would affect the subsequent calculation of velocity and therefore power, so a pause at the knee was performed to ensure this (46).

Figure 4.1-Sequence of the pull from the knee

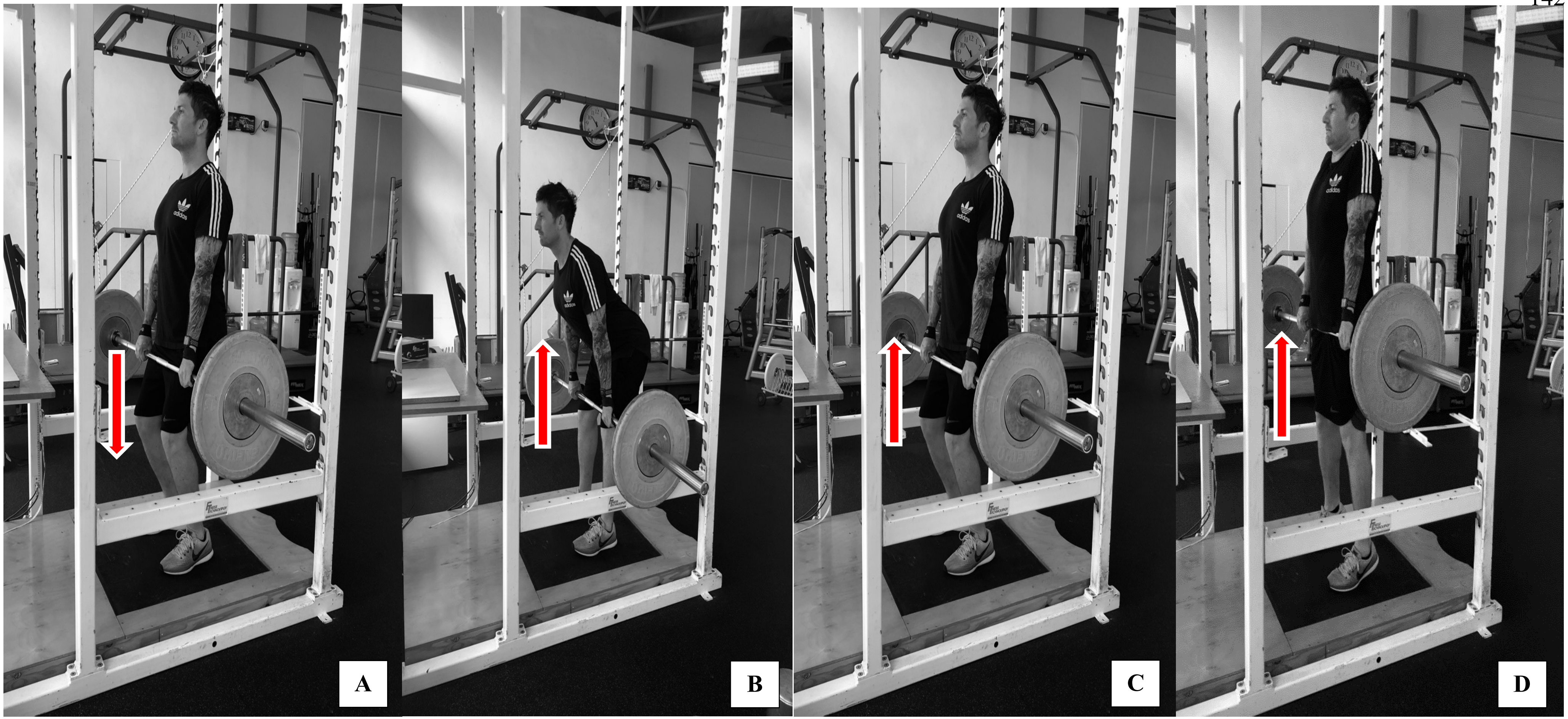


Figure 4.2- Sequence of the hang pull. A) Descent including unweighting and braking phases, B) End of braking/start of propulsion, C) Transition to power position, D) Second pull/Triple extension

Force-Time Data Analysis

Force-time data analysis for the HP were conducted using a forward dynamics approach, using identical methods outlined in study 1, (Section 3.3.3, page 112).

Measurement of Barbell Velocity

Peak BV was measured using an LPT and was determined as the greatest velocity during the second pull phase (GymAware Power Tool Kinetic Performance Technologies, Canberra, Australia) with data transmitted via Bluetooth to a tablet (iPad; Apple Inc., Cupertino, CA). Peak BV was obtained via differentiation of the barbell displacement-time data.

4.4. STATISTICAL ANALYSES

Statistical analyses were performed using Statistical Package for the Social Sciences software version 24 (SPSS, Chicago, IL). For each variable, the mean output of the 3 pull trials was taken forward for statistical analysis. A 2-way fixed effects model intraclass correlation coefficients (ICCs) and coefficients of variation (CV) were used to determine reliability and variability of performance measures using the criteria of Cortina (69), where ICC of > 0.80 is considered highly reliable and a CV of ≤ 10% was considered to be reflective of acceptable variability (57). Distribution of data were analysed via Shapiro-Wilks's test of normality, with differences between exercises determined using a series of paired samples t-tests or Wilcoxon's test, at each load, with the resultant p values corrected using Bonferroni's correction. Standardised differences were calculated using Hedges' g effect sizes as previously described (148) and interpreted according to Hopkins et al. (152), which defined values as trivial (≤ 0.19), small (0.20-0.59), moderate (0.60-1.19), large (1.20-1.99), and very large (2.0-4.0). An a priori alpha level was set at $p < 0.05$. Subsequently, the effect of load was determined using a contrast analysis and Hedges' g effect sizes to determine the magnitude of main effects across loads. Because it was assumed that force and impulse would increase with load, and system power and velocity would decrease with an increase in load, lambda weights were assigned to each corresponding load, with PF, MF, and net impulse assigned weights of -5, -3, -1, 1, 3, and 5, whereas PV, MV, peak BV, PP, and MP were assigned with 5, 3, 1, -1, -3, and -5, respectively.

4.5. RESULTS

Power clean 1-RM performances were highly reliable (ICC = 0.988; 95% confidence interval = 0.968–0.995) between sessions 1 (84.17 ± 21.64 kg) and 2 (85.28 ± 20.09 kg). All PFK variables demonstrated acceptable reliability and variability except for MSV at 60% (ICC = 0.638) and 120% 1-RM (ICC = 0.565) (Table 4.1). All HP variables demonstrated acceptable reliability and variability except for peak BV at 40% (ICC = 0.660) and 80% 1-RM (ICC = 0.676).

Table 4.1-Intraclass correlation coefficients and coefficients of variations of kinetic and kinematic variables during the PFK and HP

	Intensity	**40%**		**60%**		**80%**		**100%**		**120%**		**140%**	
Variable	**Exercise**	**ICC**	**%CV**	**ICC**	**%CV**	**ICC**	**%CV**	**ICC**	**%CV**	**ICC**	**%CV**	**ICC**	**%CV**
Peak Force	PFK	0.962	2.3%	0.982	2.3%	0.971	2.4%	0.990	2.0%	0.976	2.3%	0.987	1.9%
	HP	0.969	2.8%	0.917	3.6%	0.953	3.2%	0.987	1.8%	0.967	2.7%	0.975	2.5%
Mean Force	PFK	0.961	3.0%	0.951	3.1%	0.969	2.5%	0.975	2.5%	0.976	2.6%	0.967	3.0%
	HP	0.968	3.0%	0.948	2.9%	0.971	2.8%	0.995	1.3%	0.989	2.0%	0.991	1.7%
Peak Velocity	PFK	0.954	2.0%	0.937	2.7%	0.883	2.8%	0.976	1.3%	0.977	1.6%	0.973	1.7%
	HP	0.931	2.0%	0.969	1.3%	0.964	1.3%	0.920	1.5%	0.970	1.2%	0.955	1.8%
Mean Velocity	PFK	0.787	6.1%	0.638	6.6%	0.837	3.5%	0.726	5.8%	0.565	8.4%	0.712	6.7%
	HP	0.885	3.3%	0.858	4.2%	0.916	3.4%	0.914	3.4%	0.906	3.4%	0.941	3.0%
Peak Power	PFK	0.901	4.5%	0.971	3.9%	0.902	4.2%	0.981	2.2%	0.974	3.0%	0.986	2.1%
	HP	0.952	4.5%	0.973	3.1%	0.978	2.0%	0.968	2.9%	0.974	2.3%	0.980	2.6%
Mean Power	PFK	0.882	4.8%	0.937	4.6%	0.926	4.1%	0.956	4.2%	0.904	5.8%	0.929	4.8%
	HP	0.970	2.6%	0.969	3.1%	0.969	3.2%	0.984	2.6%	0.983	2.8%	0.975	2.9%
Impulse	PFK	0.971	2.2%	0.983	2.7%	0.956	2.7%	0.982	1.9%	0.989	1.7%	0.985	1.6%
	HP	0.987	1.9%	0.986	1.6%	0.992	1.2%	0.998	1.6%	0.993	1.2%	0.987	1.9%
Barbell Velocity	PFK	0.835	4.2%	0.868	2.6%	0.828	2.9%	0.789	3.9%	0.915	2.7%	0.914	3.6%
	HP	0.660	3.8%	0.820	2.1%	0.676	3.8%	0.819	2.5%	0.892	2.6%	0.927	2.4%

PFK = Pull from knee; HP = Hang Pull; ICC = Intraclass correlation coefficient; %CV = percentage coefficient of variation

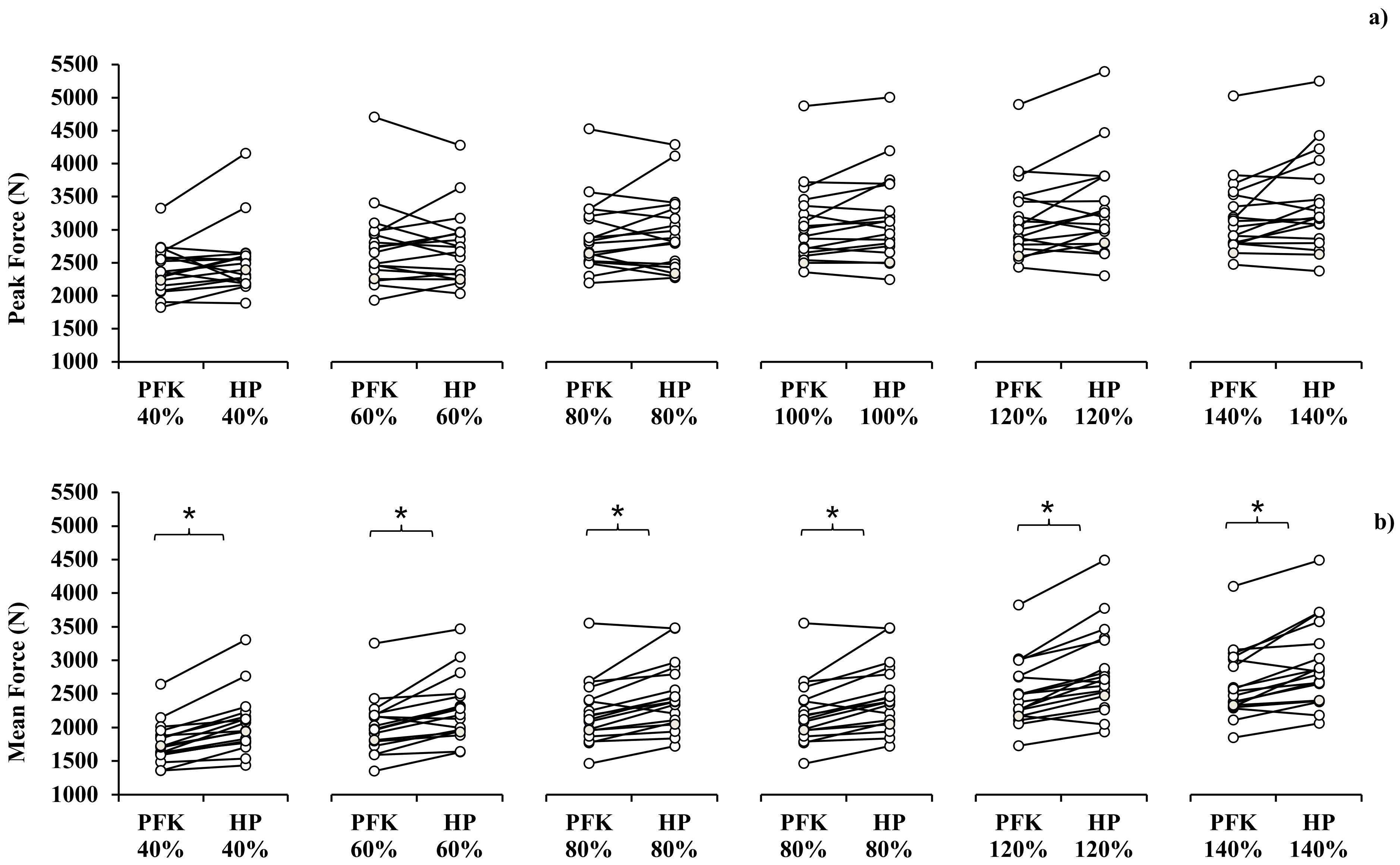
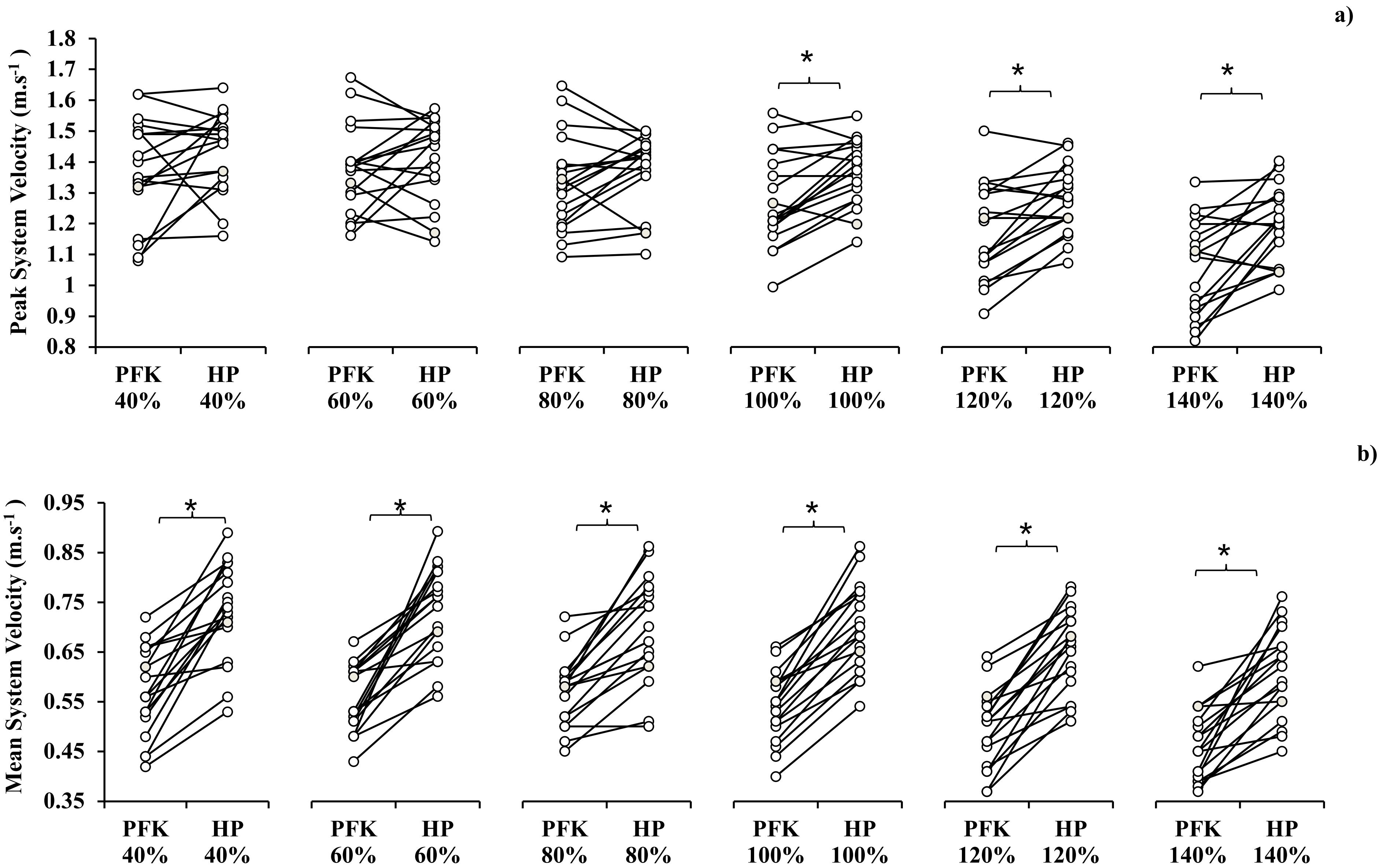


Figure 4.3-Comparison of individual differences peak (a) and mean (b) force between pull from knee (PFK) and hang pull (HP) across % 1-RM load in trained male participants (n=18). Note: * Denotes significant difference between PFK and HP ($p \leq 0.001$)


a)
Peak System Velocity (m.s-1)
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
*
PFK 40%
HP 40%
PFK 60%
HP 60%
PFK 80%
HP 80%
PFK 100%
HP 100%
PFK 120%
HP 120%
PFK 140%
HP 140%
b)
Mean System Velocity (m.s-1)
0.95
0.85
0.75
0.65
0.55
0.45
0.35

c)

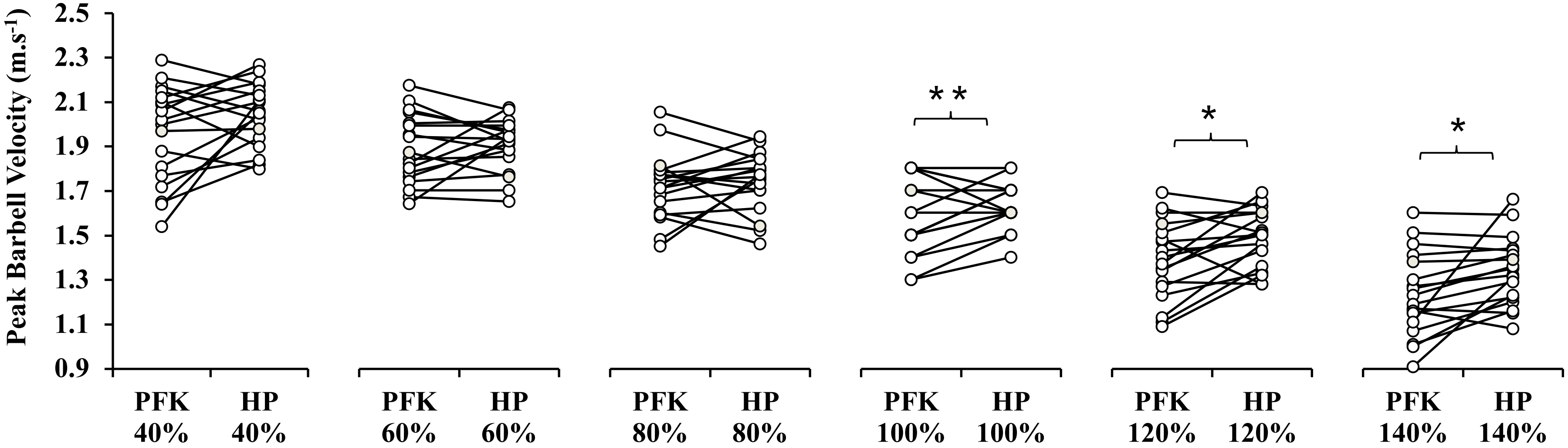


Figure 4.4-Comparison of individual differences peak (a), mean (b) and peak barbell velocity (c) between pull from knee (PFK) and hang pull (HP) across % 1-RM load in trained male participants (n=18). * Denotes significant difference between PFK and HP ($p \leq 0.011$)

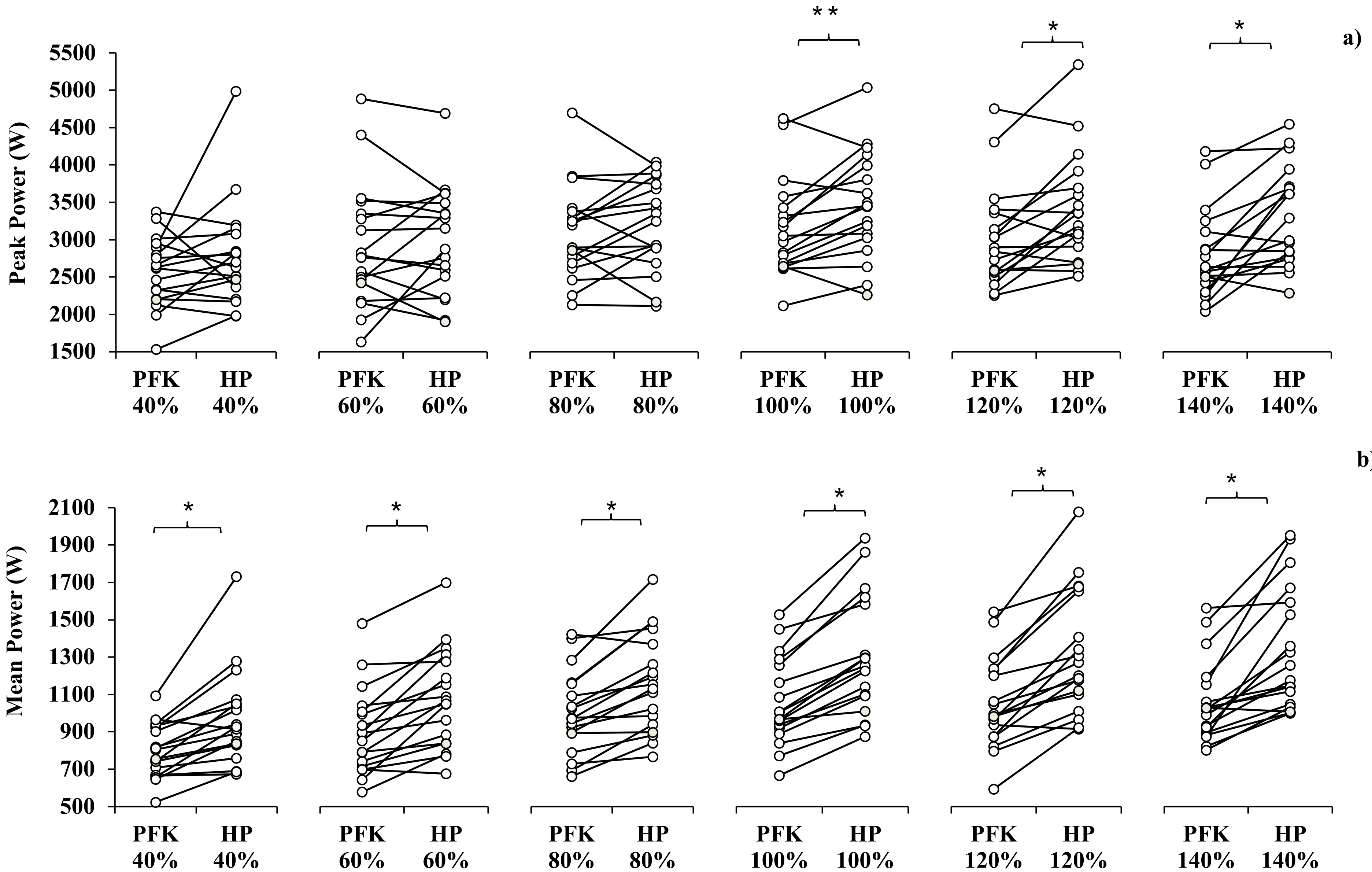


Figure 4.5-Comparison of individual differences in peak (a) and mean (b) power between pull from knee (PFK) and hang pull (HP) across % 1-RM load in trained male participants (n=18). * Denotes significant difference between PFK and HP ($p \leq 0.011$); ** Denotes significant difference between PFK and HP ($p = 0.002$)

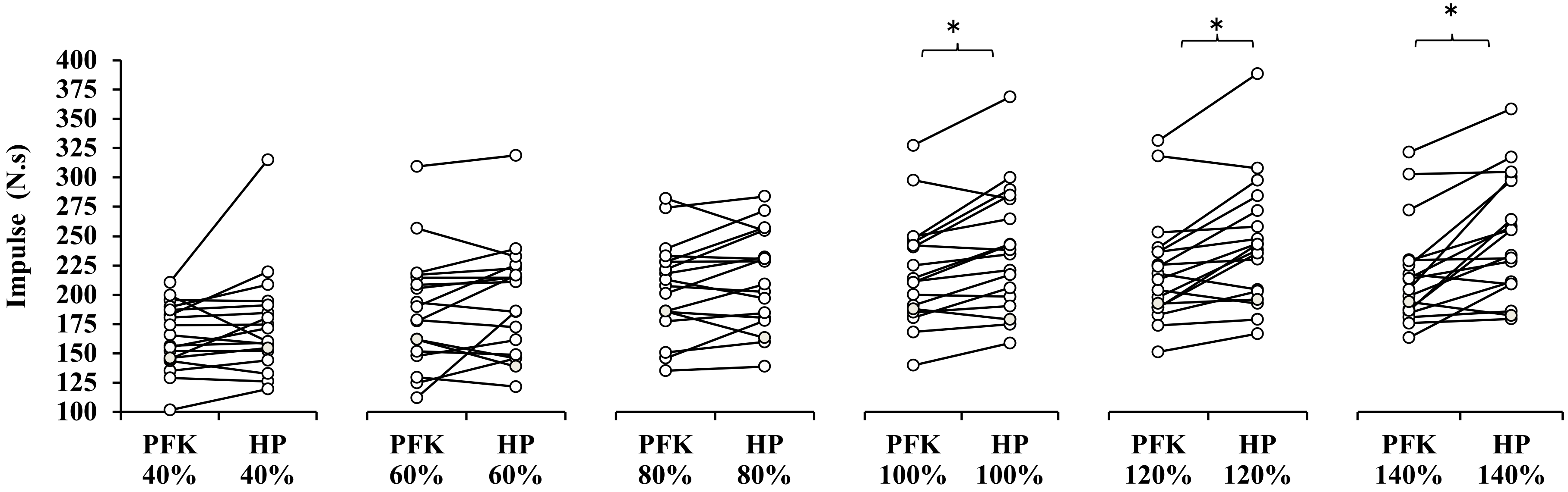


Figure 4.6-Comparison of individual differences in net impulse during the pull from knee (PFK) and hang pull (HP) across % 1-RM load in trained male participants (n=18). Note: * Denotes significant difference between PFK and HP (p = 0.001)

Comparisons Between Exercise Variations

There were trivial-to-small nonsignificant differences in PF between exercises across all loads (p > 0.05; g = 0.01–0.27) (Figure 4.3a). In contrast, there was a small to moderate, yet significantly greater MF in the HP compared with the PFK across all loads ($p \leq 0.001$; g = 0.47–0.73) (Figure 4.3b). Peak system velocity showed small nonsignificant differences between exercises at 40–80% 1-RM (p > 0.05; g = 0.34–0.45), although this was moderately and significantly greater (p = 0.001; g = 0.64–0.94) during the HP compared with the PFK at 100–140% 1-RM (Figure 4.4a). Mean system velocity during the HP was significantly greater and of a large-to-very large magnitude, across all loads (p < 0.001; g = 1.36–2.18) compared with the PFK (Figure 4.4b). Similar to PSV, peak BV was consistently higher for the HP compared with the PFK, although this was small and nonsignificant (p > 0.05; g = 0.14–0.48) at 40–80% 1-RM but small to moderate and significant ($p \leq 0.033$, g = 0.49–0.63) between 100 and 140% 1-RM (Figure 4.4c).

Peak power was consistently higher in the HP compared with the PFK, although this was small and nonsignificant (p > 0.05; g = 0.10–0.36) between 40 and 80% 1-RM yet small to moderate and significant ($p \leq 0.011$; g = 0.44–0.78) between 100 and 140% 1-RM (Figure 4.5a). Mean power was moderately and significantly greater ($p \leq 0.001$; g = 0.64–0.98) during the HP across all loads when compared with the PFK (Figure 4.5b). Net impulse during the HP was consistently higher than the PFK (Figure 4.6), although this was trivial to small and nonsignificant (p > 0.05; g = 0.18–0.29) between 40 and 80% 1-RM, yet small to moderate and significant between 100 and 140% 1-RM (p = 0.001; g = 0.36–0.66).

Effect of Load on Kinetics and Kinematics During the Pull from the Knee

The linear contrast analysis revealed significant differences in PF, MF, PSV, MSV, MP, and net impulse across loads (all $p < 0.001$), whereas PP demonstrated no significant differences across loads during the PFK ($p > 0.05$).

Peak force progressively increased (t[102] = 4.828; $p < 0.001$; $g = 1.14$) with load with the greatest PF occurring at 140% 1-RM, with a moderate to large main effect. Similarly, MF progressively increased (t[102] = 6.719; $p < 0.001$; $g = 1.58$) as load increased, with the greatest MF achieved at 140% 1-RM, demonstrating a large main effect. Peak system velocity progressively decreased (t[102] = 6.406; $p < 0.001$; $g = 1.21$) across loads, with the greatest PSV occurring at 40% 1-RM (Table 4.2), with a large main effect across loads. Mean system velocity progressively decreased (t[102] = 5.151; $p < 0.001$; $g = 1.14$) across load, with the greatest MSV at 40% 1-RM (Table 4.2), with a moderate to large main effect across loads. Peak BV progressively decreased (t[102] = 14.986; $p < 0.001$; $g = 3.53$) across load, with the greatest BV occurring at 40% 1-RM (Table 4.2), with a very large main effect across loads. Peak power demonstrated progressive increase with an increase (t [102] = 1.197; $p > 0.05$; $g = 0.28$) in load from 40 to 100% 1-RMwith the greatest PP occurring at 100% 1-RM, with a small main effect. In contrast, MP progressively increased (t[102] = 4.261; $p < 0.001$; $g = 1.00$) with load with the greatest load occurring at 140% 1-RM, with a moderate main effect. Net impulse demonstrated a progressive increase (t[102] = 4.537; $p < 0.001$; $g = 1.07$) with load with the greatest net impulse occurring at 120% 1-RM, with a moderate to large main effect.

Table 4.2-Comparison of load on kinetic and kinematic variables during the pull from the knee

Intensity	Peak Force (N)	Mean Force (N)	Peak Velocity ($m.s^{-1}$)	Mean Velocity ($m.s^{-1}$)	Peak Power (W)	Mean Power (W)	Impulse ($N.s^{-1}$)	Barbell Velocity ($m.s^{-1}$)
40%	2404 ± 356	1762 ± 305	**1.37 ± 0.17***	**0.57 ± 0.09***	2563 ± 468	794 ± 143	164 ± 28	**1.96 ± 0.22***
60%	2735 ± 611	2016 ± 408	1.35 ± 0.18	0.55 ± 0.07	2903 ± 828	896 ± 230	186 ± 49	1.88 ± 0.16
80%	2890 ± 545	2211 ± 467	1.34 ± 0.16	0.57 ± 0.07	3089 ± 623	1001 ± 221	206 ± 40	1.72 ± 0.15
100%	3054 ± 592	2371 ± 487	1.29 ± 0.16	0.54 ± 0.07	**3143 ± 658***	1055 ± 233	220 ± 45	1.57 ± 0.17
120%	3148 ± 594	2505 ± 483	1.18 ± 0.16	0.49 ± 0.07	3007 ± 670	1049 ± 242	**220 ± 46***	1.38 ± 0.18
140%	**3179 ± 585***	**2628 ± 514***	1.07 ± 0.16	0.46 ± 0.07	2796 ± 596	**1057 ± 219***	216 ± 43	1.23 ± 0.19
*Peak performance in each variable								

Table 4.3-Comparison of load on kinetic and kinematic variables during the hang pull

Intensity	Peak Force (N)	Mean Force (N)	Peak Velocity ($m.s^{-1}$)	Mean Velocity ($m.s^{-1}$)	Peak Power (W)	Mean Power (W)	Impulse ($N.s^{-1}$)	Barbell Velocity ($m.s^{-1}$)
40%	2521 ± 512	2043 ± 437	**1.44 ± 0.13***	**0.73 ± 0.10***	2782 ± 707	968 ± 257	175 ± 44	**2.05 ± 0.14***
60%	2732 ± 555	2261 ± 470	1.41 ± 0.13	0.73 ± 0.09	2985 ± 719	1075 ± 263	195 ± 48	1.90 ± 0.12
80%	2945 ± 576	2444 ± 505	1.39 ± 0.13	0.69 ± 0.10	3205 ± 604	1159 ± 262	214 ± 41	1.74 ± 0.13
100%	3163 ± 672	2660 ± 582	1.38 ± 0.11	0.70 ± 0.09	**3461 ± 741***	1296 ± 314	238 ± 53	1.64 ± 0.10
120%	3293 ± 732	2819 ± 636	1.29 ± 0.11	0.65 ± 0.08	3389 ± 629	1317 ± 327	243 ± 54	1.48 ±0.13
140%	**3360 ± 715***	**2910 ± 620***	1.21 ± 0.13	0.61 ± 0.09	3300 ± 664	**1335 ± 327***	**248 ± 51***	1.34 ± 0.15
*Peak performance in each variable								

Effect of Load on Hang Pull Kinetics and Kinematics

The linear contrast analysis revealed significant differences in PF, MF, PSV, MSV, MP, and net impulse across loads ($p \leq 0.004$), whereas PP demonstrated nonsignificant differences across loads during the HP ($p > 0.05$).

Peak force progressively increased (t[102] = 4.888; $p < 0.001$; $g = 1.15$) with load with the greatest PF occurring at 140% 1-RM, which showed a moderate to large main effect across loads. Similarly, MF progressively increased (t[102] = 5.773; $p < 0.001$; $g = 1.36$) as load increased, with the greatest MF achieved at 140% 1-RM, with a large main effect. Peak system velocity progressively decreased (t[102] = 6.153; $p < 0.001$; $g = 1.45$) across loads, with the greatest PSV occurring at 40% 1-RM, demonstrating a large main effect difference. Similarly, MSV progressively decreased (t[102] = 4.664; $p < 0.001$; $g = 1.10$) across loads, with the greatest PSV occurring at 40% 1-RM, with a moderate to large main effect. Peak BV was greatest at 40% 1-RM and showed a progressive decrease (t[102] = 18.984; $p < 0.001$; $g = 4.45$) across loads, with a very large main effect. Peak power progressively increased (t[102] = 2.967; $p = 0.004$; $g = 0.70$) with load from 40 to 100% and was maximised at 100% 1-RM, demonstrating a moderate main effect. Similarly, MP showed a progressive increase (t[102] = 4.670; $p < 0.001$; $g = 1.10$) as load increased and was greatest at 140% 1-RM, demonstrating a moderate to large main effect. Net impulse progressively increased (t[102] = 5.621; $p < 0.001$; $g = 1.32$) with load with the greatest magnitude occurring at 140% 1-RM, demonstrating a moderate to large main effect.

4.6. DISCUSSION

The primary aim of this study was to investigate the effect of the inclusion of a countermovement on whole-body kinetic and kinematic variables during the pull from knee

(HP vs. PFK). The results reveal that the inclusion of the countermovement (HP) resulted in a significantly greater MF, MSV, and MP across all loads, compared with the PFK. In addition, the HP demonstrated significantly greater PSV, BV, PP, and net impulse compared with the PFK across loads of 100–140% 1-RM. To the authors' knowledge, this is the first study to compare the effects of the inclusion of a countermovement in weightlifting pulling derivatives from the knee. In line with our other hypotheses, an increase in load resulted in a decrease in velocity and an increase in force and impulse.

There were small to trivial nonsignificant greater PF during the HP compared with the PFK, across all loads except 60% 1-RM. The minimal difference at 60% could be a result of a lack of true effort at this load, which is likely a warm up-load when the subjects are regularly performing at the exercises with loads of >100% 1-RM PC. These findings highlight that initiating the movement with countermovement may provide greater force characteristics across loads a spectrum of loads; however, coaches need to ensure that subjects perform a maximal effort at each load.

The results of the current study are in line with previous research during weightlifting pulling derivatives which indicated that the greatest loads result in the greatest PF (52, 55, 181, 232, 300). Although the maximal PF reported in this study was greater than one study (55) and lower than another (52), the differences are likely a result of lifting competence and BW differences considering the 1-RM power clean values were similar between studies. Additionally, because the subjects in this study performed derivatives which included the transition phase, it may be possible that the subjects had problems maintaining positional strength at loads >1-RM. However, further kinematic research (e.g., 3-D motion analysis) is needed to answer this question.

Similar to PF, MF was also maximised at the greatest load, however, in contrast to PF, MF during the HP was meaningfully and significantly greater in the HP than the PFK across all loads. Although valuable performance characteristics, peak variables only represent instantaneous points during an athletic movement, however during sporting movements, force is applied over time. Whilst peak force values have been reported in several weightlifting derivative studies, mean force has not been reported (52, 55, 301, 302). Peak and mean force in both variations were highly reliable across all loads (Table 4.1; PF ICC $\geq$ 0.917; CV = 1.8-3.2%; MF ICC $\geq$ 0.948; CV = 1.3-3%). Therefore, it is likely that practitioners can select either measure, as both PF and MF showed a progressive increase with load and was greatest at the highest loads in both variations.

The HP PSV was significantly and meaningfully greater compared to PFK across loads of 100-140% 1-RM (Figure 4.4a), with only small non-significant differences at loads of 40-80%, highlighting that a countermovement should be performed to optimise velocity at loads $\geq$100% 1-RM. During the HP, PSV was maximised at 40% 1-RM and decreased by 16% from 40% to 140% 1-RM, whilst the greatest PSV in the PFK occurred at 40% 1-RM and showed a decrease of 21.9% from 40% to 140% 1-RM during the PFK. These results indicate that practitioners seeking to develop athlete's movement velocity during a pull from the knee should prescribe loads of 40-100% of 1-RM PC during the PFK and HP. In addition, the HP is superior in terms of the velocities achieved resulting in higher velocities at loads >100% 1-RM PC, with a smaller decrement in velocity as load increased from the smallest to greatest load.

Previous research in weightlifting pulling derivatives has shown that the lowest load results in the greatest velocities and the findings of this study substantiates this, and appears unaffected by the modality of the pulling derivative (298, 300). Suchomel et al. (300) investigated force-time characteristics during the hang high pull (HHP) and reported peak COM velocities of (2.05 ± 0.25 $m.s^{-1}$ and 1.95 ± 0.18 $m.s^{-1}$) for 30 and 45% 1-RM and (1.78 ± 0.14 and 1.68 ±0.14) $m.s^{-1}$) at 65 and 80% 1-RM HPC, which are greater than the velocities in this study. Differences in velocities are likely due to technical and strength ability between subjects in both studies. Additionally, Suchomel et al. (298) demonstrated jump shrug peak COM velocity values of (2.66 ± 0.16 and 2.27 ± 0.13 $m.s^{-1}$) for 30 and 45% 1-RM and (1.97 ± 0.16 and 1.79 ± 0.15 $m.s^{-1}$) at 65 and 80% 1-RM HPC respectively. However, the jump shrug is a weightlifting derivative where the subject leaves the ground and therefore accelerates through a full range of motion through to take off (302). However, during the PFK and HP and particularly at lower loads, there is likely a deceleration phase during the concentric phase of the lift as the subjects were encouraged not to jump off the platform. However, in light of the lower velocities produced in this study compared to a previous study (298), it may be more appropriate to prescribe the HP and CMS during a strength-speed phase (301) given the ability to use loads in >1-RM, whilst still achieving moderately high velocities. Mean system velocity during the HP was meaningfully and significantly greater compared to the PFK across all loads (Figure 4.4b) and was greatest at 40% in both the PFK (Table 4.2) and HP (Table 4.3) and showed a general decrease across loads. Further research is needed to investigate the benefit of mean force-time variables, however like PSV, there was a smaller decrease in velocity from 40-140% 1-RM during the HP (16.4%) (Table 4.3) compared to the PFK (19.2%) (Table 4.2). Practically, the inclusion of the countermovement may allow the lifter to maintain greater velocities as load increases.

Peak BV in the HP demonstrated small to moderate significant differences across loads of 100-140% 1-RM compared to the PFK (Figure 4.4c). Peak BV in both the HP and PFK was maximised at 40% 1-RM and showed a progressive decrease in load, although the HP produced significantly greater BV at all loads. Additionally, during the PFK and HP, there was a velocity decrement of 37.2% (Table 4.2) and 36.3% (Table 4.3) from 40% to 140% 1-RM, respectively. The findings in the current study agree with previous research during the MTP, where BV was maximised at 40% and showed a progressive decrease with an increase in load (52, 55). When performing the MTP from a static position, Comfort at al. (52) found that 40% 1-RM was not significantly different to 60%, which is in agreement to this study, with similar BV values reported in both studies. However, in the current study, when initiating the pull with a countermovement, differences occurred between 40% and all loads (Table 4.3). Differences in velocities between studies are likely attributed to differences is start position at the knee compared to the mid-thigh position, and therefore had a greater distance and time to accelerate the barbell. It is also worth considering the ability to perform maximal effort with loads as light as 40% 1-RM with the same intent performed at supra-maximal loads, as there will very likely be a deceleration at lower loads in non-ballistic variations (247). Finally, it appears that both BV or system velocity can be used by practitioners as a similar trend was observed when load increased; however, they should not be used interchangeably (198).

It should be noted that the greater variability observed in the PFK compared to the HP is likely a result of holding the barbell at the knee position. It is likely that the lower reliability observed in system velocity compared to barbell velocity is likely because system velocity is calculated from force-time data, which assumes that velocity is zero during the period of quiet standing, which can vary, therefore, slightly reducing reliability of these measures.

There was significantly greater PP observed during the HP compared to the PFK across loads of 100-140% 1-RM, with consistently higher PP with the inclusion of the countermovement. Therefore, it is recommended that S&C coaches should use a countermovement in the PFK to develop power at loads ≥ 1-RM PC. During the HP, PP was maximised at 100% (Figure 4.5a). Similarly, PP during the PFK was also maximised at 100% 1-RM (Table 4.2), highlighting that initiating the pull with a countermovement may accelerate higher loads at greater speed. These findings are in contrast to other pulling derivatives, that indicate PP is maximised at lower loads in the MTP (52, 55, 124, 181), jump shrug (298, 316) and HHP (300, 316, 323). However, it should be noted that no significant differences existed across loads of 30-120% 1-RM (181), 80-100% (124), 40-60% (55) during the MTP, 30-45% (300) , 30-60% (323) during the HHP and 30-45% during the jump shrug (298). Comfort et al. (52) demonstrated a decrease in BV of 49% with an increase in PF of 8.8% during the MTP compared to (34.6% and 33.2%) during the HP and (37.2% and 32.1%) during the PFK in this study. The similar increases in force and decrease in velocity likely explains why PP occurred at greater loads in this study in both variations compared to the above study.

The PP values at loads of 80% and 100% 1-RM are greater than the values previously reported at similar loads (2440.2 ± 236.9 W, 2404.0 ± 251.0 W, respectively), which may be a result of the MTP being initiated from the blocks (124). Further, the PP values at 80% in this study are much less that the values presented by Suchomel et al. (300) (4190.3 ± 812.80 W) during the HHP when the movement was performed from the knee and initiated with a countermovement, which is similar to the HP, although a HHP results in a much greater vertical displacement. Differences are likely a result of strength differences and the velocities achieved between that study and this one. From a practical standpoint, the HP should be performed to target PP development instead of the PFK as PP was consistently higher in the HP at all loads compare to the PFK. It seems that using a variety of loads targeting the entire force-velocity curve may be more appropriate to develop power due to similarities in power across a spectrum of loads (122, 301, 302).

Mean power was meaningfully and significantly greater during the HP when compared to the PFK at all loads (Figure 4.5b), although MP in both variations showed a progressive increase with an increase in load and was maximised at 140% 1-RM.These findings are likely explained by MF increasing by 29.8%, whilst velocity only decreased by 16.4% across loads. Similarly, during the PFK, MP at 140% which was likely a result of an increase in MF of 33% from 40-140%, and a decrease in velocity by 19.3%.

The HP resulted in a small to moderate significantly greater net impulse compared to the PFK across loads of 100-140%, but not 40-80%, although it was consistently greater during the HP. The greater net impulse between the HP and PFK is likely due to the greater magnitudes of forces produced over greater duration through the inclusion of the countermovement. Impulse is defined as the product of the force magnitude and the time over which it is expressed (313) , and has been shown to have a perfect correlation to jump height and is strongly related to change of direction and agility tasks (349). In this study, PFK net impulse showed a progressive increase with load and was maximised at 120% (Table 4.2). During the HP, impulse increased with load and was maximised at 140% (Table 4.3). These findings agree with other authors that demonstrated that the greatest loads resulted in the greatest impulses in pulling derivatives (52, 55, 313). In agreement to this study, Comfort et al., (52) demonstrated that although impulse was maximised at 140%, it was not significantly different to 80-120%. It is evident that as load increases, a countermovement variation should be used to develop greater net impulse as it consistently produced a greater impulse regardless of load.

The findings of this study are not without their limitations. This study and many previous studies have investigated force-time characteristics of weightlifting pulling derivatives using loads that have been calculated from the 1-RM of a weightlifting catching variation (55, 124, 181, 298, 300, 307, 313, 314, 316). The PFK and HP exercises theoretically have a greater 1-RM based on the omission of the catch phase, decreased load displacement, and ROM (301), and therefore there may be discrepancies in the effort that is produced across each load. The authors acknowledge that it likely impractical to perform 1-RM tests for certain pulling movements due to the absence of criteria for what determines a successful repetition.

As loads of true maximal effort during pulling variations have not yet been investigated, the prescribed load percentages may not be a true reflection of weightlifting pulling ability and may in fact result in a greater 1-RM, and therefore greater loads during testing. The authors acknowledge that the load that maximises peak BV during the HP and PFK may be at loads < 40% 1-RM, however these loads were not tested as not to induce fatigue by performing excessive repetitions and a lack of true maximal effort by the participants. When comparing individual differences in kinetic and kinematic variables between both the PFK and HP, it is evident that the inclusion of the countermovement did not always result in values as one would likely expect, due to the stimulation of the SSC. This may be due to many effects such as individual competency in the movements, lack of true effort, difficulties in effectively using the SCC over a greater ROM in both accelerating and/or decelerating the barbell. Additionally, some subjects, depending on their familiarity with performing supramaximal pulling derivatives, may find it fatiguing to hold a static position prior to the initiation of the pull. Similarly, as there is a paucity of literature in snatch derivatives, it is recommended that future research investigated snatch pulling derivatives to determine if there are difference in force-time characteristics between clean and snatch derivatives.

4.7. PRACTICAL APPLICATIONS

It is imperative for S&C coaches to select exercises that maximise their athletes' athletic capabilities and identify which muscle strength quality is the primary focus throughout the training cycle. The HP results in consistently higher kinetic and kinematic variables compared to the PFK across all loads, although only significantly and meaningfully greater at all loads in MF, MP and MSV, whilst significant differences were evident at loads ≥100% for PV, BV, PP, and net impulse. The results of this study demonstrate that the greatest force and impulse is maximised at the higher loads, while in contrast, the greatest PSV range occurs at lighter loads, during both the PFK and HP. It is important to note that in order to train the entire load–velocity curve and facilitate adaptations across the force-velocity profile that a range of loads exercises should be prescribed in a sequenced and periodised manner, as it appears that the load maximises kinetic and kinematic outputs is exercise specific and occurs across a spectrum of loads (122, 283).

4.8. APPLIED RESEARCH PERSPECTIVE

Based upon the results of the above study, the HP appears to be a preferential exercise to acutely maximise kinetic and kinematic outputs compared to the PFK across loads, likely due to the benefits of the SCC. Whilst gross measures are important, these findings only provide a basic understanding on kinetics and kinematics, and important information regarding the effect of loading on the entire movement strategy may be overlooked. Therefore, it is suggested that a more detailed analysis of the entire movement, across the force-time waveform may show how these gross measures are achieved throughout the movement, and how this differs between loads.

The chapter below has been accepted for publication in the Journal of Sports Sciences and the reference numbers in this thesis will differ from the published manuscript. Any typos and grammatical errors from the published manuscript have been amended in this version, with the reference numbers in line with the references throughout the thesis.

Chapter 5: Study 3- Comparing Biomechanical Time Series Data Across Countermovement Shrug Loads

5.1. ABSTRACT

The effect of load on time series data has yet to be investigated during weightlifting derivatives. This study compared the effect of load on the force-time and velocity-time curves during the countermovement shrug (CMS). Twenty-nine males performed the CMS at relative loads of 40, 60, 80, 100, 120, and 140% one repetition maximum (1-RM) power clean (PC). A force plate measured the vertical ground reaction force (VGRF), which was used to calculate the barbell-lifter system velocity. Time series data were normalised to 100% of the movement duration and assessed via statistical parametric mapping (SPM). SPM analysis showed greater negative velocity at heavier loads early in the unweighting phase (12-38% of the movement), and greater positive velocity at lower loads during the last 16% of the movement. Relative loads of 40% 1-RM PC maximised propulsion velocity, whilst 140% 1-RM maximised force. At higher loads, the braking and propulsive phases commence at an earlier percentage of the time-normalised movement, and the total absolute durations increase with load. It may be more appropriate to prescribe the CMS during a maximal strength mesocycle given the ability to use supramaximal loads. Future research should assess training at different loads on the effects of performance.

5.2. INTRODUCTION

Numerous researchers have investigated gross kinetic and kinematic differences in weightlifting derivatives. These have included the power clean [PC] (45-47), hang power clean (185, 188, 316), countermovement shrug (CMS) (232), mid-thigh pull (52, 232), snatch pull (169), hang pull (230), hang high pull (306, 307), pull from the knee (56, 230) and jump shrug (185, 188, 298, 306, 307, 316). Researchers have investigated the kinetic and kinematic characteristics of the second pull, commencing from the mid-thigh ('power') position (79), and have reported that this phase produces the greatest force and power in experienced weightlifters during the clean, snatch and PC (91, 286). Additionally, the result of previous cross-sectional research indicates that weightlifting pulling derivatives (i.e., those that exclude the catch phase) may provide a comparable (45-47) or greater (56, 188, 302, 307, 313, 314, 316) training stimulus to catching derivatives, and may be easier to coach and implement (47, 302).

Recently, investigators have reported greater kinetic and kinematic parameter values (peak and mean force, power, velocity, net impulse and barbell velocity) during the propulsion phase of the CMS compared to the mid-thigh pull (232), highlighting the potential superiority of the CMS as a training stimulus to enhance force-time characteristics. Although valuable, these gross measurements only represent instantaneous (i.e., peak) or mean values, usually during the concentric (propulsion) phase (45, 47, 301). It would be beneficial to further understand the kinetics and kinematics of such exercises throughout the entire movement, including any changes in the specific phase durations (i.e., unweighting [where relevant], braking, propulsion). A detailed analysis of phases with respect to time may provide a greater mechanistic understanding of biomechanical differences between relative loads during the CMS and how this could be implemented to inform load selection, given that appropriate force production (e.g., maximal force vs. rate of force development) for sporting tasks is considered a primary training consideration when developing a training programme (313).

Whilst mean and peak kinetic and kinematic variables have been extensively reported, a more sophisticated and detailed analysis of the force-time data may provide additional insight into where the differences occur between loading conditions, and how practitioners can appropriately implement these exercises. It is recommended that when testing non-directed hypotheses involving biomechanical vector fields, researchers should implement statistical parametric mapping analysis (SPM) as it is generally biased to test one dimensional data (1D) using zero dimensional methods, and SPM may reduce such bias (262-264). Researchers have utilised time-normalised curve analysis (sometimes termed waveform or temporal phase analysis) to assess force-, velocity-, power- and displacement-time data during weightlifting derivatives (185, 313, 314) and jumps (61, 62, 225, 226). A variety of statistical techniques have been used for these comparisons, including SPM and a continuous band of 95% confidence intervals (curve analysis), which creates upper and lower confidence limits and identifies non-overlapping areas (223). Briefly, SPM uses random-field theory to construct probability distributions based on continuous curve or time series data (260), whilst 95% confidence intervals utilise pair-wise comparison across data time points (185).

Kipp, Comfort and Suchomel (185) performed both SPM and curve analysis to compare differences in the force-, velocity-, power-, and displacement-time curves during the hang power clean and the jump shrug at 70% one repetition maximum (1-RM). Curve analysis indicated that the jump shrug exhibited greater ground reaction force from ~46-50% of the movement and lower vertical velocities and power from ~72-76% and ~70-76% of the movement, when compared to the hang power clean. However, these differences were not observed with the SPM analysis, highlighting that the differences observed in the curve analysis may be related to an increase in type one error (264). Statistical parametric mapping has been previously used to compare performances in jumping (158) and weightlifting derivatives (185), and may be a more appropriate analysis of time-series data compared to a temporal phase analysis (185). The SPM algorithm calculates the test statistic field across the entire waveform and retains a family-wise type I error rate of $\alpha = 0.05$ by calculating the critical test statistic threshold by using the smoothness and size of data, based on random field theory (262).

Suchomel and Sole (313) investigated differences in time-normalised force characteristics between the jump shrug, hang high pull and hang power clean at relative loads of 30, 45, 65 and 80% of 1-RM hang power clean, demonstrating that the jump shrug produced greater force, impulse, and rate of force development, and a different force-time profile compared the other exercises, particularly in the last 20-25% of movement time. This is likely due to biomechanical differences later in the movement, with no deceleration until around the point that plantar flexion occurs during the jump shrug, to ensure that the subject jumps, highlighting the potential superiority of the jump shrug when focusing on movement velocity. Such findings help the practitioner make informed decisions regarding exercise and load selection, which may be most beneficial to developing specific muscular attributes. Although researchers have previously compared force-time, velocity-time, and power-time curves during the jump shrug, hang power clean and hang high pull (185, 313, 314), no study to date has investigated curve analysis during the CMS or across a spectrum of loads. It could be surmised that an increase in load alters the relative phase duration (unweighting, braking, and propulsion) and the shape of the waveform, therefore further investigations of the effect of load on the resulting waveforms are needed. The limitations of prescribing training loads based on acute evaluations of power output have been previously discussed, and are evident in the fact that power can be maintained across a spectrum of loads due to the interaction between load related changes in force and velocity (230, 232). Additionally, training at the loads that elicit the maximal power does not appear to be more beneficial than heavy load training for developing power (122, 146). Therefore, the primary purpose of this study was to investigate differences in the force-time and velocity-time curves during the CMS across loads of 40, 60, 80, 100, 120 and 140% 1-RM PC. It was hypothesised that an increase in load would result in greater values in the time-normalised force and lower time-normalised velocity values with an increase in load. Due to the lack of prior literature, no *a priori* hypotheses were made pertaining the timings of any differences between loads, however, we hypothesised that the total CMS absolute durations would increase with an increase in load.

5.3. METHODS

5.3.1. Experimental Approach to the Problem

A within-subject repeated-measures experimental research design was used to examine the effect of load on vertical ground reaction force (VGRF), barbell-lifter system centre of mass vertical velocity throughout the entire movement of the CMS. These variables were measured with subjects performing all lifts on a force platform using progressively increasing relative loads of 40, 60, 80, 100, 120, 140% 1-RM PC. Progressive loads were used to ensure ecological validity (as this is how they would be implemented in a training session). Prior to the experimental trials, subjects visited the S&C facility on 2 occasions, at the same time of day (5–7 days apart), to establish 1-RM PC reliability, following the protocol previously used in similar research (52, 232), and were all familiar with the exercises based on their recent training programmes. All lifts were increased with a minimum of 2.5 kg increments. Subjects were encouraged to use a consistent technique between conditions, with no change in countermovement depth. A Friedman's test was performed comparing the effect of relative load on countermovement depth, which was not significant ($p = 0.684$). Further, initially an *a priori* power analysis was performed, albeit based on the effect of load on gross measures, with statistical power of 0.80 and an alpha level of 0.05, a minimum sample size of 28 subjects was determined GPower 3.1 software (94).

5.4. SUBJECTS

Twenty-nine male subjects (age 27.9 ± 3.5 years, height 1.79 ± 0.09 m, body mass 85.3 ± 16.8 kg, resistance training experience 5.6 ± 2.1 years, relative 1-RM PC 1.02 BW) from various national level sports such as rugby, soccer, martial arts, athletics (long jump and javelin), and fencing, who participated in regular resistance training including experience with weightlifting derivatives, volunteered to participate in this study. Due to competition, injury, COVID-19 lockdowns, and training camps restricted the recruitment of a homogenous group. Subjects were free from injury and provided written informed consent prior to the commencement of testing. They were requested to perform no strenuous activity during the 48 hours before testing, maintain their normal dietary intake before each session, and to attend testing sessions in a hydrated state.

5.5. PROCEDURES

5.5.1. 1-RM Power Clean Testing

Each subject's 1-RM PC was assessed following a standardised protocol (8). For a detailed description of the protocol, see additional detail in study 1, (Section 3.3.3 page 107).

5.5.2. Countermovement Shrug Testing

All subjects performed the CMS with identical methods highlighted in study 1, (Section 3.3.3, page 107). A photo sequence of the CMS is shown in Figure 3.2, page 111.

5.6. DATA ANALYSIS

Force-time data analysis for the CMS were analysed using a forward dynamics approach, using identical methods outlined in study 1, (Section 3.3.3, page 112). Time series data were normalised to 101 data points in line with previous research (185) representing 0-100% of the movement from initial countermovement to peak velocity. The average of the two trials which were the closest in propulsive peak velocity at each relative load was used for statistical analysis. Raw vertical force-time data for each trial were exported as text files and analysed in Microsoft Excel (version 2016; Microsoft Corp., Redmond, WA, USA).

5.6.1. Statistical Analyses

Reliability of the 1-RM power clean was determined via a two-way mixed effects intraclass correlation coefficients (ICC) and coefficient of variation (CV), as well as their 95% confidence interval (CI). The ICC were interpreted as poor < 0.50; 0.50 ≤ moderate < 0.75; 0.75 ≤ good < 0.9, and excellent ≥ 0.90 (193), and the %CV considered acceptable if < 10% (57). The primary analyses were to perform SPM repeated-measures analysis of variance (ANOVA) to assess the effect of load on force- and velocity-, waveforms during the CMS, using open-source Matlab 2021b (MathWorks, Natick, MA) code (http://www.spm1d.org). Where significant effects (α = 0.05) were reported, the SPM paired samples t-test was used to compare between loads. A Bonferroni correction resulted in a critical threshold for significance of $p \leq 0.003$. For each test, the critical test statistic, and supra-threshold cluster were reported where the test statistic field exceeded the critical test statistic threshold. The secondary exploratory analysis of the effects of load on phase durations, both absolute and as a percentage of movement time, were determined via repeated measures analysis of variance (ANOVA) with Bonferroni post hoc analysis. Distribution of data was analysed via Shapiro-Wilks' test of normality, with differences between loads determined using Wilcoxon's tests. Statistical analyses for phase durations were performed using Statistical Package for the Social Sciences software version 27 (SPSS, Chicago, Ill, USA). Standardised differences were calculated using Hedges' *g* effect sizes as previously described (148) and interpreted as trivial (≤ 0.19), small (0.20-0.59), moderate (0.60-1.19), large (1.20-1.99), and very large (2.0-4.0) (152). An *a priori* alpha level was set at $p \leq 0.05$.

5.7. RESULTS

The 1-RM power clean performances were highly reliable (ICC = 0.99, [95% CI: 0.97-0.99], %CV= 2.0% [0.9-2.3%]) between sessions 1 (87.84 ± 18.82 kg) and 2 (88.10 ± 18.40 kg). Increased barbell load resulted in an increased force production throughout the time-normalised movement durations and a change in the shape of the velocity-time curve due to decreases in velocity and changes in the phases of the movement (Figure 5.1, Table 5.1). For clarity and brevity, any non-significant differences between loads or significant differences across the entire waveform (i.e., 0-100%) are not described in detail but simply highlighted (all figures and results are shown in Appendices 10.5). The results for the effect of load on absolute phase durations and percentage of movement time are shown in Table 5.1

5.7.1. Force-time

The SPM repeated-measures ANOVA indicated a significant effect of load on force ($p < 0.001$, $F^* = 3.559$, Figure 5.2a) throughout the entire time-normalised movement. Force was generally greater at greater relative loads (Figure 5.1a). For example, force at 40% 1-RM PC was less than at 60, 80, 100, 120, and 140% 1-RM PC during 67%, 91%, 94%, 100% and 100% of the movement, respectively (Figure 5.3a). All pairwise comparisons revealed significantly greater force during higher loads for early (0-14%), mid (36-54%), and late (90-100%) time-normalised movement. Peak force was 24.9% greater at 140% compared to 40% 1-RM and occurred between 79-82% of time-normalised movement in all loads (Figure 5.1a). All differences between loads are illustrated in Figure 5.3a.

5.7.2. Velocity-time

Load had a significant effect on velocity between 12-38%, 47-79% and 84-100% of time-normalised movement. ($p < 0.001$, $F^* = 3.713$, Figure 5.2b). The effect of load on velocity followed these three distinct phases (Figure 5.1b, Figure 5.3b, Figure 5.4b). Higher, compared to lower, loads resulted in more negative velocities in the first phase, less negative / more positive velocities in the middle phase, and less positive velocities during the last phase. There were no significant differences in velocity between the smallest increments in load of 40 vs. 60%, 60 vs. 80%, 80 vs. 100% and 100 vs. 120 1-RM (Figure 5.3b). All other comparisons are displayed in Figure 5.3b. An example of the SPM output and 95% CI is shown in Figure 5.4.

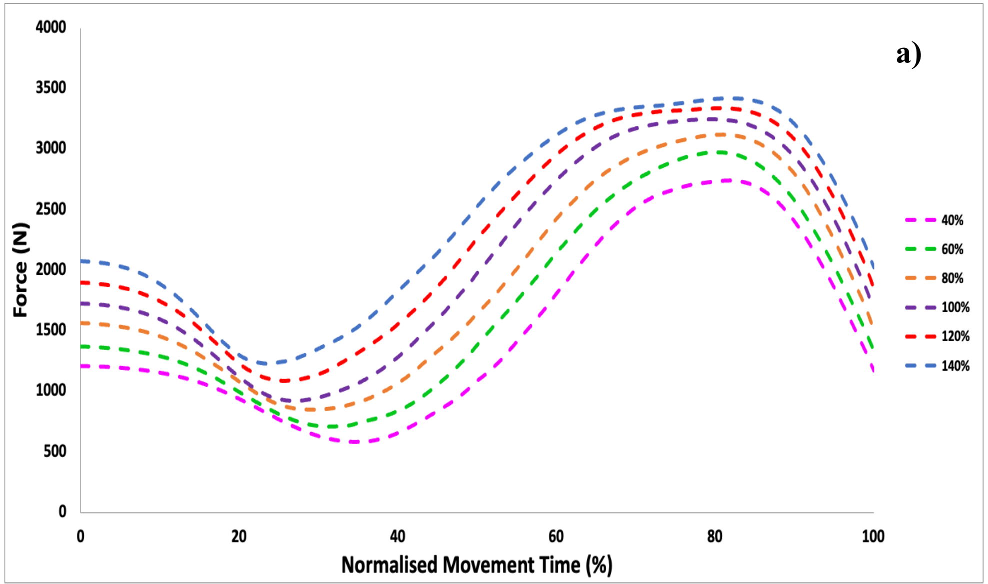
5.7.3. Absolute Phase Durations

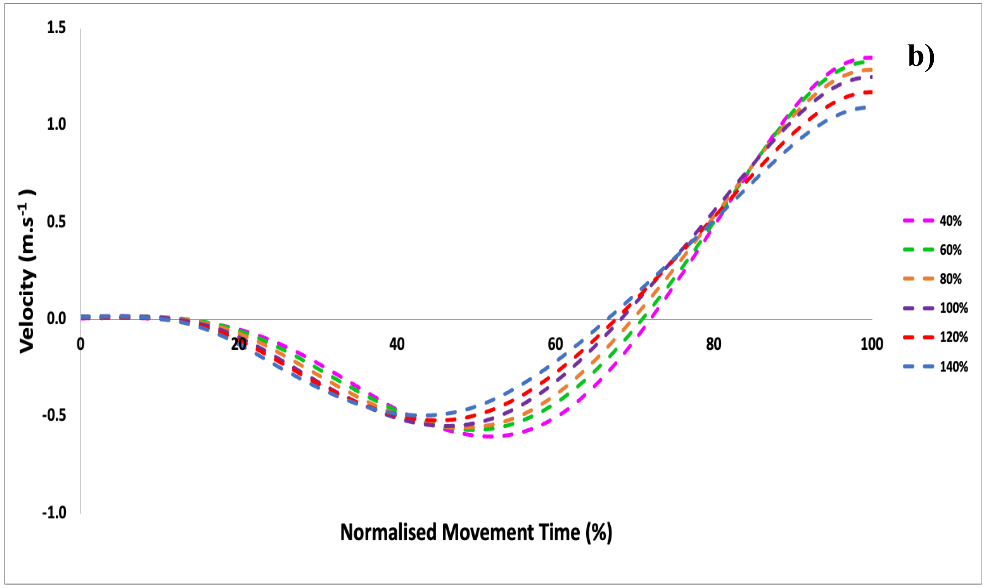
There were no significant or meaningful differences ($p > 0.05$, $g = 0\text{-}0.39$) in the total duration of the unweighting phase between loads (Table 5.1). The duration of the braking phase increased with load and was greatest at 140% 1-RM, which was significantly greater ($p \leq 0.03$,

$g = 0.43\text{-}1.12$) than all other loads, with small to moderate effect sizes (Table 5.1). The duration of the propulsion phase increased with an increase in load, and was greatest at 140% 1-RM, which was significantly greater than all other loads ($p \leq 0.003$, $g = 0.43\text{-}2.32$), with a small to very large effect size. The total movement duration progressively increased with load. The greatest duration occurred at 140% 1-RM, which demonstrated a significantly greater duration ($p < 0.001$, $g = 0.97\text{-}1.42$, moderate to large) than 40-100% 1-RM, but not significantly different to 120% 1-RM ($p > 0.05$, $g = 0.31$). All other total movement results are shown in Table 5.1.

5.7.4. Percentage of Absolute Movement Time

The greatest relative (as a percentage of movement time) duration of the unweighting phase occurred at 40% 1-RM. which demonstrated a significantly greater percentage duration compared to 80-140% 1-RM ($p \leq 0.045$, $g = 0.44\text{-}0.99$, small to moderate), but not significantly different to 60% 1-RM ($p > 0.05$, $g = 0.22$) (Table 5.1). The greatest relative duration of the braking phase occurred at 140% 1-RM, which was significantly greater than at 40-60 ($p = 0.015$, $g = 0.62\text{-}1.16$, moderate) and 100% ($p = 0.007$, $g = 0.96$, moderate) 1-RM. All other braking phase results are shown in Table 5.1. The greatest relative duration of the propulsion phase occurred at 100% 1-RM, which was significantly and moderately greater ($p = 0.003$, $g = 0.66$) than 40% 1-RM only, with 140% 1-RM also showing a significantly greater duration than 40% 1-RM ($p = 0.045$, $g = 0.33$, small).





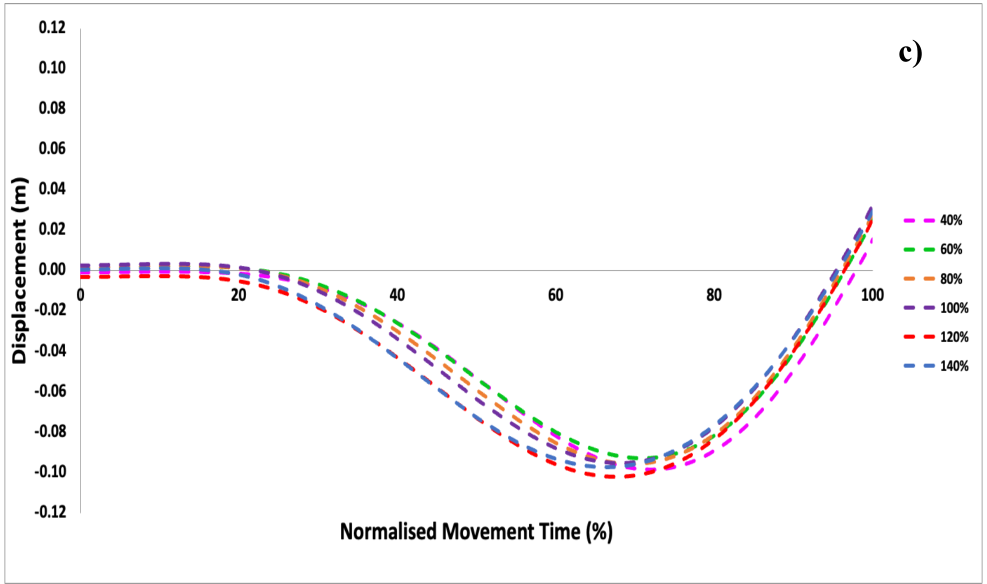


Figure 5.1-Comparison of the average force-time (a), velocity-time (b), and displacement-time (c) curves during the countermovement shrug with loads of 40-, 60-, 80-, 100-, 120- and 140% 1-RM power clean. The differences between loads are described in results section

Table 5.1-Comparison of absolute phase durations and expressed as a percentage of movement duration during the CMS

Intensity	Unweighting Phase % of Total Movement	Braking Phase % of Total Movement	Propulsion Phase % of Total Movement	Unweighting Phase Duration (s)	Braking Phase Duration (s)	Propulsion Phase Duration (s)	Total Movement Duration (s)
40%	**39 ± 4**	15 ± 3	46 ± 3	0.263 ± 0.05	0.104 ± 0.03	0.305 ± 0.02	0.672 ± 0.07
60%	38 ± 5	16 ± 4	46 ± 3	0.263 ± 0.06	0.107 ± 0.03	0.312 ± 0.03	0.685 ± 0.07
80%	37 ± 5	17 ± 4	47 ± 3	0.258 ± 0.04	0.118 ± 0.03	0.325 ± 0.03	0.702 ± 0.06
100%	36 ± 4	16 ± 2	**48 ± 3**	0.253 ± 0.04	0.117 ± 0.02	0.338 ± 0.03	0.709 ± 0.06
120%	36 ± 4	17 ± 2	47 ± 4	0.268 ± 0.06	0.127 ± 0.02	0.350 ± 0.04	0.748 ± 0.09
140%	35 ± 4	**18 ± 2**	47 ± 3	**0.269 ± 0.04**	**0.138 ± 0.03**	**0.365 ± 0.03**	**0.773 ± 0.07**
			p (g)				
40 vs. 60	>0.05 (0.22)	>0.05 (0.28)	>0.05 (0.00)	>0.05 (0.00)	>0.05 (0.10)	>0.05 (0.27)	>0.05 (0.18)
40 vs. 80	*0.045 (0.44)	>0.05 (0.56)	>0.05 (0.33)	>0.05 (0.11)	*0.015 (0.46)	*<0.001 (0.77)	>0.05 (0.45)
40 vs. 100	*0.003 (0.74)	>0.05 (0.39)	*0.003 (0.66)	>0.05 (0.22)	*0.045 (0.50)	*<0.001 (1.23)	*0.011 (0.56)
40 vs. 120	*0.010 (0.74)	>0.05 (0.77)	>0.05 (0.28)	>0.05 (0.09)	*0.001 (0.89)	*<0.001 (1.40)	*0.003 (0.93)
40 vs. 140	*<0.001(0.99)	*0.015 (1.16)	*0.045 (0.33)	>0.05 (0.13)	*<0.001 (1.12)	*<0.001 (2.32)	*<0.001 (1.42)
60 vs. 80	>0.05 (0.20)	>0.05 (0.25)	>0.05 (0.33)	>0.05 (0.10)	*0.03 (0.36)	*<0.001 (0.43)	>0.05 (0.26)
60 vs. 100	>0.05 (0.44)	>0.05 (0.00)	>0.05 (0.66)	>0.05 (0.19)	>0.05 (0.39)	*<0.001 (0.86)	*0.045 (0.36)
60 vs. 120	*0.03 (0.64)	>0.05 (0.31)	>0.05 (0.28)	>0.05 (0.08)	*<0.001 (0.77)	*<0.001 (1.06)	*0.004 (0.77)
60 vs. 140	*0.002 (0.65)	*0.015 (0.62)	>0.05 (0.33)	>0.05 (0.12)	*<0.001 (1.02)	*<0.001 (1.74)	*<0.001 (1.24)
80 vs. 100	>0.05 (0.22)	>0.05 (0.31)	>0.05 (0.33)	>0.05 (0.12)	>0.05 (0.03)	*0.014 (0.43)	>0.05 (0.12)
80 vs. 120	>0.05 (0.22)	>0.05 (0.00)	>0.05 (0.00)	>0.05 (0.19)	>0.05 (0.35)	*<0.001 (0.70)	*0.003 (0.59)
80 vs. 140	>0.05 (0.44)	>0.05 (0.31)	>0.05 (0.00)	>0.05 (0.27)	*0.007 (0.66)	*<0.001 (1.32)	*<0.001 (1.07)
100 vs. 120	>0.05 (0.00)	>0.05 (0.49)	>0.05 (0.28)	>0.05 (0.12)	*0.015 (0.49)	>0.05 (0.33)	*0.02 (0.50)
100 vs. 140	>0.05 (0.25)	*0.007 (0.96)	>0.05 (0.33)	>0.05 (0.39)	<0.001 (0.81)	*<0.001 (0.89)	*<0.001 (0.97)
120 vs. 140	>0.05 (0.15)	>0.05 (0.49)	>0.05 (0.00)	>0.05 (0.12)	*0.03 (0.43)	*0.003 (0.42)	>0.05 (0.31)

*Denotes significant difference between loads

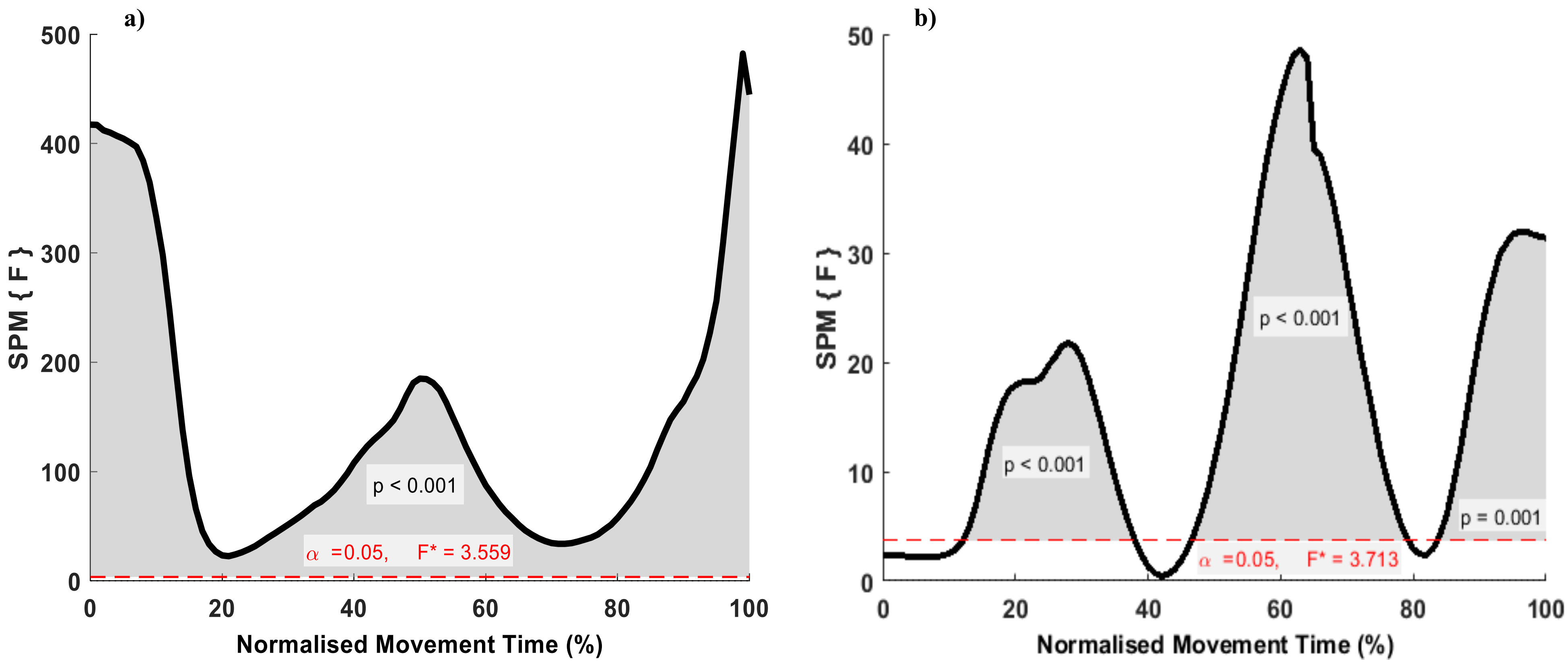


Figure 5.2-SPM Repeated measures ANOVA (SPM{F}statistic) during the countermovement shrug at 40-140% 1-RM comparing a) force-time and b) velocity-time series. The dashed horizontal line designates the critical threshold for the SPM[F]statistics. The grey shaded area represents supra-threshold clusters, indicating statistically significant differences at those timepoint

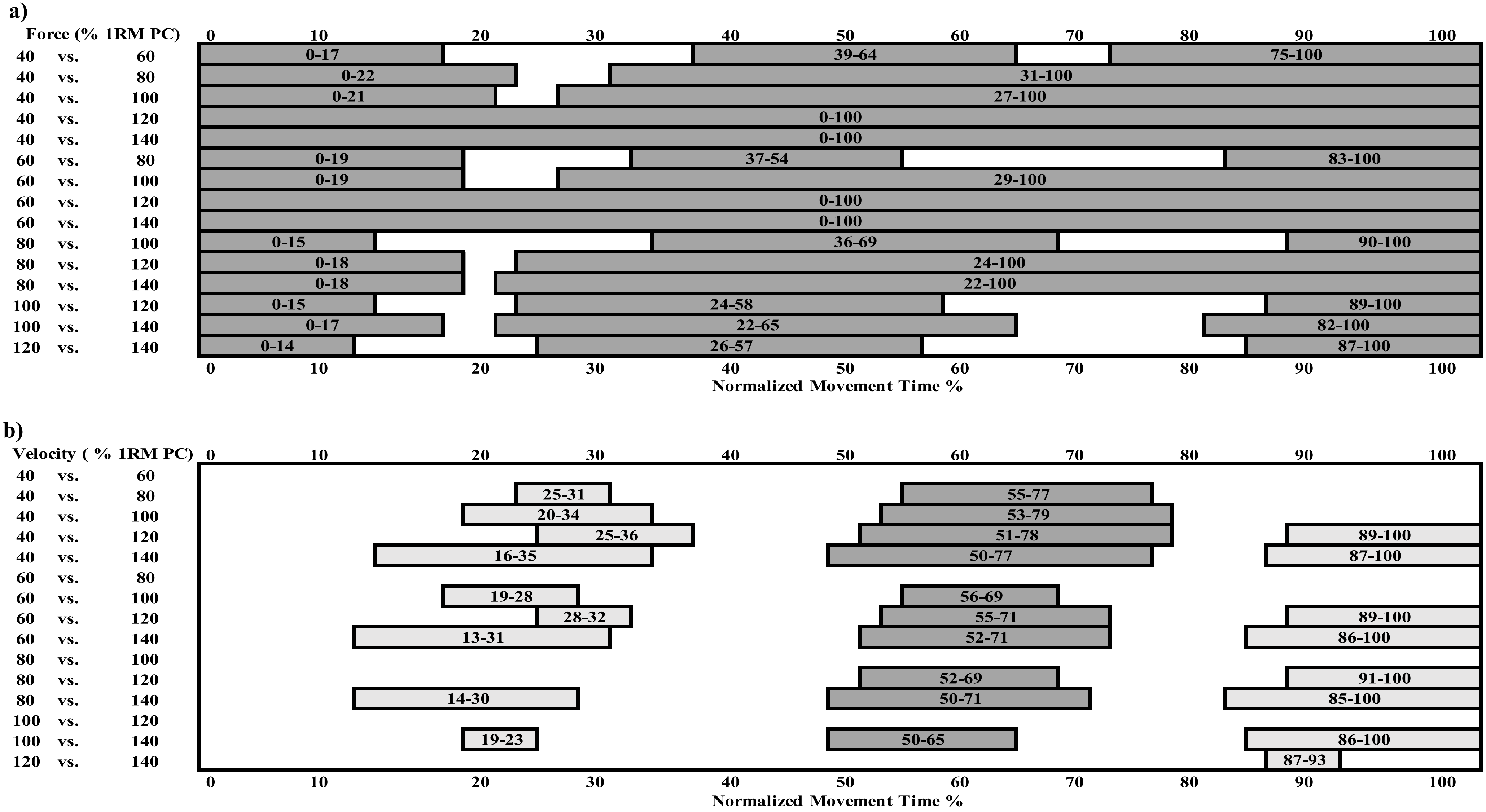


Figure 5.3-Summary of differences between countermovement shrug intensity of loads of 40-,60,80,100,120 and 140% 1-RM power clean (1-RM PC) from SPM analysis for a) normalised force-time series, b) normalised velocity-time series. Shaded area illustrates significant differences between time points and intensity of load.

Higher load greater Lower load greater No difference

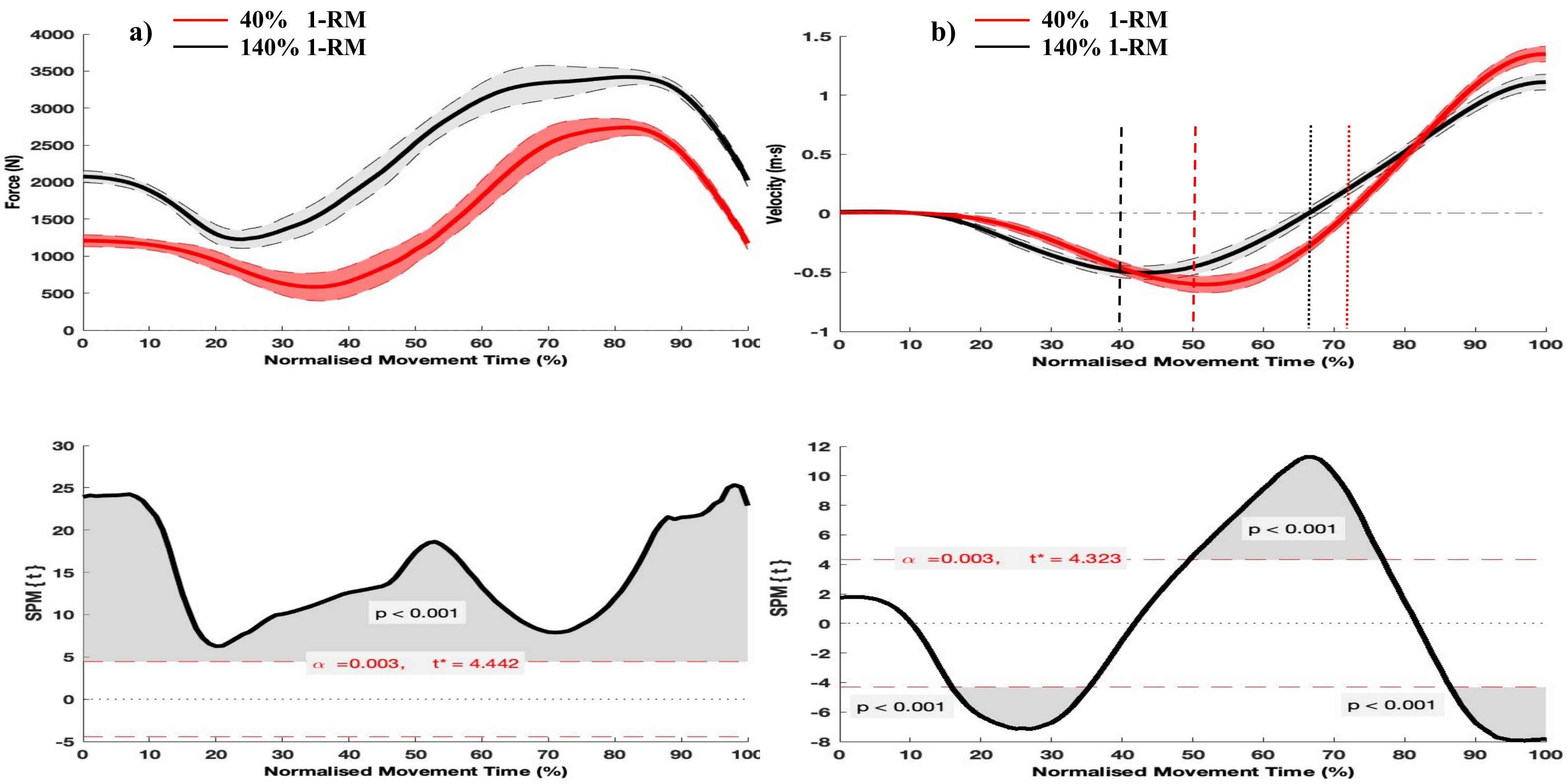


Figure 5.4-Top- mean and 95% confidence intervals for 40 vs.140% 1-RM a) time-normalised force, and b) time-normalised velocity. Bottom- Statistical parametric mapping (SPM) paired t-test for 40 vs.140% 1-RM - inference curve as a function of time, with suprathreshold clusters (shaded) and critical threshold for SPM[t]statistics (dashed line) that indicates the random field theory critical thresholds for significance ($\alpha = 0.003$). The grey shaded area represents a significant difference at those time points. Vertical black dashed line = onset of braking 140% 1-RM; red dashed line = onset of braking 40% 1-RM; black dotted line = onset of propulsion 140% 1-RM; red dotted line = onset of propulsion 40% 1-RM.

5.8. DISCUSSION

The purpose of this study was to investigate the effect of load on CMS force-time and velocity-time curves. The findings may have implications for researchers analysing time series data, and S&C practitioners who prescribe weightlifting pulling derivatives. As expected, a greater force was produced as load increased from 40-140% 1-RM. The greatest force was observed at 140% 1-RM, in line with previous research (232). There was an initial greater negative velocity (unweighting earlier) at higher loads, followed by positive velocity being greater during early propulsion and lower during late propulsion, with velocity being maximised at 40% 1-RM (Figure 5.1b; Figure 5.2b; Figure 5.3b). Force increased with an increase in load, with 140% 1-RM resulting in 24.9% greater peak force than 40% 1-RM (Figure 5.1a; Figure 5.2a; Figure 5.3a). As load increased, there were differences throughout the time-normalised movement. This provides a greater mechanistic understanding to S&C practitioners about where differences may exist outside of peak values, as a previous investigation during the CMS only reported peak and mean kinetic and kinematic variables (232). This is the first study to include SPM analysis of the CMS across a spectrum of loads, with other studies comparing weightlifting exercises at the same loads (185, 313, 314), loaded jumps (61) and unloaded jumps (223, 224). However, these findings need to be interpreted with caution in relation to other pulling derivatives, as the specific task constraints differ compared to the CMS.

A unique aspect of the current study was the comparison of time-normalised velocity curves between loads. The increase of load also alters the shape of the average velocity-time curves, with peak negative velocity in 140% 1-RM occurring 9% earlier in the time-normalised total movement than 40% 1-RM, thus affecting the phases of the time-normalised movement (Figure 5.1b). The greater the load, the greater the duration of significant differences in velocity compared to 40% 1-RM. Indeed, 140% showed significant differences across 59% of total movement time when compared to 40% 1-RM, highlighting key differences that occur outside peak variables (Figure 5.3b). The results of this study demonstrate that supramaximal loads may not be appropriate to train propulsion velocity. This is particularly true in late-stage propulsion due to the significant reduction in velocity at relative loads >100% 1-RM compared to all relative loads of <100% 1-RM (Figure 5.3b), illustrative of the load-velocity relationship. Subjects likely managed to accelerate through the full triple extension more at loads of > 100% 1-RM. It is important to note that performance outcomes will be partly influenced by intent during the propulsion phase, which may be submaximal at lighter loads. During the CMS, and particularly at lower loads, there is likely a deceleration during the late propulsive phase of the lift as the subjects were encouraged not to jump off the platform as in a jump shrug (298, 302), therefore the CMS is likely an inferior exercise to develop propulsive velocity compared to the jump shrug at comparable loads.

Understanding where differences occur within the movement (i.e., early, or late phase) may allow for more precise exercise prescription to target specific components of the second pull. Practically, this is of paramount importance as the increased phase durations results in increased time under tension, and the increased force production will likely determine the adaptive responses, especially within a task where maximal intent is essential. Visual inspection of the average time-normalised velocity curves in the present study shows that load affects when the braking and propulsion phase commences (Figure 5.1b and Figure 5.4b). At 140% compared to 40% 1-RM, the braking phase occurs earlier (43-67% compared to 52-73%). This results in a shorter unweighting phase (43% of movement, compared to 52%) and longer braking (24% vs 21%) and propulsive (33% vs 27%) phases. Therefore, caution is warranted when interpreting differences between loads due to the misalignment of phases.

Practitioners also should note that the training mesocycle focus, sets and repetitions in which the loads >100% 1-RM are prescribed may impact performance. Excessive duration of repetitions may be detrimental to performance in certain mesocycles, such as speed-strength blocks. As an increase in load will result in an increased repetition duration, performing the same set and repetitions for high vs lower loads may also impact performance due to the increased volume load and duration. To improve an athlete's force-velocity profile with weightlifting derivatives, a combination of heavy/lighter loads is recommended (301). Therefore, practitioners need to carefully consider excessive volumes in certain training mesocycles (e.g., competition) where the avoidance of fatigue accumulation is important. It is clear that force and velocity are interdependent and that maximal power occurs at compromised levels of maximal force and velocity (122). Therefore, low-load, high-velocity movements can address the high-velocity component of the force- velocity relationship, while heavier loads develop the high-force component (122). This allows for power output during the CMS to be maximised at loads of 80-140% 1-RM PC, as previously shown (232).

The present results provide an understanding of the effect of load on force-, and velocity-time characteristics during the CMS; however, to fully understand the potential benefits of training at different loads during the CMS a longitudinal training intervention needs to be conducted. As loads of true maximal effort during pulling variations such as the CMS have not yet been investigated, the load percentages may not be a true reflection of true weightlifting pulling ability and may in fact result in a greater 1-RM, and therefore greater loads during testing sessions. The authors acknowledge that it may be impractical to perform 1-RM tests for certain weightlifting derivatives due to the absence of criteria for a successful repetition. This study is not without its limitations. Firstly, although only male subjects were recruited, these results are also generalisable to athletes of comparable strength levels and training status, with no significant differences in the magnitude or ratio of muscle activity during a maximal isometric squat (252), and no differences in the effect of load between the sexes on kinetics or kinematics during the mid-thigh pull (52, 252). It is acknowledged that a greater sample size may be required for 1D data analysis (271). It is therefore possible that the present study was only adequately powered to detect effects of a slightly larger magnitude than that used in the discrete parameter power analysis. Nonetheless, the largest effects of relative load on force and velocity time-histories have been reported. Additionally, onset of movement was calculated based on thresholds from jump and isometric mid-thigh pull research. Future research should assess whether this method is still appropriate for loaded exercises in which large dynamic system masses are prevalent.

5.9. PRACTICAL APPLICATIONS

The results indicate that there is greater negative velocity at heavier compared to lower loads early in the unweighting phase (12-38% of the movement), and greater positive velocity at lower loads during the last 16%. These results demonstrate that load impacts differently throughout different portions of the time-normalised movement, and practitioners may be able to prescribe specific loads to target specific phases of the movement, with relative loads of 40% power clean 1-RM most appropriate to maximise velocity during the CMS, and relative loads of 140% to maximise force. Practitioners are encouraged to use a combination of heavy and light loads when prescribing weightlifting pulling derivatives, to emphasise force and velocity or to maximise power. It may be more appropriate to prescribe the CMS during a strength-speed and maximal strength phase given the ability to use loads greater than the athlete's 1-RM. The results also show that the braking and propulsion phases commence at an earlier percentage of time-normalised movement at higher loads, whilst absolute durations are also greatest at higher loads. Future research should assess the effect of load on individual time-normalised phases to determine if differences between loads exist within each time-normalised phase.

5.10. APPLIED RESEARCH PERSPECTIVE

Based upon the above findings, direct comparisons between phases cannot be performed as an increase in load results in a reduced unweighting phase and a longer propulsion phase. Due to the CMS having a lower range of motion compared to the HP, it would be beneficial to investigate if temporal differences between loads are greater due to an increase in range of motion and exercise complexity.

Chapter 6: Study 4- Comparing Biomechanical Time Series Data Across Hang Pull Loads

6.1. ABSTRACT

The effect of load on time series data has yet to be investigated during weightlifting derivatives. This study compared the effect of load on the force-time and velocity-time curves during the hang pull (HP). Twenty-seven males performed the HP at relative loads of 40, 60, 80, 100, 120, and 140% one repetition maximum (1-RM) power clean (PC). A force plate measured the vertical ground reaction force (VGRF), which was used to calculate the barbell-lifter system velocity. Time series data were normalised to 100% of the movement duration and assessed via statistical parametric mapping (SPM). SPM analysis showed greater negative velocity at heavier loads early in the unweighting phase (11-29% of the movement), and greater positive velocity at lower loads during the last 13% of the movement. Relative loads of 40% 1-RM PC maximised propulsion velocity, whilst 140% maximised force. At higher loads, the braking and propulsive phases commence at an earlier percentage of the time-normalised movement, and the total absolute durations increase with load. It may be more appropriate to prescribe the HP during a maximal strength mesocycle given the ability to use loads > 1-RM PC. Future research should assess training at different loads on the effects of performance.

6.2. INTRODUCTION

Researchers have investigated gross kinetic and kinematic differences in weightlifting catching derivatives such as the power clean [PC] (45-47), hang power clean (185, 188, 316), or weightlifting pulling derivatives (i.e., those excluding the catch) including countermovement shrug (232), mid-thigh pull (52, 232), snatch pull (169), hang pull (HP) (230), hang high pull

(306, 307), pull from the knee (56, 230) and jump shrug (185, 188, 298, 306, 307, 316). Researchers investigating kinetic and kinematic characteristics of the second pull, commencing from the mid-thigh ('power') position (79), reported that this phase produces the greatest force and power in experienced weightlifters during the clean, snatch and PC (91, 286). Furthermore, the results of previous cross-sectional research indicates that weightlifting pulling derivatives may provide a comparable (45-47) or greater (56, 188, 302, 307, 313, 314, 316) training stimulus to catching derivatives, and may be easier to coach and implement (47, 302), with researchers reporting superior kinetic and kinematic parameter values (peak and mean force, power, velocity, net impulse and barbell velocity) during the propulsion phase of the HP compared to the PFK (230), highlighting the potential superiority of the HP as a training stimulus to enhance force-time characteristics. Although valuable, gross measurements only represent instantaneous (i.e., peak) or mean values, usually during the concentric (propulsion) phase (45, 47, 301). It would be beneficial to further understand the kinetics and kinematics of such exercises throughout the entire movement, including any changes in the specific phase durations (i.e., unweighting [where relevant], braking, propulsion). A comprehensive analysis of phases with respect to time may provide a greater mechanistic understanding of biomechanical differences between relative loads during the HP and how this could be implemented to inform load selection, given that appropriate force production (e.g., maximal force vs. rate of force development) for sporting tasks is considered a principal training consideration (313).

Whilst mean and peak kinetic and kinematic variables have been extensively reported, a more sophisticated and detailed analysis of the force-time data may provide additional insight into where the differences occur between loading conditions, and how practitioners can appropriately implement these exercises. A detailed overview of SPM is discussed in Chapter

5.2. Kipp, Comfort and Suchomel (185) implemented both SPM and curve analysis to compare differences in the force-, velocity-, power-, and displacement-time curves during the hang power clean and the jump shrug at 70% 1-RM. Curve analysis indicated that the jump shrug exhibited greater ground reaction force from ~46-50% of the movement and lower vertical velocities and power from ~72-76% and ~70-76% of the movement, when compared to the hang power clean. However, these differences were not observed with the SPM analysis. Statistical parametric mapping has been previously used to compare performances in jumping (158) and weightlifting derivatives (185), and may be a more appropriate analysis of time-series data compared to a temporal phase analysis (185). Suchomel and Sole (313) demonstrated that the jump shrug produced greater force, impulse, and rate of force development, and a different force-time profile compared to the hang high pull and hang power clean at relative loads of 30, 45, 65 and 80% of 1-RM hang power clean, particularly in the last 20-25% of movement time. This is likely due to biomechanical differences later in the movement, with no deceleration until around the point that plantar flexion occurs during the jump shrug to ensure that the subject jumps, highlighting the potential superiority of the jump shrug when focusing on movement velocity. Such findings help the practitioner make informed decisions regarding exercise and load selection, which may be most beneficial to developing specific muscular attributes. Although researchers have previously compared force-time, velocity-time, and power-time curves during the jump shrug, hang power clean and hang high pull (185, 313, 314), no study to date has investigated curve analysis during the HP or across various loads. It could be surmised that an increase in load alters the relative phase duration (unweighting, braking, and propulsion) and the shape of the waveform, therefore further investigations of the effect of load on the resulting waveforms are needed. Prescribing training loads based on acute evaluations of power output have been discussed previously, and are evident given that power can be maintained across a spectrum of loads during weightlifting derivatives due to the interaction between load related changes in force and velocity (230, 232). Additionally, training at the loads that elicit the maximal power does not appear to be more advantageous than heavy load training for developing power (122, 146).

Therefore, the primary purpose of this study was to investigate differences in the force-time and velocity-time curves during the HP across loads of 40, 60, 80, 100, 120 and 140% 1-RM PC. Whilst the previous chapter examined the countermovement shrug, larger differences may be prevalent during the HP due to more distinct unweighting, braking and propulsion phases due to the greater range of movement. It was hypothesised that an increase in load would result in greater values in the time-normalised force and lower time-normalised velocity values with an increase in load. Due to the lack of prior literature, no *a priori* hypotheses were made pertaining the timings of any differences between loads, however, we hypothesised that the total HP absolute durations would increase with an increase in load.

6.3. METHODS

6.3.1. Experimental Approach to the Problem

A within-subject repeated-measures experimental research design was used to examine the effect of load on vertical ground reaction force (VGRF), barbell-lifter system centre of mass vertical velocity throughout the entire movement of the hang pull. A detailed description of the research design used in this study for the HP is shown in study 3, (Section 5.3.1, page 168). Further, a Friedman's test was performed comparing the effect of relative load on countermovement depth, which was not significant ($p = 0.134$).

6.4. SUBJECTS

Twenty-seven athletic males (age 28.29 ± 3.33. years, height 1.78 ± 0.09 m, body mass 85.10 ± 17.17 kg, resistance training experience 5.55 ± 2.18 years, relative 1-RM PC 1.04 ± 0.19 $kg.kg^{-1}$) from various national level sports such as rugby, soccer, martial arts, athletics (long jump and javelin), and fencing, who participated in regular resistance training including experience with weightlifting derivatives, volunteered to participate in this study. Subjects were free from injury and provided written informed consent prior to the commencement of testing. They were requested to perform no strenuous activity during the 48 hours before testing, maintain their normal dietary intake before each session, and to attend testing sessions in a hydrated state

6.5. PROCEDURES

6.5.1. 1-RM Power Clean Testing

Each subject's 1-RM PC was assessed following a standardised protocol (8). For a detailed description of the protocol, see additional detail in Section 3.3.3 page 107.

6.5.2. Hang Pull Testing

All subjects performed the HP with identical methods highlighted in study 2, (Section 4.3.3 page 139). A photo sequence of the HP is shown in Figure 4.2, page 142.

6.6. DATA ANALYSIS

Force-time data for the HP were analysed using a forward dynamics approach, using methods outlined in study 1, (Section 3.3.3, page 112). Time series data were normalised to 101 data points in line with previous research (185) representing 0-100% of the movement from initial countermovement to peak velocity. The average of the two trials which were the closest in propulsive peak velocity at each relative load was used for statistical analysis.

6.6.1. Statistical Analyses

A detailed description on the statistical procedures utilised in this chapter is discussed in detail in study 3, (Section 5.6.1, page 170). Reliability was assessed suing ICC and %CV. Comparisons between loads were evaluated using SPM repeated-measures analysis of variance (ANOVA). Where significant effects ($\alpha = 0.05$) were reported, the SPM paired samples t-test was used to compare between loads. A Bonferroni correction resulted in a critical threshold for significance of $p \leq 0.003$.

6.7. RESULTS

Power clean 1-RM performances were highly reliable (ICC = 0.988, [95% CI = 0.974–0.994], %CV = 2.0% [0.9–2.4%]) between sessions 1 (86.94 ± 19.22 kg) and 2 (87.31 ± 18.98 kg). Increased barbell load resulted in an increased force production throughout the time-normalised movement durations and a change in the shape of the velocity-time curve due to decreases in velocity and changes in the phases of the movement **(**Figure 6.1**;** Table 6.1**).** For clarity and brevity, any non-significant differences between loads or significant differences across the entire waveform (i.e., 0-100%) are not described in detail but simply highlighted (Appendices 10.6). The results for the effect of load on absolute phase durations and percentage of movement time are shown in Table 6.1**.**

6.7.1. Force-time

The SPM repeated-measures ANOVA indicated a significant effect of load on force ($p < 0.001$, $F^* = 3.522$, Figure 6.2a) throughout the entire time-normalised movement. Force was generally greater at greater relative loads (Figure 6.1a). For example, force at 40% 1-RM PC was lower than at 60% 1-RM PC during 88% of the movement and lower during 100% of the movement for 80-140% 1-RM PC, respectively (Figure 6.3a). Peak force was 28.7% greater at 140% compared to 40% 1-RM and occurred between 89-91% of normalised movement time in all loads (Figure 6.1a). All differences between loads are illustrated in Figure 6.3a. An example of the SPM output and 95% CI is shown in Figure 6.4a.

6.7.2. Velocity-time

Load had a significant effect on velocity between 10-33%, 41-72% and 85-100% of time-normalised movement ($p \leq 0.002$, $F^* = 3.708$, Figure 6.2b). The effect of load on velocity followed these three distinct phases (Figure 6.1b, Figure 6.3b, Figure 6.4b). Higher, compared to lower, loads resulted in higher negative velocities in the first period, less negative / more positive velocities in the middle period, and less positive velocities during the last period. There were no significant differences in velocity between 40 vs. 60% and 80 vs. 100% 1-RM (Figure 6.3b). All other comparisons are displayed in Figure 6.3b. An example of the SPM output and 95% CI is shown in Figure 6.4b.

6.7.3. Absolute Phase Durations

There were no significant or meaningful differences ($p > 0.05$, $g = 0$-0.43) in the total duration of the unweighting phase between loads (Table 6.1). The duration of the braking phase increased with load and was greatest at 140% 1-RM, which was significantly greater ($p \leq 0.03$, $g = 0.33$-0.72) than 40-80% 1-RM, with small to moderate effect sizes (Table 6.1). The duration of the propulsion phase increased with an increase in load, and was greatest at 140% 1-RM, which was significantly greater than all other loads ($p \leq 0.001$, $g = 0.35$-1.45), with a small to large effect size. The total movement duration progressively increased with load. The greatest duration occurred at 140% 1-RM, which demonstrated a significantly greater duration ($p \leq 0.002$, $g = 0.45$-0.89, small to moderate) than 40-100% 1-RM, but not significantly different to 120% 1-RM ($p > 0.05$, $g = 0.19$). All other total movement results are shown in Table 6.1.

6.7.4. Percentage of Absolute Movement Time

The greatest relative (as a percentage of movement time) duration of the unweighting phase occurred at 40% 1-RM. which demonstrated a significantly greater percentage duration compared to all loads ($p \leq 0.045$, $g = 0.36$-0.99, small to moderate) (Table 6.1). The greatest relative duration of the braking phase occurred at 140% 1-RM, which was significantly greater than at 40% 1-RM only ($p = 0.03$, $g = 0.54$, small). All other braking phase results are shown in Table 6.1. The smallest relative duration of the propulsion phase occurred at 40% 1-RM, which was significantly and moderately smaller ($p \leq 0.019$, $g = 0.44$-0.65) than 80-100% 1-RM and 140% 1-RM ($p = 0.019$, $g = 0.72$, moderate) (Table 6.1).

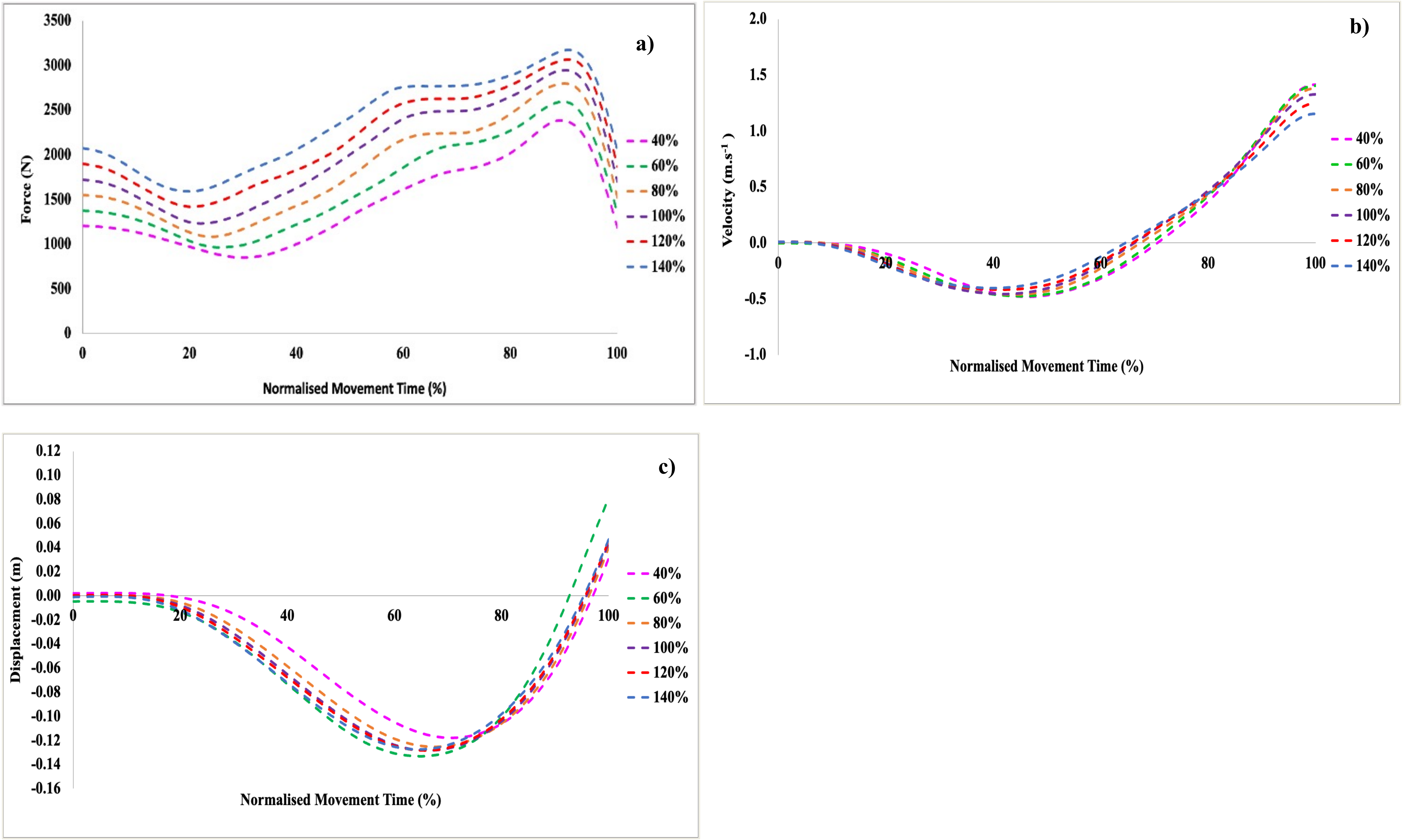


Figure 6.1-Comparison of the average force-time (a), velocity-time (b), and displacement-time (c) curves during the hang pull with loads of 40-, 60-, 80-, 100-, 120- and 140% 1-RM power clean. The differences between loads are described in results section.

Table 6.1-Comparison of absolute phase durations and expressed as a percentage of movement duration during the HP

Intensity	Unweighting Phase % of Total Movement	Braking Phase % of Total Movement	Propulsion Phase % of Total Movement	Unweighting Phase Duration (s)	Braking Phase Duration (s)	Propulsion Phase Duration (s)	Total Movement Duration (s)
40%	**39 ± 6**	19 ± 5	43 ± 5	**0.344 ± 6**	0.171 ± 0.07	0.381 ± 0.05	0.899 ± 0.145
60%	37 ± 5	20 ± 5	44 ± 4	0.325 ± 5	0.183 ± 0.07	0.394 ± 0.05	0.904 ± 0.137
80%	35 ± 5	20 ± 6	45 ± 4	0.325 ± 5	0.203 ± 0.10	0.420 ± 0.07	0.949 ± 0.183
100%	34 ± 5	21 ± 6	46 ± 4	0.320 ± 5	0.209 ± 0.10	0.437 ± 0.07	0.969 ± 0.179
120%	34 ± 6	21 ± 6	45 ± 4	0.339 ± 6	0.225 ± 0.10	0.452 ± 0.07	1.019 ± 0.180
140%	33 ± 6	**22 ± 6**	**46 ± 3**	0.336 ± 6	**0.238 ± 0.11**	**0.479 ± 0.08**	**1.056 ± 0.200**
				p (g)			
40 vs. 60	*0.045 (0.36)	>0.05 (0.20)	>0.05 (0.22)	>0.05 (0.34)	>0.05 (0.17)	>0.05 (0.26)	>0.05 (0.03)
40 vs. 80	*<0.001(0.71)	>0.05 (0.18)	*0.019 (0.44)	>0.05 (0.34)	>0.05 (0.37)	*0.002 (0.63)	>0.05 (0.30)
40 vs. 100	*<0.001 (0.89)	>0.05 (0.36)	*0.005 (0.65)	>0.05 (0.43)	*0.005 (0.43)	*<0.001 (0.91)	*0.015 (0.42)
40 vs. 120	*<0.001(0.82)	>0.05 (0.36)	>0.05 (0.44)	>0.05 (0.08)	*0.002 (0.62)	*<0.001 (1.15)	*<0.001 (0.72)
40 vs. 140	*<0.001 (0.99)	*0.03 (0.54)	*0.019 (0.72)	>0.05 (0.13)	*0.002 (0.72)	*<0.001 (1.45)	*<0.001 (0.89)
60 vs. 80	>0.05 (0.39)	>0.05 (0.00)	>0.05 (0.25)	>0.05 (0.00)	>0.05 (0.23)	*<0.001 (0.42)	*0.045 (0.27)
60 vs. 100	*0.03 (0.59)	>0.05 (0.18)	>0.05 (0.49)	>0.05 (0.10)	*0.045 (0.30)	*<0.001 (0.70)	*<0.001 (0.40)
60 vs. 120	>0.05 (0.54)	>0.05 (0.18)	>0.05 (0.25)	>0.05 (0.25)	*0.012 (0.48)	*<0.001 (0.94)	*<0.001 (0.71)
60 vs. 140	*<0.001 (0.71)	>0.05 (0.36)	>0.05 (0.56)	>0.05 (0.20)	*0.005 (0.59)	*<0.001 (1.26)	*<0.001 (0.87)
80 vs. 100	>0.05 (0.20)	>0.05 (0.16)	>0.05 (0.25)	>0.05 (0.10)	>0.05 (0.06)	*0.043 (0.24)	>0.05 (0.11)
80 vs. 120	>0.05 (0.18)	>0.05 (0.16)	>0.05 (0.00)	>0.05 (0.25)	>0.05 (0.22)	*<0.001 (0.45)	*0.002 (0.38)
80 vs. 140	*0.015 (0.36)	>0.05 (0.33)	>0.05 (0.28)	>0.05 (0.20)	*0.03 (0.33)	*<0.001 (0.77)	*<0.001 (0.55)
100 vs. 120	>0.05 (0.00)	>0.05 (0.00)	>0.05 (0.25)	>0.05 (0.34)	>0.05 (0.16)	>0.05 (0.21)	*0.011 (0.27)
100 vs. 140	>0.05 (0.18)	>0.05 (0.16)	>0.05 (0.00)	>0.05 (0.29)	>0.05 (0.27)	*<0.001 (0.55)	*0.002 (0.45)
120 vs. 140	>0.05 (0.16)	>0.05 (0.00)	>0.05 (0.28)	>0.05 (0.05)	>0.05 (0.12)	*<0.001(0.35)	>0.05 (0.19)

* Denotes significant difference

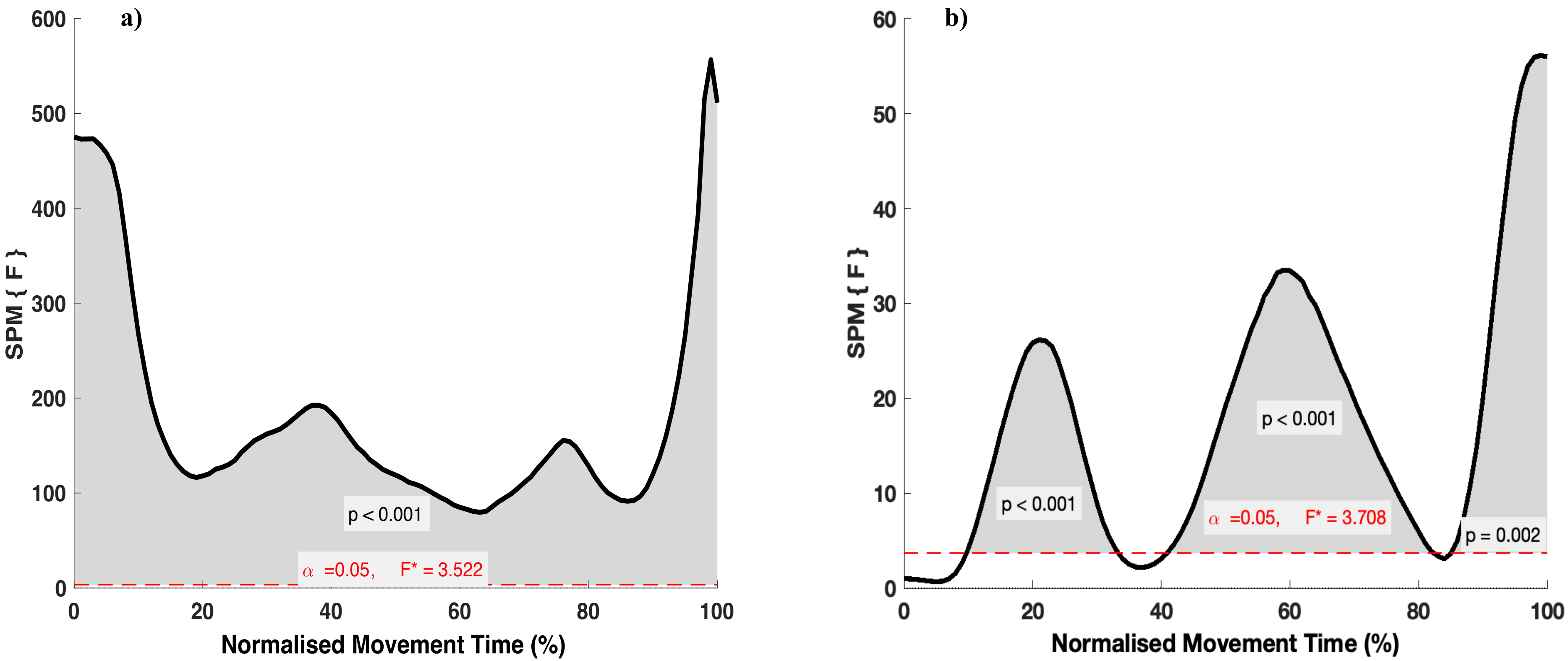


Figure 6.2-SPM Repeated measures ANOVA (SPM (F) statistic) during the hang pull at 40-140% 1-RM comparing a) force-time and b) velocity-time series. The dashed horizontal line designates the critical threshold for the SPM[F]statistics. The grey shaded area represents supra-threshold clusters, indicating statistically significant differences at those timepoints.

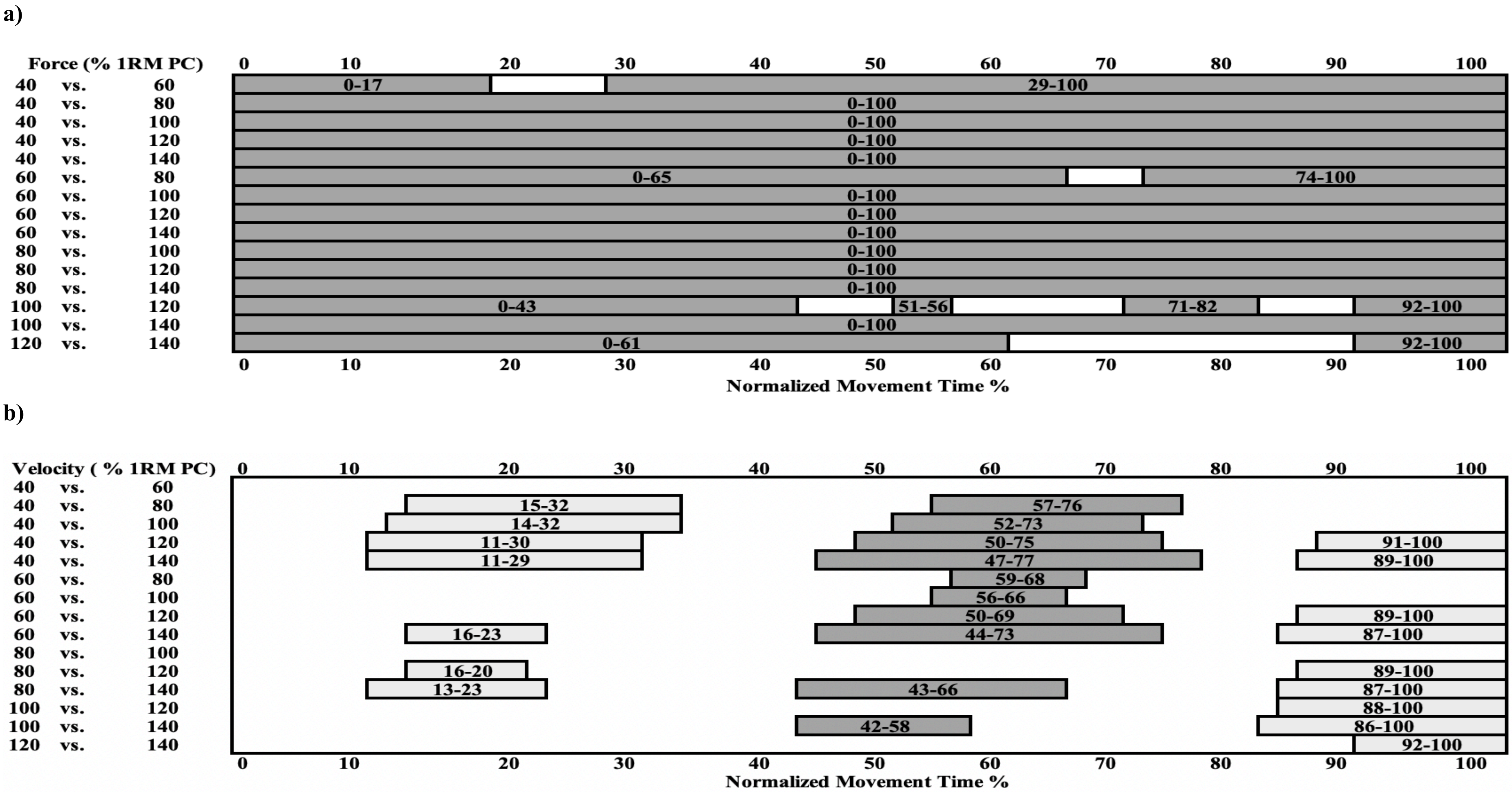


Figure 6.3-Summary of differences between hang pull intensity of loads of 40-,60,80,100,120 and 140% 1-RM power clean (1-RM PC) from SPM analysis for a) normalised force-time series, b) normalised velocity-time series, c) normalised power-time series. Shaded area illustrates significant differences between time points and intensity of load.

Higher load greater Lower load greater No differences

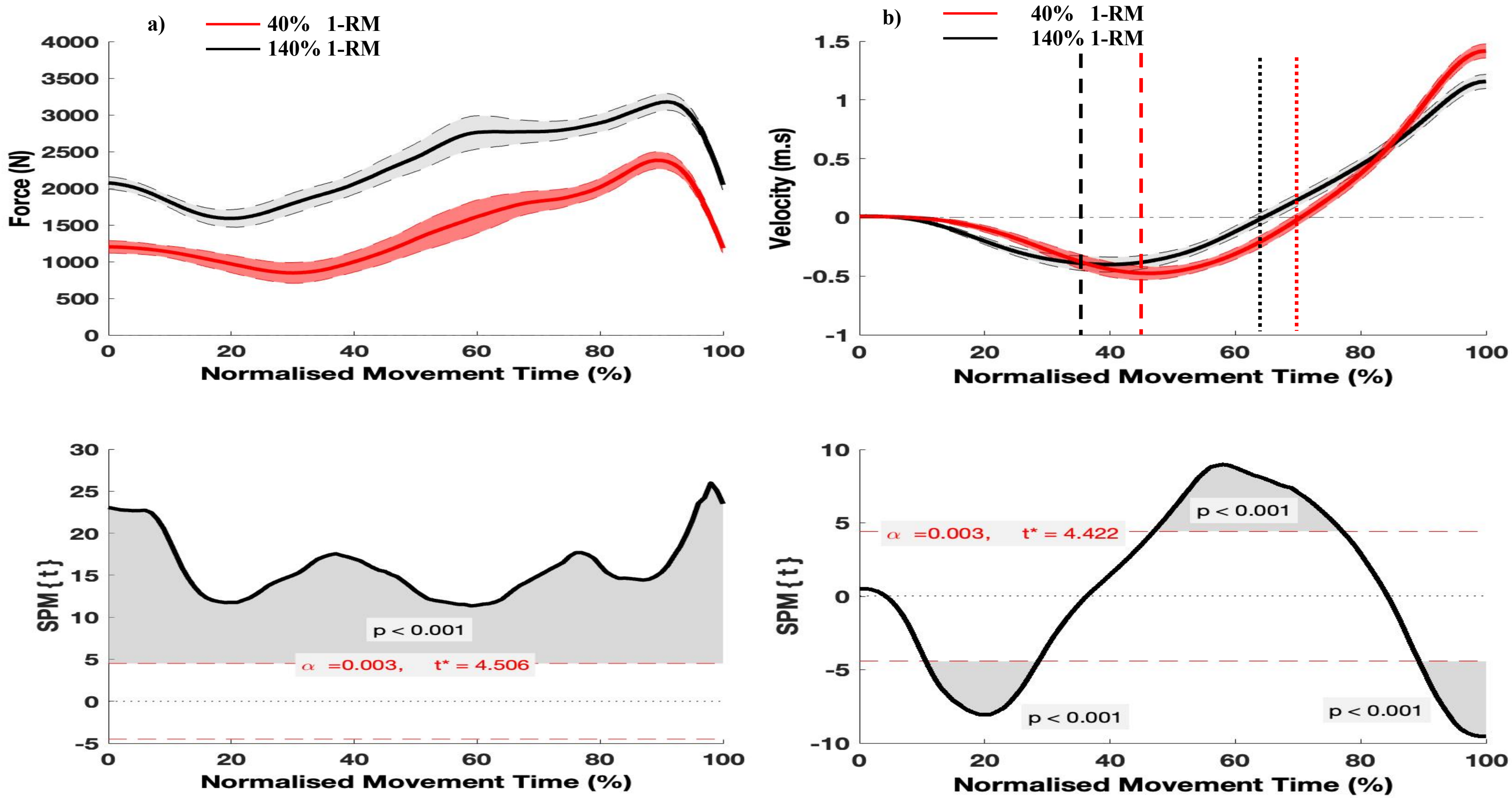


Figure 6.4-Top- mean and 95% confidence intervals for 40 vs.140% 1-RM a) time-normalised force, and b) time-normalised velocity. Bottom- Statistical parametric mapping (SPM) paired t-test for 40 vs.140% 1-RM - inference curve as a function of time, with suprathreshold clusters (shaded) and critical threshold for SPM[t] statistics (dashed line) that indicates the random field theory critical thresholds for significance (α = 0.003). The grey shaded area represents a significant difference at those time points. Vertical black dashed line = onset of braking 140% 1-RM; red dashed line = onset of braking 40% 1-RM; black dotted line = onset of propulsion 140% 1-RM; red dotted line = onset of propulsion 40% 1-RM.

6.8. DISCUSSION

The primary aim of this study was to determine how load affects HP force-time and velocity-time curves. These results may be applicable for researchers investigating time series data, and practitioners who prescribe weightlifting pulling derivatives within S&C programmes. As expected, a greater force was produced as load increased from 40-140% 1-RM. The greatest force was observed at 140% 1-RM, in line with previous research during the HP (230).

There was an initial greater negative velocity (unweighting earlier) at higher loads, followed by greater positive velocity during early propulsion phase and lower during late propulsion phase, with velocity being greatest at 40% 1-RM (Figure 6.1b; Figure 6.2b; Figure 6.3b). As intensity of load increased, force subsequently increased, with 140% 1-RM PC demonstrating 28.7% greater peak force than 40% 1-RM (Figure 6.1a; Figure 6.2a; Figure 6.3b). Similarly, as load increased, there were differences throughout the time-normalised movement, with 140% 1-RM PC showing greater force during 100% of time-normalised movement compared to 40-100% 1-RM PC, and 69% of time-normalised movement compared to 120% 1-RM PC (Figure 6.3a). This may provide an more comprehensive understanding to practitioners and researchers about where differences may occur outside of peak kinetic outputs, as only instantaneous peak and mean kinetic and kinematic variables have been described during the HP (230).

This is the first study to include SPM analysis of the HP across various loads, with previous authors investigating weightlifting derivatives at the same loads (185, 313, 314). However, these findings need to be interpreted carefully in relation to other weightlifting derivatives, as the specific task constraints differ compared to the HP.

A unique component of this study was the comparison of time-normalised velocity curves between loads. The increase of load altered the shape of the average velocity-time curves, with peak negative velocity in 140% 1-RM occurring 6% earlier in the time-normalised total movement than 40% 1-RM, thus affecting the phase alignment of the time-normalised movement Figure 6.1b**).** The greater the load, the greater the duration of significant differences in velocity compared to 40% 1-RM. Indeed, 140% showed significant differences across 59% of total movement time when compared to 40% 1-RM, but only 9% when comparing 40% and 60% 1-RM PC, highlighting key differences that occur outside peak variables **(**Figure 6.3b**)**.

The findings of this study demonstrate that supramaximal loads may not be appropriate to train propulsion velocity. This is evident during the late-stage propulsion phase due to the significant reduction in velocity at relative loads >100% 1-RM compared to all relative loads of <100% 1-RM (Figure 6.3b), in which there were significant differences in late-stage propulsion velocity between 40 vs. 120-140% 1-RM PC, which were not evident between 40 vs. 60-100% 1-RM PC (Figure 6.3b). Subjects likely managed to accelerate through the full triple extension more at loads of > 100% 1-RM, due to the likely reduced deceleration at heavier loads in a semi-ballistic task such as the HP. Performance outcomes will be partly influenced by intent during the propulsion phase, which may be submaximal at lighter loads. During the HP, and particularly at lower loads, deceleration occurs during the late propulsive phase of the lift as the subjects were instructed not to perform a full ballistic type movement such a jump shrug (298, 302), therefore the HP is likely an inferior exercise to develop propulsive velocity compared to the jump shrug at comparable loads.

Understanding where differences exist within the movement (i.e., early, or late phase) may allow for more detailed exercise prescription to target specific aspects of the second pull. Practically, the increased phase durations with load (i.e., braking, propulsion, and total movement time) results in increased time under tension, and the increased force production will likely determine the adaptive responses, especially within a task where maximal intent is essential. Visual inspection of the average time-normalised velocity curves in the present study shows that load affects when the braking and propulsion phase commences (Figure 6.1b and Figure 6.4b). At 140% 1-RM PC compared to 40% 1-RM PC, the braking phase occurs earlier (40-65% compared to 46-71%), which results in a shorter unweighting phase (40% of movement, compared to 46%), identical braking phase (25%) and longer propulsive (35% vs 29%) phases. Therefore, caution is necessary when interpreting differences between loads due to the misalignment of phases.

Practitioners need to consider that the training mesocycle focus, sets and repetitions in which the loads >100% 1-RM are prescribed may affect performance. Whilst peak force was greatest at 140% 1-RM PC, the repetition duration was also highest at 140% 1-RM PC and was significantly greater in duration than all loads (range = 3.6-16.1% greater **[**Table 6.1**]).** These longer durations of repetitions may be detrimental to performance in certain mesocycles, such as speed-strength and peaking mesocycles, in which athletes are aiming to peak for competitions, in which low levels of fatigue are generally warranted.

As an increase in load will result in an increased repetition duration, performing the same set and repetitions for high vs. lower loads may also influence performance due to the enlarged volume load and duration, therefore it is important that practitioners carefully select the most appropriate exercises with this in mind. To develop an athlete's force-velocity profile with weightlifting derivatives, a combination of heavy/lighter loads is recommended (301). Therefore, practitioners need to carefully consider excessive volumes in certain training mesocycles (e.g., competition) where the avoidance of fatigue accumulation is important. It is generally recommended that during peaking or competition phases, coaches should consider a reduction is training volume, whilst maintaining a greater intensity, as observed with exercises with a reduced range of motion (157), such as a HP.

It is evident that force and velocity are interdependent and that maximal power occurs at compromised levels of maximal force and velocity (122). Therefore, low-load, high-velocity exercises can elicit the high-velocity aspect of the force- velocity relationship, whereas greater loads address the high-force aspect (122). This relationship allows for power output during the HP to be greatest at loads of 100-140% 1-RM PC, compared to loads of < 100% 1-RM PC (230).

These results provide an understanding of the effect of load on force-, and velocity-time characteristics during the HP; however, to fully understand and investigate the purported benefits of training at varying loads during the HP, a longitudinal training intervention needs to be conducted. As loads of true maximal effort during pulling variations such as the HP have not yet been investigated, the load percentages may not be a true reflection of true weightlifting pulling ability and may in fact result in a greater 1-RM, and therefore greater loads during testing sessions. The authors acknowledge that is impractical to perform 1-RM tests for certain weightlifting derivatives due to the absence of criteria for a successful repetition. This study is not without its limitations. Firstly, although only male subjects were recruited, these results are also generalisable to athletes of comparable strength levels and training status, with no significant differences in the magnitude or ratio of muscle activity during a maximal isometric squat (252), and no differences in the effect of load between the sexes on kinetics or kinematics during the mid-thigh pull (52, 252). It is acknowledged that a greater sample size may be required for 1D data analysis (271). It is therefore possible that the present study was only adequately powered to detect effects of a slightly larger magnitude than that used in the discrete parameter power analysis. Additionally, onset of movement was calculated based on thresholds from jump and isometric mid-thigh pull research. Future research should assess whether this method is still appropriate for loaded exercises in which large dynamic system masses are prevalent.

6.9. PRACTICAL APPLICATIONS

These findings indicate that a greater negative velocity occurs at heavier loads compared to lower loads early in the unweighting phase (11-29% of the movement), and greater positive velocity at lower loads during the last 13%. These results demonstrate that load impacts differently throughout different portions of the time-normalised movement, and practitioners may be able to prescribe specific loads to target specific phases of the movement, with relative loads of 40% 1-RM PC most appropriate to maximise velocity during the HP, and relative loads of 140% 1-RM PC to maximise force. Practitioners are encouraged to use a combination of heavy and light loads when prescribing weightlifting pulling derivatives, to emphasise force and velocity or to maximise power. It may be more appropriate to prescribe the HP during a strength-speed and maximal strength phase given the ability to perform loads greater than the athlete's 1-RM PC. The results also show that the braking and propulsion phases commence at an earlier percentage of time-normalised movement at higher loads, whilst absolute durations are also greatest at higher loads. Researchers should normalise each phase individually and assess the effect of load to investigate if differences between loads exist within each time-normalised phase.

6.10. APPLIED RESEARCH PERSPECTIVE

Direct comparisons between phases cannot be performed as an increase in load results in a reduced unweighting phase and a longer propulsion phase which were shown in both Chapter's 5 and 6. Whilst it is beneficial in having an in depth understanding on acute differences through the entire movement in pulling derivatives, due to a reduced range of motion, it would be interesting to investigate acute whether redistributing rest periods to be shorter and more frequent periods allow for maintenance of kinetics and kinematics at 140% 1-RM PC during a weightlifting pulling derivative with a reduced range of motion.

The chapter below has been accepted for publication in the Journal of Strength and Conditioning Research and the reference numbers in this thesis will differ from the published manuscript. Any typos and grammatical errors from the published manuscript have been amended in this version, with the reference numbers in line with the references throughout the thesis.

Chapter 7: Study 5- The Effect of Rest Redistribution on Kinetic and Kinematic Variables During the Countermovement Shrug

7.1. ABSTRACT

This study compared the effects of rest redistribution (RR) on kinetic and kinematic variables during the countermovement shrug (CMS). Twenty-one male subjects (age 27.2 ± 3.3. years, height 1.78 ± 0.07 m, body mass 77.2 ± 10.6 kg, relative one repetition maximum (1-RM) power clean [PC] 1.22 ± 0.16 $kg.kg^{-1}$) performed the CMS using 140% of 1-RM PC with 3 traditional sets of 6 repetitions (TS), 9 sets of 2 repetitions with RR [45 s rest after 2 repetitions] (RR_{45}) and 6 sets of 3 repetitions with RR [72 rest after 3 repetitions] (RR_{72}). There were no significant or meaningful differences ($p > 0.05$, $g = 0.00$-0.15) between set configurations for any variables for the average of the 18 repetitions. There were no significant ($p > 0.05$) or meaningful ($g = 0.00$-0.14) differences for configuration and configuration x set for peak (PF) and mean force (MF), peak velocity (PV), impulse, phase duration, peak velocity decline, peak velocity maintenance and RPE. There was significantly greater ($p = 0.034$) albeit small ($g = 0.15$) difference for mean velocity (MV) during TS compared to RR_{72}. There were no significant or meaningful differences ($p > 0.05$, $g = 0.00$-0.09) between sets for PF, MF, PV, MV, impulse, and duration across TS, RR_{45} and RR_{72}. Rest redistribution protocols did not result in greater kinetics or kinematics during the CMS compared to TS, when total rest time was equated. Thus, shorter more frequent rest periods during the CMS may not be required to maintain force-time characteristics.

7.2. INTRODUCTION

Weightlifting pulling derivatives are a regularly programmed category of exercises as they emphasise rapid force development of the lower limbs but omit the catch phase associated with traditional weightlifting exercises, allowing for supramaximal loads (i.e., greater than the one repetition maximum [1-RM] power clean [PC]) (52, 55, 124, 126, 174, 176, 230, 232, 301, 302, 308, 309). The results of a recent study show that the countermovement shrug (CMS) results in greater kinetics (e.g., force [3640 ± 814 vs. 3135 ± 622 N , power 3100 ± 692 vs. 1839 ± 375 W]) and kinematics (e.g., velocity [1.15 ± 0.14 vs. 0.77 ± 0.12 $m.s^{-1}$) compared to the mid-thigh pull and therefore, the CMS may be a superior exercise to develop these characteristics, using loads as heavy as 140% 1-RM PC (232).

Performing multiple repetitions consecutively (i.e., traditional sets [TS]) has been shown to result in a decrease in velocity and barbell displacement in weightlifting derivatives (121, 126, 142, 176), an increased rating of perceived exertion (RPE) (176), leading to lower power outputs (142). To maintain kinetic and kinematic outputs during weightlifting exercises, the addition of intra-set rest periods, termed 'cluster sets' (CS) are frequently prescribed (126, 141, 142, 174, 176). Although a viable and effective method of exercise prescription, the accrual of time taken to complete training may not always be feasible in programmes that are time constrained due to other performance commitments. Therefore, redistribution of the total rest time (rest-redistribution [RR]) to create more frequent, lower volume, sets (some of the between set rest time is used intra-set) has become a point of interest for S&C professionals and researchers, in an attempt to minimise fatigue (140, 174, 176), and maintain kinetic and kinematic outputs (126, 141, 174, 176) during resistance training without increasing overall training duration. The reduction in rest between sets may mean that this is not as effective in minimising fatigue / maintaining kinetic and kinematic outputs, but it is a more time efficient strategy.

Tufano et al. (332) recently suggested that when compared to TS training, RR may only be beneficial when the sets are highly fatiguing, therefore the inclusion of RR at various loads may elicit different results. To the authors' knowledge, the influence of different set structures on weightlifting pulling derivatives (126, 174, 176) and catching derivatives (140-142) has only been explored in a few studies. Haff et al. (126) demonstrated greater peak barbell velocities and barbell displacement during a CS of clean pulls at 90% and 120% 1-RM PC compared to a TS. Further, Jukic and Tufano (174) demonstrated that when the inter-set rest periods of TS were redistributed via RR, to create shorter but more frequent sets, velocity and power were better maintained in the clean pull at loads of 80, 100 and 120% 1-RM PC, although power was calculated via inverse dynamics, which has been shown to overestimate power of the centre of mass (198). Additionally, Hardee et al. (140-142) showed greater vertical barbell displacement, velocity, and power output in addition to lower RPE scores during 3 sets of 6 repetitions of PC during CS structures with 80% of 1-RM compared to a TS structure.

To date, no researchers have investigated the effects of RR on kinetics and kinematics of the CMS. Further, as the CMS starts from a standing position (79) and not the floor, it is more time efficient to teach and easier to learn as compared with the full weightlifting movements, while permitting loads >1-RM and additional stimulus through the utilisation of the stretch-shortening cycle (79, 232, 302). While a reduction in exercise technique during consecutive repetitions of the PC has been previously shown (141), this might not be evident during the CMS due to it being a less complex exercise and kinetics and kinematics may be better maintained. The purpose of this study was to investigate the effects of RR on changes in kinetics (force, impulse) and kinematics (system velocity), propulsion duration, percentage decline in peak velocity, peak velocity maintenance and RPE during the CMS performed with 140% 1-RM PC. This load was chosen as it is the heaviest load previously examined, which also resulted in the greatest force produced during the CMS (232) and is likely the most fatiguing. It was hypothesised that the RR protocols containing shorter but more frequent rest periods would result in a greater force, system velocity over multiple repetitions and sets of the CMS exercise, while also resulting in lower propulsion duration, RPE and velocity loss than TS, in line with previous findings (126, 142, 173, 176).

7.3. METHODS

7.3.1. Experimental Approach to the Problem

A within-subject repeated-measures research design was used; whereby kinematic (peak and mean system velocity) and kinetic (peak and mean system force and net impulse) variables and propulsion phase duration were determined during the CMS performed with a relative load of 140% 1-RM PC, using three different set configurations. The aforementioned variables were calculated from the force-time data collected with all subjects performing all repetitions on a force plate. Prior to the experimental trials, subjects visited the S&C facility on 2 occasions (5–7 days apart), at the same time of day, to establish 1-RM PC reliability following a protocol previously used in a similar research (232). Additionally, familiarisation with 0–10 OMNI-RES scale: a resistance training specific RPE scale (269) was also undertaken during these sessions. Each subject performed the CMS exercise for one of the following randomly assigned and counterbalanced protocols: 3 TS of 6 repetitions with 180 seconds of inter-set rest (2 x 180 = 360 s of total rest), RR protocols of 9 sets of 2 repetitions with 45 seconds of inter-set rest (8 x 45 = 360 s of total rest [RR_{45}]) and 6 sets of 3 repetitions with 72 seconds of inter-set rest (5 x 72 = 360 s of total rest [RR_{72}]). All lifts were performed with a load of 140% 1-RM PC, with all subjects successfully completing a total of 18 repetitions in each of the 3 experimental sessions, which were separated by 48-72 hours (Figure 7.1).

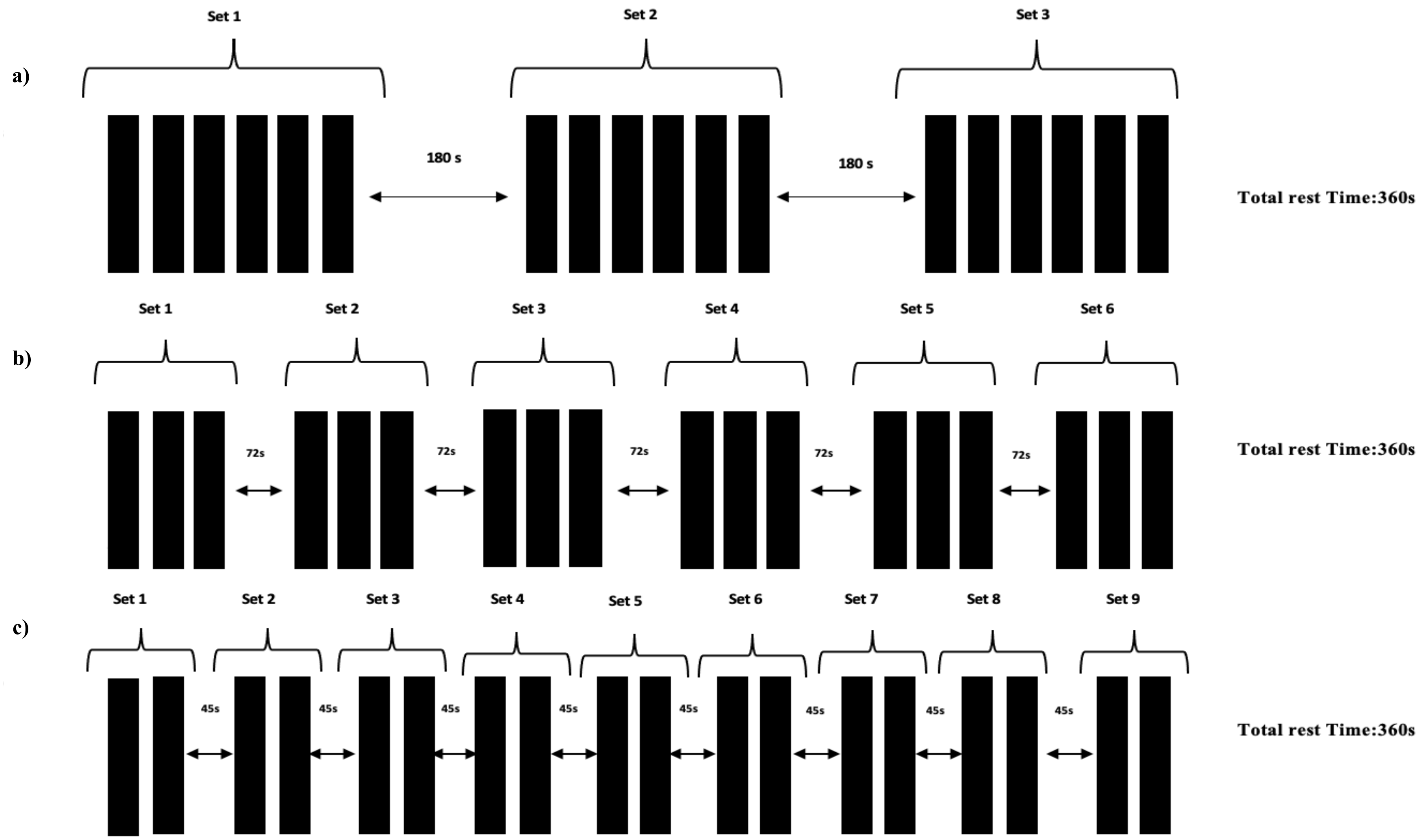


Figure 7.1-Set structure protocol. a) Traditional sets 3 sets of 6 repetitions, with 180 s of inter-set rest. b) Rest redistribution 6 sets of 3 repetitions, with 72 s of inter-set rest. c) Rest redistribution of 9 sets of 2 repetitions, with 45 s of inter-set rest.

7.4. SUBJECTS

Using the approximate average (specific values are not provided but illustrated in forest plots) effect sizes (Cohen's *d* = 0.60 [range = 0.20-1.10]) for pairwise comparisons of peak velocity, obtained by Tufano et al. (329) a statistical power of 0.80 and an alpha level of 0.05, a minimum sample size of 18 subjects was determined via *a priori* power analysis using the GPower 3.1 software (95). Twenty-one male subjects from various teams and individual sports including national level rugby, soccer, track cycling, martial arts, athletics (long jump) (age 27.2 ± 3.3. years, height 1.78 ± 0.07 m, body mass 77.2 ± 10.6 kg, resistance training experience 7.0 ± 2.2 years, relative 1-RM PC 1.22 ± 0.16 $kg.kg^{-1}$) who participated in regular resistance training (≥2 x week), including experience with weightlifting derivatives, volunteered to participate in this study. Subjects were free from injury, provided written informed consent prior to the commencement of testing and were requested to perform no strenuous activity during the 48 hours before testing. They were also asked to maintain their normal dietary intake before each session, and to attend testing sessions in a hydrated state. This investigation received prior ethical approval from the University of Salford's Institutional Ethics Committee and conformed to the principles of the World Medical Association's Declaration of Helsinki.

7.5. PROCEDURES

7.5.1. One Repetition Maximum Power Clean Testing

Each subject's 1-RM PC was assessed following a standardised protocol (8). For a detailed description of the protocol, see additional detail in (Section 3.3.3 page 107).

7.5.2. Experimental testing

For a detailed description of the experimental testing procedure performed during the CMS in this study, readers are referred to study 1, (Section 3.3.3, page 107). A photo sequence of the CMS is shown in Figure 3.2, page 111.

7.5.3. Force-Time Data Collection

Force-time data analysis for the CMS were conducted using a forward dynamics approach, using identical methods outlined in study 1, (Section 3.3.3, page 112). Since the number of repetitions per set differed between RR_{45} (2 repetitions per set), RR_{72} (3 repetitions per set) and TS (6 repetitions per set), RR_{45} sets 1 to 3, 4 to 6 and 7 to 9 and RR_{72} sets 1 to 2, 3 to 4 and 5 to 6 were grouped together to create '3 sets' for the purpose of comparing 3 RR_{45} sets, 3 RR_{72} sets to 3 TS sets.

For each protocol, the absolute values for PF, MF, PV, MV, IMP and duration were each combined and averaged across all 18 repetitions for each set configuration. In addition to the above protocol averages, the PV individual repetitions were each compared relative to each protocol's best repetition, resulting in 18 data points for each variable that were relative to the best repetition of each protocol. This was also performed for the '3 sets of 6' within each protocol.

The effect of set structure on PV decline across each set structure was also determined by a percent decline from the highest to the lowest repetition using the following equation: Percent decline = $[(\text{repetition}_{min} - \text{repetition}_{max})/\text{repetition}_{max}] \times 100$. Additionally, PV maintenance was calculated with the following equation: Maintenance set = 100 -[mean set- repetition_{max}] x100

(176). This approach was used 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 (142, 176).

7.5.4. Rating of perceived exertion

Familiarisation of the RPE scale took place during the 1-RM reliability testing sessions. During the experimental sessions, RPE (0 = no effort, 10 = maximal effort) was obtained after the 6th, 12^{th,} and 18th repetitions. Similar to previous research using weightlifting movements, these three RPE scores were averaged together to create an average RPE for each protocol and after each set (174, 176).

7.6. STATISTICAL ANALYSES

Statistical analyses were performed using SPSS version 26 (SPSS, Chicago, IL, USA). Distribution of data was analysed by using the Shapiro-Wilks test of normality. Reliability for 1-RM PC was assessed using two-way mixed intraclass correlation (ICC) and typical error expressed as a coefficient of variation percentage (CV%). The ICC was interpreted as poor (< 0.50), moderate (0.50–0.74), good (0.75–0.90), and excellent (>0.90) (193), with acceptable CV% classified as <10% (57).

Differences between set configurations and differences between individual repetitions were determined using repeated-measures analysis of variance (ANOVA) with Bonferroni post hoc analysis. An *a priori* alpha level was set at $p \leq 0.05$. Standardised differences were calculated using Hedges' *g* effect sizes and interpreted as described below. Differences between TS, RR_{45} and RR_{72} within each set was examined using two-way repeated-measures ANOVA. When a significant main effect or interaction was determined, Bonferroni post-hoc tests were conducted. Sphericity could not be assumed by the Mauchly test ($p > 0.05$) for all variables, and therefore, Greenhouse-Geisser adjustment was used. Standardised differences were calculated using Hedges' *g* effect sizes, as previously described (16) and interpreted according to Hopkins et al. (152): trivial (≤ 0.19), small (0.20-0.59), moderate (0.60-1.19), large (1.20-1.99), and very large (2.0-4.0).

7.7. RESULTS

Power clean 1-RM performances were highly reliable (ICC = 0.96, [95% CI = 0.83–0.98], %CV = 2.4% [1.7-3.1%] between session 1 (92.8 ± 13.3 kg) and session 2 (90.6 ± 12.0 kg). Countermovement shrug kinetics and kinematics assessed in this study have previously been reported to demonstrate moderate to excellent reliability and acceptable variability within our facility (232).

7.7.1. Kinetics and Kinematics Comparison between Protocols across 18 Repetitions

There were no significant or meaningful differences ($p > 0.05$, $g = 0.00\text{-}0.15$) between set configurations for any variables (Table 7.1 & Appendix 10.7.1). (Figures shown in appendices 10.7.1, 10.7.2, 10.7.3 and 10.7.4).

Table 7.1-Means ± SDs (95% Confidence Intervals) for kinetics and kinematics, phase duration and RPE for each set of 6 repetitions for traditional sets (3 x 6), rest redistribution 9 x 2 and 6 x 3

Variable	**Set 1 (95%CI)**	**Set 2 (95%CI)**	**Set 3 (95%CI)**	***p* value Hedges *g***		
				Set 1 vs Set 2	**Set 1 vs Set 3**	**Set 2 vs Set3**
Traditional Sets 3 x 6						
Peak Force (N)	3477 ± 518 (3242-3713)	3474 ± 535 (3230-3717	**3525 ± 530* (3284-3767)**	$p > 0.05$ 0.01	$p > 0.05$ 0.09	$p > 0.05$ 0.09
Mean Force (N)	3098 ± 449 (3893-3302)	3081 ± 444 (2879-3283)	**3109 ± 460* (2899-3318)**	$p > 0.05$ 0.04	$p > 0.05$ 0.06	$p > 0.05$ 0.02
Peak Velocity (m.s-^{1})	1.00 ± 0.10 (0.96-1.05)	1.01 ± 0.08 (0.97-1.04)	**1.03 ± 0.11* (0.98-1.08)**	$p > 0.05$ 0.11	$p > 0.05$ 0.28	$p > 0.05$ 0.20
Mean Velocity (m.s-^{1})	0.57 ± 0.06 (0.54-0.60)	0.57 ± 0.06 (0.54-0.60)	**0.58 ± 0.08* (0.55-0.62)**	$p > 0.05$ 0.00	$p > 0.05$ 0.14	$p > 0.05$ 0.14
Impulse (N.s)	214 ± 44 (194-234)	214 ± 40 (196-233)	**219 ± 44* (198-239)**	$p > 0.05$ 0.00	$p > 0.05$ 0.11	$p > 0.05$ 0.12
Phase Duration (s)	0.374 ± 0.050 (0.351-0.397)	0.376 ± 0.050 (0.353-0.399)	**0.378 ± 0.053* (0.354-0.402)**	$p > 0.05$ 0.04	$p > 0.05$ 0.08	$p > 0.05$ 0.04
RPE	7.02 ± 1.36 (6.40-7.64)	7.33 ± 1.28 (6.75-7.92)	**7.57 ± 1.16* (7.04-8.12)**	$p > 0.05$ 0.23	$p = 0.018$** 0.43	$p > 0.05$ 0.19
Velocity Decline (%)	13.1 ± 4.0 (14.77-11.42)	**14.9 ± 6.0 (17.85-11.96)**	13.38 ± 7.0 (16.46-10.30)	$p > 0.05$ 0.35	$p > 0.05$ 0.05	$p > 0.05$ 0.23
Velocity Maintenance (%)	**94.15 ± 0.02 (93.1-95.07)**	92.33 ± 0.04 (90.53- 94.14)	93.33 ± 0.05 (91.27-95.40)	$p > 0.05$ 0.58	$p > 0.05$ 0.22	$p > 0.05$ 0.22
Rest Redistribution 9 x 2						
Peak Force (N)	3471 ± 508 (3240-3702)	**3476 ± 552* (3225-3727)**	3475 ± 514 (3241-3709)	$p > 0.05$ 0.01	$p > 0.05$ 0.01	$p > 0.05$ 0.00
Mean Force (N)	3079 ± 437 (2880-3277)	3076 ± 456 (2868-3284)	**3083 ± 447* (2880-3287)**	$p > 0.05$ 0.01	$p > 0.05$ 0.01	$p > 0.05$ 0.02
Peak Velocity (m.s-^{1})	1.01 ± 0.10 (0.96-1.05)	1.01 ± 0.11 (0.96-1.06)	**1.02 ± 0.12* (0.97-1.08)**	$p > 0.05$ 0.00	$p > 0.05$ 0.09	$p > 0.05$ 0.09
Mean Velocity (m.s-^{1})	0.56 ± 0.06 (0.53-0.59)	0.56 ± 0.07 (0.53-0.59)	**0.57 ± 0.08* (0.54-0.60)**	$p > 0.05$ 0.00	$p > 0.05$ 0.14	$p > 0.05$ 0.13
Impulse (N.s)	214 ± 44 (194-234)	216 ± 44 (195-236)	**218 ± 45* (198-239)**	$p > 0.05$ 0.04	$p > 0.05$ 0.09	$p > 0.05$ 0.04
Phase Duration (s)	0.377 ± 0.058 (0.351-0.403)	**0.383 ± 0.062* (0.354-0.411)**	0.381 ± 0.058 (0.355-0.407)	$p > 0.05$ 0.10	$p > 0.05$ 0.07	$p > 0.05$ 0.03
RPE	6.71 ± 1.23 (6.15-7.27)	7.36 ± 1.11 (6.85-7.86)	**7.55 ± 1.30* (6.95-8.14)**	$p = 0.002$** 0.54	$p = 0.002$** 0.65	$p > 0.05$ 0.15
Velocity Decline (%)	**16.38 ± 7.0 (19.55-13.22)**	13.1 ± 4.0 (14.9-11.22)	13.29 ± 7.0 (16.07-10.51)	$p > 0.05$ 0.56	$p > 0.05$ 0.47	$p > 0.05$ 0.03
Velocity Maintenance (%)	92.10 ± 0.03 (90.52-93.67)	**93.62 ± 0.02 (92.64-94.60)**	93.43 ± 0.03 (92.13-94.73)	$p > 0.05$ 0.58	$p > 0.05$ 0.43	$p > 0.05$ 0.07
Rest Redistribution 6 x 3						
Peak Force (N)	3444 ± 512 (3211-3677)	3424 ± 511 (3192-3657)	**3465 ± 551* (3214-3716)**	$p > 0.05$ 0.04	$p > 0.05$ 0.04	$p > 0.05$ 0.08
Mean Force (N)	3069 ± 426 (2876-3263)	3053 ± 435 (2855-3251)	**3070 ± 457* (2862-3279)**	$p > 0.05$ 0.04	$p > 0.05$ 0.00	$p > 0.05$ 0.04
Peak Velocity (m.s-^{1})	1.01 ± 0.07 (0.97-1.04)	1.00 ± 0.10 (0.96-1.05)	**1.01 ± 0.10* (0.97-1.06)**	$p > 0.05$ 0.11	$p > 0.05$ 0.00	$p > 0.05$ 0.11
Mean Velocity (m.s-^{1})	0.56 ± 0.04 (0.54-0.58)	0.56 ± 0.06 (0.53-0.58)	**0.56 ± 0.07* (0.53-0.59)**	$p > 0.05$ 0.00	$p > 0.05$ 0.00	$p > 0.05$ 0.00
Impulse (N.s)	214 ± 39 (196-232)	214 ± 43 (194-233)	215 ± 43 (195-235)	$p > 0.05$ 0.00	$p > 0.05$ 0.02	$p > 0.05$ 0.02
Phase Duration (s)	0.380 ± 0.055 (0.355-0.406)	0.386 ± 0.057 (0.359-0.412	**0.386 ± 0.060* (0.358-0.414)**	$p > 0.05$ 0.10	$p > 0.05$ 0.10	$p > 0.05$ 0.00
RPE	6.98 ± 1.23 (6.42-7.54)	7.43 ± 1.15 (6.90-7.95)	**7.76 ± 1.26* (7.19-8.34)**	$p = 0.001$** 0.37	$p < 0.001$** 0.61	$p = 0.037$ ** 0.62
Velocity Decline (%)	**15.52 ± 7.0 (18.55-12.50)**	14.81 ± 5.0 (13.31-12.31)	12.57 ± 5.0 (15.00-12.15)	$p > 0.05$ 0.11	$p > 0.05$ 0.48	$p > 0.05$ 0.44
Velocity Maintenance (%)	91.90 ± 0.03 (90.43-93.38)	92.71 ± 0.03 (91.47-93.95)	**94.14 ± 0.03 (92.95-95.33)**	$p > 0.05$ 0.26	$p > 0.05$ 0.73	$p > 0.05$ 0.47
Bold denotes peak value in each set across 6 repetitions; ** denotes significant differences between sets						

Table 7.2-Differences between each repetition for peak velocity in each protocol using Hedge's *g* effect size

Set Protocol	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 4**	**Rep 5**	**Rep 6**	**Rep 7**	**Rep 8**	**Rep 9**	**Rep 10**	**Rep 11**	**Rep 12**	**Rep 13**	**Rep 14**	**Rep 15**	**Rep 16**	**Rep 17**	**Rep 18**
TS vs. RR_{45}	0.09	0.41	0.36	0.09	0.10	0.32	0.10	0.16	0.16	0.18	0.08	0	0.18	0.08	0.45	0.09	0.15	0.16
TS vs. RR_{72}	0.10	0.17	0.11	0.56	0.29	0.39	0	0	0.16	0.21	0.28	0	0.18	**0.39***	0.27	0.39	0	0.13
RR_{45} vs. RR_{72}	0	0.27	0.48	0.47	0.39	0	0.09	0.15	0.33	0.34	0.36	0	0	**0.44***	0.22	0.41	0.16	0.33

TS = Traditional Set; RR_{45} = Rest Redistribution 45 seconds; RR72 = Rest Redistribution 72 seconds; Rep = repetition
***Significant difference between each repetition in each protocol ($p \leq 0.028$)**

7.7.2. Kinetic and Kinematic Differences between Individual Repetitions within Each Protocol

Traditional Sets

During the TS, there were no significant or meaningful differences between repetitions for PF ($p > 0.05$, $g = 0.00$-0.27), MF ($p > 0.05$, $g = 0.00$-0.20) or IMP (Appendix 10.7.1 a-b,e shown). There were no significant differences for between repetitions PV ($p > 0.05$, $g = 0.00$-0.71) or MV ($p > 0.05$, $g = 0.14$-0.83), albeit trivial to moderate magnitude (Appendix 10.7.1 3c-d). Propulsion phase duration was significantly greater during repetitions 11 and 12 vs. 10 ($p \leq 0.046$, $g = 0.35$-0.57) (Appendix 10.7.1f).

Rest Redistribution 9x2 (RR_{45})

During the RR_{45} configuration, there were no significant or meaningful differences between repetitions for PF and MF ($p > 0.05$, $g = 0.02$-0.20) (Appendix 10.7.1a-b). In contrast, there was significantly and meaningfully greater PV during repetition 2 vs. 1 and 3 ($p \leq 0.046$, $g = 0.57$-0.67) (Appendix 10.7.1c), with no significant or meaningful differences for MV ($p > 0.05$, $g = 0.00$-0.61) or propulsion phase duration between repetitions ($p > 0.05$, $g = 0.08$-0.47) (Appendix 10.7.1d and appendix 10.7.1f). There was significantly greater IMP during repetition 3 vs. 2 ($p = 0.031$, $g = 0.31$) (Appendix 10.7.1e). All figures shown in appendix 10.7.1.

Rest Redistribution 6x3 (RR_{72})

During the RR_{72} configurations, there were no significant or meaningful differences between repetitions for PF ($p > 0.05$, $g = 0.06$- 0.31), MF ($p > 0.05$, $g = 0.02$- 0.91), PV ($p > 0.05$, $g = 0$-0.65) and MV ($p > 0.05$, $g = 0.15$-0.60), (Appendix 10.7.1a-d). Impulse was significantly greater during repetition 17 vs. 10 ($p = 0.046$, $g = 0.27$) (Appendix 10.7.1e), whilst propulsion phase duration during repetitions 8 was significantly greater than 13 (p = 0.015; g = 0.36) (Appendix 10.7.1f).

Set by Set Comparison

There were no significant ($p > 0.05$) or meaningful differences (g = 0.00-0.14) for configuration and configuration x set interaction for PF, MF, PV, IMP, phase duration, peak velocity decline (PVD), peak velocity maintenance (PVM) and RPE (Appendix 10.7.1 a-f; Appendix 10.7.2 a-b; Appendix 10.7.3a-b; Appendix 10.7.4 a-b), whilst there was a significantly greater (p = 0.034), yet small (g = 0.15) difference in MV during TS compared to RR_{72}. There were no significant or meaningful differences ($p > 0.05$, g = 0.00-0.09) between sets for PF, MF, PV, MV, IMP, and duration across TS, RR_{45} and RR_{72}. (Appendix 10.7.1a-f). There were no significant or meaningful differences in PVD ($p > 0.05$, g = 0.03- 0.56) (Appendix 10.7.3a-b), whilst between-set PVM also showed no significant, yet trivial-to-moderate differences (p > 0.05, g = 0.07- 0.73) (Appendix 10.7.2a-b). There was significantly greater RPE in set 3 compared to set 1 (p = 0.018, g = 0.43) for the TS configuration, and significantly and meaningfully (p = 0.002, g = 0.15-0.65) greater RPE during sets 2 and 3 compared to set 1 for the RR_{45} configuration. There was significantly and meaningfully greater ($p \leq 0.001$, g = 0.37-0.61) RPE during sets 2 and 3 compared to set 1, and significantly and meaningfully (p = 0.037, g = 0.62) greater RPE during set 3 compared to set 2 during RR_{72} (Table 7.1; Appendix 10.7.4a).

7.8. DISCUSSION

The primary aim of this study was to investigate the effects of RR protocols on kinetics, kinematics and perceptual fatigue during the CMS performed using 140% 1-RM PC, when compared to TS protocols. The main finding was that when compared across all 18 repetitions, RR protocols did not result in greater kinetics (PF, MF, IMP) or kinematics (PV, MV) propulsion phase duration, PVD and PVM, compared to TS, highlighting that shorter more frequent rest periods during the CMS may not be required to maintain force-time characteristics. When assessing differences between sets within each set protocol, no significant or meaningful differences existed for any variable except RPE (Table 7.1).

Measurement of RPE across entire set-protocols was not significantly different in RR protocols compared to TS, which is not surprising giving that there were no significant differences in kinetics or kinematics between protocols, although the RR_{45} protocol reported the lowest RPE, with the greatest RPE during set 3 in all configurations. Although the RPE is similar across the 18 repetitions, the lowest RPE reported was still reported within the RR_{45} protocol. It is also worth considering that the barbell was placed on the safety rack after each set. The TS group therefore unracked for 3 sets, the RR_{45} group 9 sets and the RR_{72} for 6 sets, which may have contributed to the overall fatigue.

The small to trivial differences may be attributed to the fact that the CMS may not actually be fatiguing, owing to a small barbell displacement from mid-thigh to triple extension (79, 232, 302), even though this exercise was performed with loads of 140% 1-RM, highlighted by the non-significant differences in kinetic, kinematic and RPE measures. It is purposed that an increased occurrence of rest periods may improve kinetics, kinematics and lower RPE (174). Further, due to significant differences observed between some repetitions, future research should focus on identifying individual differences between repetitions as some athletes may benefit from short and more frequent RR, whilst others may benefit for a TS loading paradigm. In contrast, Haff et al. (126) demonstrated that barbell velocity and displacement decreased with TS during the clean pull at loads of 90% and 120% 1-RM PC, although a greater displacement, and therefore work was performed compared to the CMS. Jukic et al. (174) also demonstrated when the long inter-set rest periods of TS were redistributed into shorter, but more frequent sets, barbell velocity and power were better maintained during the clean pull. It should be noted that several of the participants verbally reported that the RPE may be related to 'hand and grip' issues rather than the exertion of the exercise, and that the most difficult part was holding for the duration of the set.

In agreement with previous findings (15, 174), the results of this study also demonstrate that the first repetition is not always the fastest (Appendix 10.7.1c). Many factors likely contribute to this, but it may be explained by the enhanced use of elastic energy during the second or third repetitions (15). Although not directly measured, this is likely if the velocity of the countermovement changes between repetitions. Given the fact that propulsion velocities differ between some repetitions (Appendix 10.7.1c), it is possible that this could be related to the athlete performing each repetition with maximal intent and stimulation of the stretch shortening cycle (333). When the athlete starts the CMS, the eccentric loading in terms of barbell momentum is likely limited by CMS depth. However, as the system centre of mass is vertically propelled via the rapid triple extension during the first repetition, momentum is increased for the subsequent repetition, and barbell oscillation may occur due to the 140% load. As the system falls back from this greater displacement, it generates more speed, which can be used to increase greater eccentric rate of force development (15). It is important not to base fatigue or calculate decrements based on the first repetition of a set if this does not exhibit the best performance, but identifying the best and the worst repetition, using those and all the other repetitions within a training session to provide a more thorough analysis of the training session, which can be used to prescribe more precise training programmes.

When comparing the system PV of each individual repetition in each protocol to each individual repetition in the other (i.e., TS repetition 1 vs. RR_{45} repetition 1 vs. RR_{72} repetition 1) and so on, there were no significant differences, except during repetition 14 in which TS and RR_{45} were significantly greater ($p \leq 0.028$) than RR_{72} (Table 7.2). It is logical to deduce that the 3rd repetition of a RR_{72} protocol would be slower than the 3rd repetition during RR_{45} (as the 3rd repetition always comes after a 45 second recovery). As this only occurred in one repetition of 18, it is likely an anomaly in the findings and cannot be explained clearly. However, it is possible that the greater un-racking and re-racking of the barbell may contribute to the overall subjective intensity of each set. Similar trends existed between IMP and PV with significantly greater PV and IMP during for example repetition 2 vs. 1 and 3 which may be explained by the impulse-momentum theorem, as a greater impulse will result in a greater velocity (279).

It is clear that the repetition-velocity relationship between studies will likely result in different findings across exercise selection, exercise difficulty and exercise intensity, as not all studies showed a linear decrease across repetitions (15, 174, 329, 330). Similarly, the amount of work performed would likely be different due to differences in displacement between exercise selection, as the greater displacement would result in greater work performed, in which exercises with lower displacements (i.e., CMS) could result in in a more efficient method of a strength-power stimulus, which is potentially beneficial during competition periods (302).

In determining how fatigue during a set structure can influence a training session, researchers often assess the decline of velocity or power to determine the efficacy of the protocol (173, 174, 329, 331). The decline in variables are often calculated as the absolute or percentage difference between the first and the final repetition (330), with it being assumed that the first repetition is the fastest and the last is the slowest, which is not always evident (142, 174). In agreement with the findings of those studies, the results of this study also show that the first repetition is not always the fastest or the last repetition the slowest (Appendix 10.7.1c-d), and this could be partly explained by the subject's motivation, the adoption of a 'pacing strategy', or the method of the data collection process. In this study, data were collected with the subjects standing on a force plate, and the onset of movement was determined in line with previous research, where a quiet period of a minimum of 1 s is needed (259). This is not required when movement is collected via a linear position transducer, therefore holding supramaximal loads for a duration of 1 s for multiple sets could potentially result in additional fatigue when compared to a linear position transducer measurement during a clean pull from the floor, in which the barbell rests on the floor between repetitions (174, 176), making direct comparisons to this study difficult, although the first repetition was always not the best in another study (174). This approach of holding the barbell during repetitions was used in all set configurations and was therefore standardised across all configurations. Similar to Tufano et al. (330), the inclusion of RR_{45} or RR_{72} did not have a positive effect on MF or PF production, as there was no significant or meaningful change in PV or MV through the inclusion of RR protocols, as such a change in power output is unlikely.

When assessing the decline in PV from the best repetition (fastest out of the 18 repetitions) to worst repetition (slowest out of the 18 repetitions) during the TS structure, PV showed a decline of 22.2% across all 18 repetitions. However, when calculated relative to fastest repetition, PV maintenance (when all repetitions are accounted for) was 88.7%, which only shows a drop in velocity of 11.3%. Similarly, when RR_{45} and RR_{72} was assessed, PV showed a decline (fastest to slowest) of 22.7% and 22.8% respectively whilst PV was maintained at 88.9% and 89.4%. Using only decline calculations that include differences between two repetitions (either first to last or best to worst) may result in misleading interpretations of the true reflection of the demands of the training session as the other 16 repetitions are not accounted for. Tufano et al. (330) reported a decline in velocity and power of 23% during the back squat, but when all repetitions were taken into account (i.e. maintenance was calculated), they reported a maintenance of 92%, resulting in an average decline of 8%. When assessing the clean pull exercise from the floor, Jukic and Tufano. (174) reported a decrease in velocity between 14-17%, and a velocity maintenance of 91.6-93.6%. Further investigation is needed to determine if reporting decline or maintenance metrics is the most appropriate method to inform practitioners. Although not assessed in this study, the use of first to last repetition yields interesting findings. For example, during TS, there was an increase in velocity of 6.1% from first to last, with 8 of 21 subjects demonstrating a decrease in PV. For RR_{45}, a 10.2% increase was noted with 7 of 21 subjects demonstrating a decrease in PV and, for $RR_{72,}$ a 4% increase was shown, with 8 of 21 subjects decreasing from first to last repetition This therefore highlights practical implications that individual responses may be preferential when reporting the efficacy of PV decrements, due to the differences observed between subjects.

Researchers have previously examined the effect of a multiple set protocol on RPE and reported significant increases in RPE across repetitions with each subsequent set (140, 176). In agreement, this study also showed significantly meaningful differences in RPE within each individual set configurations (Table 7.1; Appendix 10.7.4a). Given the fact that there was no significant difference and reduction in force and velocity (and therefore power) it could be assumed that phosphocreatine did not deplete substantially as this would likely also decrease force production capabilities during high-intensity exercise as previously shown (32).

In this study, RPE scores progressively increased from set 1 to set 3 for TS, RR_{45} and RR_{72}, with the 3rd set often eliciting the greatest kinetic and kinematic values (Table 7.1; Appendix 10.7.4a), which is comparable to other studies that investigated weightlifting derivatives. Hardee et al. (140) investigated the effect of 3 traditional sets of 6 of PC 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) was performed, with the RPE showing a linear increase with an increase in sets which is similar to this study (Table 7.1; Appendix 10.7.4a). Regardless of whether RR or TS configurations were performed, Jukic et al. (176) also showed that RPE increased across sets at all loads, but demonstrated that RR was perceptually easier compared to TS, even though previous authors have suggested that the number of repetitions in sequence may have an important role in RPE response (216). When averaged across the 18 repetitions, Jukic and Tufano (176) reported significantly lower RPE during the RR protocols compared to TS, which is in contrast to this study. Other studies have also shown that set configurations with fewer repetitions per set result in lower RPE (174, 176, 216). Differences between this study and other studies may be a result of the different exercises performed, with the other studies performing lower intensities, but more importantly, exercises with a much greater movement displacement (i.e., parallel squat and clean pull from the floor) when compared to the CMS. Further investigations on the hang snatch pull and hang clean pull at supramaximal loads are needed to potentially clarify this statement. Additionally, from a practical perspective, having athletes perform RR protocols should allow practitioners to give more frequent technical feedback.

7.9. PRACTICAL APPLICATIONS

The results demonstrated that a lack of meaningful differences in velocity and force (and likely power) may have been due to the lack of high levels of fatigue during TS, potentially due to the minimal displacement of the CMS. If practitioners seek to implement RR protocols instead of TS configurations, this may only be beneficial if the TS configuration is highly fatiguing or when an exercise with a larger range of motion is performed. Therefore, RR is not required during sets of 6 repetitions of CMS at 140% 1-RM PC, likely due to the limited displacement and therefore work performed, which did not result in a meaningful decrease in force, velocity, or impulse. As 3x6 repetitions did not result in any significant or meaningful differences between sets for kinetic or kinematic variables, it may be possible for athletes to perform > 6 repetitions per set at 140% 1-RM PC, which may allow for higher repetition supramaximal loading in the CMS, and this warrants further investigation. Practitioners need to be aware of the issues when interpreting differences between two repetitions on velocity decrement. Future direction should investigate individual responses to training which will likely result in more accurate training prescription.

7.10. APPLIED RESEARCH PERSPECTIVE

Based upon the above findings, it appears that RR does not improve kinetic or kinematic compared to TS sets during the CMS at 140% 1-RM PC, likely due to the reduced ROM during the CMS. Therefore, it is suggested to investigate if this is evident during the HP at 140% 1-RM as there is a greater ROM, and theoretically a more difficult pulling derivative to perform.

Chapter 8: Study 6- The Effect of Rest Redistribution on Kinetic and Kinematic Variables During the Hang Pull

8.1. ABSTRACT

The aim of this study was to compare the effects of rest redistribution (RR) on kinetics and kinematics during the hang pull (HP). Twenty-one male athletes (age 29.5 ± 4.3 years, height 1.78 ± 0.07 m, body mass 75.17 ± 11.11 kg, relative one repetition maximum [1-RM] power clean [PC] 1.17 ± 0.14 kg.kg^{-1}) performed the HP using 140% of 1-RM PC with 3 traditional sets of 6 repetitions (TS), 9 sets of 2 repetitions with RR [45 s rest after 2 repetitions] (RR_{45}) and 6 sets of 3 repetitions with RR [72 rest after 3 repetitions] (RR_{72}). There was a higher peak velocity (PV) during RR_{72} (1.18 ± 0.11 m.s^{-1}) compared to RR_{45} (1.14 ± 0.11m.s^{-1}) for the average of 18 repetitions ($p = 0.025$, $g = 0.36$). There was a main effect for set configuration with greater peak force (PF) ($p < 0.001$, $g = 0.14$) during RR_{72} compared to RR_{45}, with greater PV and impulse ($p < 0.001$, $g = 0.19$-0.36) during RR_{72} compared to RR_{45}, with greater velocity decline during RR_{45} compared to TS and RR_{72} ($p \leq 0.043$, $g \geq 0.43$) and peak velocity maintenance (PVM), with greater ($p = 0.042$, $g = 0.44$) PVM for RR_{72} compared to RR_{45}. Rest redistribution protocols did not result in greater kinetics or kinematics during the HP compared to TS; although performing RR_{72} resulted in higher PF, PV, and impulse, with improved PVM, whilst minimizing PVD compared to RR_{45}.

8.2. INTRODUCTION

Weightlifting pulling derivatives are regularly implemented as they emphasise rapid force development, however, omitting the catch phase allowing for the use of loads greater than an athlete's one repetition maximum (1-RM) power clean (PC) (126, 174, 176, 230, 232, 302).

Recently published results show that the hang pull (HP) results in consistently higher mean system force, power, and velocity across multiple loads, with greater peak system velocity, barbell velocity, peak power, and net impulse compared to the pull from the knee with loads ≥100% 1-RM PC (230). As such, this may be a superior exercise to develop these characteristics compared to weightlifting derivatives that do not emphasise the utilisation of the stretch-shortening cycle (SSC [e.g., the pull from the knee]), especially at loads >1-RM PC (230).

When performing multiple repetitions consecutively (i.e., traditional sets [TS]) there is a general trend of a progressive decrease in barbell velocity and displacement in weightlifting derivatives (126, 142, 176), with an increased rating of perceived exertion (RPE) (176), leading to reductions in power output (142). To maintain kinetics and kinematics during weightlifting exercises, additional intra-set rest periods, termed 'cluster sets' are frequently prescribed (126, 141, 142, 174, 176). While 'cluster sets' are an excellent method of minimizing intra-set fatigue, the additional time taken to complete training (due to the added intra-set rest between clusters) is not always feasible in time constrained training sessions or performance commitments. Redistribution of the total rest time (rest-redistribution [RR]) to construct more frequent sets (some of the between set rest time is used intra-set) has been prescribed to minimise fatigue (140, 174, 176) and maintain kinetics and kinematics (126, 141, 174, 176), without increasing training duration may be of benefit to practitioners in applied environments.

Jukic and Tufano (174) suggested that when compared to TS training, RR may only be beneficial when the sets are highly fatiguing, therefore, RR implemented across various loads or different displacements may result in different findings (231). Previously, researchers have demonstrated that cluster sets and RR are generally better at maintaining velocity, power, barbell displacement, with lower RPE than TS structures across various loads during weightlifting movements (126, 140-142, 174). As greater power has been previously associated with lower RPE scores in weightlifting movements (140), non-fatiguing set structures are likely beneficial in weightlifting pulling derivatives.

To date, no researchers have investigated the effects of RR on the kinetics and kinematics of the hang pull (HP). As the HP omits the catch (230) performing loads >100% 1-RM PC are achievable (230, 302). While PC technique has been show to deteriorate across consecutive repetitions (141), this may not be evident during the HP due to it being a less complex exercise with a reduced range of motion compared to the PC, and as such, kinetics and kinematics may be better maintained within and across multiple sets. This may also allow for an alternative stimulus for the prescription of a high force and semi-ballistic training modality with higher training volumes within a training session.

The purpose of this study was to investigate the effects of RR on changes in kinetics (force, impulse) and kinematics (system velocity), propulsion duration, percentage decline in peak velocity (PVD), peak velocity maintenance (PVM), and RPE at 140% 1-RM PC during the HP over multiple repetitions and sets. This load was selected as it was the load that previously maximised force during the HP and is likely the most fatiguing, as it is the heaviest load previously examined (230). It was hypothesised that the RR protocols containing shorter but more frequent rest periods would result in a greater force and system velocity over multiple repetitions and sets of the HP exercise, while also resulting in lower propulsion duration and RPE compared to TS configurations, in agreement with previous findings (126, 142, 173, 176).

8.3. METHODS

8.3.1. Experimental Approach to the Problem

A within-subject repeated-measures research design was used; whereby kinematic (peak and mean system velocity) and kinetic (peak and mean system force and net impulse) variables and propulsion phase duration were determined during the HP performed with a relative load of 140% 1-RM PC, using three different set configurations. A comprehensive and detailed description of the research design and experimental protocols used in this study for the HP are highlighted in study 5, (Section 7.3.1, page 207).

8.4. SUBJECTS

An *a priori* sample size calculation was performed, identifying a minimum sample of 18 subjects was required, for a statistical power of 0.80 at an alpha level of 0.05, based on an average effect size of 0.60 for differences in peak velocity (329). Twenty-one male subjects from various teams and individual sports including rugby, soccer, track cycling, martial arts, and athletics (long jump, javelin) (age = 29.50 ± 4.30. years, height = 1.78 ± 0.07 m, body mass = 75.17 ± 11.11 kg, resistance training experience = 7.50 ± 1.48 years, relative 1-RM PC = 1.17 ± 0.15 $kg.kg^{-1}$) who participated in regular resistance training (≥2 x week), including experience with weightlifting derivatives, volunteered to participate in this study. Subjects were free from injury, provided written informed consent, and were requested to perform no strenuous activity during the 48 hours before testing, maintain their normal dietary intake before each session, and to attend testing sessions in a hydrated state. This investigation received ethical approval from the Institutional Ethics Committee and conformed to the principles of the World Medical Association's Declaration of Helsinki.

8.5. PROCEDURES

8.5.1. One Repetition Maximum Power Clean Testing

Each subject's 1-RM PC was assessed following a standardised protocol (8). For a detailed description of the protocol, see additional detail in section 3.3.3 page 107.

8.5.2. Experimental testing

All subjects performed the HP with identical methods highlighted in study 2, (Section 4.3.3, page 139). A photo sequence of the HP is shown in Figure 4.2, page 142.

8.5.3. Force-Time Data Collection

Force-time data analysis for the HP were conducted using a forward dynamics approach, using identical methods outlined in study 1, (Section 3.3.3, page 112). Since the number of repetitions per set differed between RR_{45} (2 repetitions per set), RR_{72} (3 repetitions per set), and TS (6 repetitions per set), RR_{45} sets 1 to 3, 4 to 6 and 7 to 9 and RR_{72} sets 1 to 2, 3 to 4, and 5 to 6 were grouped together to create '3 sets' for comparison purposes. Raw vertical force-time data for each trial was exported as text files and analysed using a customised Excel spreadsheet (version 2016; Microsoft Corp., Redmond, WA, USA). For each protocol, the absolute values for PF, MF, PV, MV, IMP, and propulsion duration were each combined and averaged across all 18 repetitions for each configuration. This was also performed for the '3 sets of 6' within each protocol. The effect of set structure on PV decline across each set structure was also determined by a percent decline from the fastest to the slowest repetition using the following equation: Percent decline = $[(\text{repetition}_{min} – \text{repetition}_{max})/\text{repetition}_{max}] \times 100$. In addition, PV maintenance was calculated with the following equation: Maintenance set = 100 -[mean set – repetition_{max}] x100 (176). This approach was used rather than comparing the first and last repetitions, as the first repetition is not always the fastest and the last repetition is not always the slowest (142, 176).

8.5.4. Rating of perceived exertion

Details of the familiarisation of the RPE scale procedure is described in detail in chapter 7, (Section 7.5.4, page 212).

8.6. STATISTICAL ANALYSES

Statistical analyses were performed using SPSS version 26 (SPSS, Chicago, IL, USA). Distribution of data were analysed by using the Shapiro-Wilks test of normality. Reliability for 1-RM PC was assessed using two-way mixed intraclass correlation (ICC), with associated 95% confidence intervals (CI) and typical error expressed as a coefficient of variation percentage (CV%)]. The ICC was interpreted as poor (< 0.50), moderate (0.50-0.74), good (0.75-0.90), and excellent (>0.90), based on the lower bound 95% CI (193). Acceptable within-session variability was classified as <10% (57). Differences between configurations were determined using repeated-measures analysis of variance (ANOVA) with Bonferroni post hoc analysis or Friedman's tests with multiple Wilcoxon's tests (including Bonferroni correction for multiple comparison to reduce the risk of Type 1 errors) for data that were not normally distributed.

Differences between TS, RR_{45}, and RR_{72} within each set was examined using a series of two-way repeated-measures ANOVA. When a significant main effect or interaction was determined, Bonferroni post-hoc tests were conducted. Sphericity could not be assumed by the Mauchly test ($p > 0.05$) for all variables, and therefore, Greenhouse-Geisser adjustment was used. Standardised differences were calculated using Hedges' *g* effect sizes, as previously described (16) and interpreted as trivial (≤ 0.19), small (0.20-0.59), moderate (0.60-1.19), large (1.20-1.99), and very large (2.0-4.0) (152). An *a priori* alpha level was set at $p \leq 0.05$.

8.7. RESULTS

Power clean 1-RM performances were highly reliable (ICC = 0.98, [95% CI = 0.85-0.99], %CV = 3.0% [1.3-3.1%] between session 1 (87.29 ± 14.24 kg) and session 2 (84.81 ± 14.74 kg). The HP kinetics and kinematics assessed in the study have been previously reported to demonstrate moderate to excellent reliability and acceptable variability (230).

8.7.1. Kinetics and Kinematics Comparison between Protocols across 18 Repetitions

During the RR_{72} sets, there was significantly greater PV compared to RR_{45} ($p = 0.025$, $g = 0.36$) (Table 8.1). There were no significant or meaningful differences ($p > 0.05$, $g = 0.00\text{-}0.59$) between configurations for any other variables (Table 8.1 & Appendix 10.8.1a-b and d-f).

8.7.2. Set by Set Comparison (Within Configuration)

Peak force was significantly greater in set 3 compared to set 1 during the TS configuration. During the RR_{72} PF was also significantly greater in set 2 and set 3 compared to set 1 (Table 8.2). There was significantly greater MV during RR_{45} in set 1 compared to set 3 (Table 8.2). There was significantly greater phase duration during RR_{72} in set 1 compared to set 3 (Table 8.2). The RPE was significantly lower for the TS configuration during set 1 compared to set 2 and set 3, and significantly lower RPE during set 2 compared to set 3 (Table 8.2). The RPE was also significantly lower for the RR_{45} configuration during set 1 compared to set 2 and set 3, and significantly lower RPE during set 2 compared to set 3 (Table 8.2). Similarly, RPE was significantly lower during the RR_{72} configuration during set 1 compared to set 2 and set 3, and significantly lower RPE during set 2 compared to set 3 (Table 8.2). There were no significant or meaningful differences between configurations for any other variables (Table 8.2).

8.7.3. Set by Set Comparison (Between Configuration)

There was a significant main effect for configuration on PF, with significantly greater PF during RR_{72} compared to RR_{45} (Table 8.3). There was a significant main effect for configuration on PV, with significantly greater PV during RR_{72} compared to RR_{45} (Table 8.3). There was a significant main effect for configuration on IMP, with greater IMP during RR_{72} compared to RR_{45} (Table 8.3). There was a significant main effect for configuration on PVD, with significantly greater PVD during RR_{45} compared to TS and RR_{45} compared to RR_{72} (Table 8.3). There was a significant main effect for configuration on PVM, with significantly greater PVM for RR_{72} compared to RR_{45} (Table 8.3). There was a significant main effect of set, with significantly lower for set 1 compared to set 2, and significantly lower for set 1 compared to set 3, with significantly lower RPE for set 2 compared to set 3 (Table 8.3). There were no other significant differences for configuration, set or set x configuration (Table 8.3).

Table 8.1-Means ± standard deviations (95% confidence intervals) for propulsive kinetics and kinematics, phase duration, peak velocity decline, peak velocity maintenance and RPE for all 18 repetitions averaged within each protocol during the hang pull at 140% 1-RM

Variable	TS (3x6) 18 repetitions (95%CI)	RR_{45} (9x2) 18 Repetitions (95% CI)	RR_{72} (6x3) 18 Repetitions (95% CI)	p- value, (*g*)		
				TS vs RR_{45}	TS vs RR_{72}	RR_{45} vs RR_{72}
Peak Force (N)	3150 ± 495 (2925-3375)	3099 ± 443 (2898-3301)	**3162 ± 476 (2945-3379)**	$p > 0.05$ (0.12)	$p > 0.05$ (0.03)	$p > 0.05$ (0.13)
Mean Force (N)	2681 ± 461 (2471-2891)	2662 ± 459 (2453-2871)	**2686 ± 451 (2481-892)**	$p > 0.05$ (0.04)	$p > 0.05$ (0.01)	$p > 0.05$ (0.05)
Peak Velocity (m.s-^{1})	1.16 ± 0.09 (1.12-1.21)	1.14 ± 0.11 (1.09-1.19)	**1.18 ± 0.11 (1.13-1.23)**	$p > 0.05$ (0.20)	$p > 0.05$ (0.20)	**$p = 0.025$**** (0.36)
Mean Velocity (m.s-^{1})	0.55 ± 0.06 (0.52-0.58)	0.55 ± 0.07 (0.52-0.58)	**0.56 ± 0.07 (0.52-0.59)**	$p > 0.05$ (0.00)	$p > 0.05$ (0.15)	$p > 0.05$ (0.14)
Impulse (N.s)	231 ± 38 (214-248)	226 ± 38 (209-243)	**233 ± 37 (216-249)**	$p > 0.05$ (0.13)	$p > 0.05$ (0.05)	$p > 0.05$ (0.18)
Phase Duration (s)	0.493 ± 0.05 (0.469-0.517)	**0.497 ± 0.07 (0.465-0.529)**	0.495 ± 0.07 (0.463-0.527)	$p > 0.05$ (0.06)	$p > 0.05$ (0.03)	$p > 0.05$ (0.03)
Velocity Decline (%)	19.2 ± 8 (22.3-15.4)	**21.9 ± 8 (25.4-18.4)**	17.4 ± 8 (20.8-14)	$p > 0.05$ (0.33)	$p > 0.05$ (0.22)	$p > 0.05$ (0.55)
Velocity Maintenance (%)	90 ± 5 (87.6-92.3)	88 ± 5 (86.-90.1)	**91 ± 5 (88.5-93.4)**	$p > 0.05$ (0.39)	$p > 0.05$ (0.20)	$p > 0.05$ (0.59)
RPE	**7.07 ± 1.03 (6.60-7.54)**	6.98 ± 0.80 (6.62-7.35)	6.87 ± 0.78 (6.53-7.23)	$p > 0.05$ (0.10)	$p > 0.05$ (0.21)	$p > 0.05$ (0.14)

Denotes peak value in set configuration across 18 repetitions; **Denotes significant differences between set configurations

Table 8.2-Between set comparisons of kinetics and kinematics, phase duration and rate of perceived exertion for each set of 6 repetitions for traditional sets (3 x 6), rest redistribution (9 x 2 and 6 x 3) Data presented as means ± standard deviations (95% confidence intervals)

Variable	Set 1 (95%CI)	Set 2 (95%CI)	Set 3 (95%CI)	*p* value Hedges (*g*)		
				Set 1 vs Set 2	Set 1 vs Set 3	Set 2 vs Set 3
Traditional Sets 3 x 6						
Peak Force (N)	3108 ± 478 (2890-3326)	3157 ± 500 (2929-3385)	**3185 ± 517 (2949-3420)**	$p > 0.05$ (0.10)	$p = 0.013$** (0.15)	$p > 0.05$ (0.05)
Mean Force (N)	2672 ± 454 (2465-2879)	2677 ± 467 (2464-2889)	**2695 ± 469 (2681-2908)**	$p > 0.05$ (0.01)	$p > 0.05$ (0.05)	$p > 0.05$ (0.04)
Peak Velocity (m.s-^{1})	1.16 ± 0.11 (1.11-1.21)	1.16 ± 0.10 (1.11-1.20)	**1.18 ± 0.09 (1.14-1.22)**	$p > 0.05$ (0.00)	$p > 0.05$ (0.20)	$p > 0.05$ (0.21)
Mean Velocity (m.s-^{1})	0.55 ± 0.06 (0.52-0.58)	0.54 ± 0.06 (0.52-0.57)	**0.56 ± 0.07 (0.53-0.60)**	$p > 0.05$ (0.16)	$p > 0.05$ (0.16)	$p > 0.05$ (0.33)
Impulse (N.s)	229 ± 37 (212-245)	230 ± 36 (212-248)	**234 ± 39 (216-252)**	$p > 0.05$ (0.03)	$p > 0.05$ (0.13)	$p > 0.05$ (0.10)
Phase Duration (s)	**0.49 ± 0.06 (0.47-0.52)**	0.49 ± 0.05 (0.47-0.52)	0.49 ± 0.05 (0.47-0.52	$p > 0.05$ (0.02)	$p > 0.05$ (0.05)	$p > 0.05$ (0.04)
RPE	6.50 ± 1.18 (5.96-7.04)	7.12 ± 1.05 (6.64-7.60)	**7.60 ± 1.04 (7.12-8.07)**	$p = 0.001$**(0.54)	$p = 0.006$**(0.97)	$p = 0.015$** (0.45)
Velocity Decline (%)	11.1 ± 5.6 (13.7-8.5)	11.8 ± 5.9 (14.5-9.1)	**12 ± 5 (14.2-9.7)**	$p > 0.05$ (0.12)	$p > 0.05$ (0.17)	$p > 0.05$ (0.12)
Velocity Maintenance (%)	94.2 ± 3 (92.9-95.6)	**94.5 ± 3.1 (93.1-95.9)**	93.5 ± 3.2 (92.1-95)	$p > 0.05$ (0.10)	$p > 0.05$ (0.22)	$p > 0.05$ (0.31)
Rest Redistribution 9 x 2						
Peak Force (N)	**3108 ± 423 (2915-3300)**	3089 ± 457 (2882-3297)	3101 ± 455 (2893-3308)	$p > 0.05$ (0.04)	$p > 0.05$ (0.02)	$p > 0.05$ (0.03)
Mean Force (N)	**2677 ± 437 (2478-2876)**	2655 ± 474 (2439-2871)	2655 ± 469 (2441-2869)	$p > 0.05$ (0.05)	$p > 0.05$ (0.05)	$p > 0.05$ (0)
Peak Velocity (m.s-^{1})	**1.16 ± 0.11 (1.11-1.21)**	1.13 ± 0.11 (1.08-1.18)	1.14 ± 0.12 (1.08-1.19)	$p > 0.05$ (0.27)	$p > 0.05$ (0.17)	$p > 0.05$ (0.09)
Mean Velocity (m.s-^{1})	**0.56 ± 0.07 (0.53-0.60)**	0.55 ± 0.07 (0.51-0.58)	0.54 ± 0.07 (0.51-0.57)	$p > 0.05$ (0.14)	$p = 0.046$**(0.28)	$p > 0.05$ (0.14)
Impulse (N.s)	**229 ± 36 (213-246)**	224 ± 40 (206-243)	224 ± 39 (207-242)	$p > 0.05$ (0.13)	$p > 0.05$ (0.13)	$p > 0.05$ (0.00)
Phase Duration (s)	0.49 ± 0.06 (0.46-0.52)	**0.50 ± 0.07 (0.47-0.53)**	0.50 ± 0.08 (0.46-0.54)	$p > 0.05$ (0.15)	$p > 0.05$ (0.14)	$p > 0.05$ (0.00)
RPE	6.24 ± 0.82 (5.87-6.61)	7.05 ± 0.88 (6.65-7.45)	**7.67 ± 0.86 (7.28-8.06)**	$p < 0.001$**(0.93)	$p < 0.001$**(1.67)	$p = 0.001$** (0.70)
Velocity Decline (%)	**14.9 ± 6.7 (17.9-11.8)**	14.3 ± 6.6 (17.3-11.3)	13.6 ± 5.8 (16.3-11)	$p > 0.05$ (0.09)	$p > 0.05$ (0.20)	$p > 0.05$ (0.11)
Velocity Maintenance (%)	91.8 ± 4.9 (89.5-94)	93.2 ± 3.3 (91.7-94.8)	**93.3 ± 4 (91.5-95.1)**	$p > 0.05$ (0.12)	$p > 0.05$ (0.34)	$p > 0.05$ (0.05)
Rest Redistribution 6 x 3						
Peak Force (N)	3130 ± 487 (2908-3352)	3175 ± 473 (2906-3391)	**3181 ± 472 (2966-3396)**	$p = 0.016$**(0.09)	$p = 0.005$**(0.10)	$p > 0.05$ (0.01)
Mean Force (N)	2667 ± 456 (2459-2874)	2691 ± 452 (2485-2897)	**2701 ± 449 (2497-2906)**	$p > 0.05$ (0.05)	$p > 0.05$ (0.07)	$p > 0.05$ (0.02)
Peak Velocity (m.s-^{1})	**1.18 ± 0.12 (1.14-1.23)**	1.17 ± 0.11 (1.12-1.23)	1.18 ± 0.12 (1.13-1.23)	$p > 0.05$ (0.09)	$p > 0.05$ (0.00)	$p > 0.05$ (0.09)
Mean Velocity (m.s-^{1})	0.55 ± 0.07 (0.52-0.59)	0.55 ± 0.08 (0.52-0.59)	**0.56 ± 0.07 (0.52-0.59)**	$p > 0.05$ (0.00)	$p > 0.05$ (0.14)	$p > 0.05$ (0.13)
Impulse (N.s)	233 ± 36 (217-250)	232 ± 36 (215-248)	**233 ± 38 (215-250)**	$p > 0.05$ (0.03)	$p > 0.05$ (0.03)	$p > 0.05$ (0.00)
Phase Duration (s)	**0.51 ± 0.07 (0.47-0.54)**	0.50 ± 0.08 (0.46-0.53)	0.49 ± 0.06 (0.46-0.51)	$p > 0.05$ (0.13)	$p = 0.003$**(0.30)	$p > 0.05$ (0.14)
RPE	6.20 ± 0.75 (5.85-6.53)	6.88 ± 0.92 (6.46-7.30)	**7.55 ± 0.89 (7.14-7.95)**	$p = 0.001$**(0.79)	$p < 0.001$**(1.61)	$p = 0.002$** (0.73)
Velocity Decline (%)	**12.8 ± 6.3 (15.6-9.9)**	12.3 ± 6 (15-9.6)	10.5 ± 5.1 (12.9-8.2)	$p > 0.05$ (0.08)	$p > 0.05$ (0.39)	$p > 0.05$ (0.32)
Velocity Maintenance (%)	93.4 ± 4.5 (91.4-95.4)	94.6 ± 3.0 (93.2-96)	**95.1 ± 2.1 (94.1-96.1)**	$p > 0.05$ (0.31)	$p > 0.05$ (0.48)	$p > 0.05$ (0.20)

Bold denote peak value in each set across 6 repetitions; ** denote significant differences between sets

Table 8.3-Results of Repeated measures Two-Way Analysis of Variance with interaction effect

ANOVA- Configuration			
Variable	**ANOVA Result**	***p*-value**	**Comparison**
Peak Force (N)	F (1.82,109) = 5.813, p = 0.005	$\boldsymbol{p < 0.001}$*	RR_{72} significantly greater than vs. RR_{45}
Mean Force (N)	F (2,120) = 1.358, p = 0.261	p = 0.296	No significant differences between protocols
Peak Velocity (m.s-1)	F (2,120) = 6.372, p = 0.002	$\boldsymbol{p < 0.001}$*	RR_{72} significantly greater than RR_{45}
Mean Velocity (m.s-1)	F (2,120) = 0.225, p = 0.799	p = 1.000	No significant differences between protocols
Impulse (N.s-1)	F (1.80, 107.9) = 5.876, p = 0.005	$\boldsymbol{p < 0.001}$*	RR_{72} significantly greater than RR_{45}
Phase Duration (s)	F (2, 120) = 0.315, p = 0.730	p = 1.000	No significant differences between protocols
Velocity Decline (%)	F (2, 120) = 5.317, p = 0.006	$\boldsymbol{p = 0.008}$* $\boldsymbol{p = 0.043}$*	RR_{45} significantly greater than TS RR_{45} significantly greater than RR_{72}
Velocity Maintenance (%)	F (2, 120) = 4.179, p = 0.018	$\boldsymbol{p = 0.042}$*	RR_{72} significantly greater than RR_{45}
RPE	F (1.81, 109) = 1.273, p = 0.282	$p \geq 0.407$	No significant differences between protocols
ANOVA-Set			
Variable	**ANOVA Result**	***p*-value**	**Comparison**
Peak Force (N)	F (2,60) = 0.040, p = 0.961	p = 1.000	No significant differences between sets
Mean Force (N)	F (2,60) = 0.004, p = 0.996	p = 1.000	No significant differences between sets
Peak Velocity (m.s-1)	F (2,60) = 0.091, p = 0.913	p = 1.000	No significant differences between sets
Mean Velocity (m.s-1)	F (2, 60) = 0.101, p = 0.904	p = 1.000	No significant differences between sets
Impulse (N.s-1)	F (2, 60) = 0.017, p = 0.983	p = 1.000	No significant differences between sets
Phase Duration (s)	F (2, 60) = 0.036, p = 0.965	p = 1.000	No significant differences between sets
Velocity Decline (%)	F (2, 60) = 0.265, p = 0.768	p = 1.000	No significant differences between sets
Velocity Maintenance (%)	F (2, 60) = 1.078, p = 0.347	p = 0.545	No significant differences between sets
RPE	F (2, 60) = 15.763, p < 0.001	$\boldsymbol{p = 0.010}$* $\boldsymbol{p < 0.001}$* $\boldsymbol{p = 0.041}$*	Set 2 significantly greater than Set 1 Set 3 significantly greater than Set 1 Set 3 significantly greater than 2
ANOVA- Set x Configuration			
Peak Force (N)	F (3.63,109) = 0.996	p = 0.408	No significant differences
Mean Force (N)	F (4,120) = 0.696	p = 0.596	No significant differences
Peak Velocity (m.s-1)	F (4,120) = 1.146,	p = 0.338	No significant differences
Mean Velocity (m.s-1)	F (4,120) = 1.099	p = 0.360	No significant differences
Impulse (N.s-1)	F (3.597, 107.9) = 1.103	p = 0.357	No significant differences
Phase Duration (s)	F (4, 120) = 1.395	p = 0.240	No significant differences
Velocity Decline (%)	F (4, 120) = 0.535	p = 0.710	No significant differences
Velocity Maintenance (%)	F (4, 120) = 0.905	p = 0.463	No significant differences
RPE	F (3.622, 109) = 0.357	p = 0.821	No significant differences
*Denotes significant differences			

8.8. DISCUSSION

The primary aim of this study was to compare the effects of RR protocols on kinetics, kinematics and perceptual fatigue during the HP performed using 140% 1-RM PC, when compared to a TS protocol. When compared across the average of all 18 repetitions, incorporating RR protocols did not result in different PF, MF, MV, IMP, propulsion duration, PVD, PVM, or RPE. However, the RR_{72} protocol resulted in greater PV compared to RR_{45} averaged across 18 repetitions, although these were not different compared to the TS protocol Table 8.1). Therefore, shorter more frequent rest periods during the HP may not be required to maintain force-time characteristics across a multiple set protocol in this cohort. Caution is needed when comparing the results of this study to other studies as the HP utilises the SSC and is a semi-ballistic task which requires maximal intent, whereas squats and bench press include a substantial deceleration phase (90) and may not be conducive to perform with a comparable ballistic intent, which may negate the effectiveness of direct comparisons.

In agreement with this study, Haff et al. (126) showed conflicting findings when assessing barbell velocity during the clean pull exercise in which at 90% 1-RM, the first repetition was not the fastest, but in contrast to 120% 1-RM, the first repetition was the fastest. The second repetition of each set in the 9x2 (RR_{45}) configuration resulted in a greater peak velocity, phase duration and impulse than the previous repetition, although MF was not always greater during the 2nd repetition. As the mass is constant during the HP, the greater impulse (as determined by an increase in repetition duration) shown in the 2nd repetition resulted in a greater velocity during the 2nd repetition. Interestingly, during all the TS and RR_{45} sets, the 2nd repetition was always faster than the 1st repetition (Appendix 10.8.1a). It could be surmised that the inclusion of multiple RR protocols would allow for greater velocity compared to TS protocols, due to the short rest period preceding the next repetition (e.g., repetition 3 of RR_{45} vs. repetition 3 of TS [there is 45 s second IRR between the 2nd and 3rd repetition]). However, this was not always evident with repetitions 5, 11, and 17, the first repetition in each of sets of 2 being slower than the corresponding repetition during the RR_{72} configuration, which highlights the requirement for the practitioner to carefully consider optimal set and repetition structures to maximise kinetic and kinematic output within a training session.

When assessing the decline in PV from the fastest repetition to slowest repetition during the TS structure, PV showed a decline of 19.2% across all 18 repetitions; however, when calculated relative to fastest repetition, PV maintenance (when all repetitions are accounted for) was 90%, which demonstrates a velocity drop of 10%. Similarly, when RR_{45} and RR_{72} was assessed, PV showed a decline of 21.9% and 17.5% whilst velocity maintenance was 88.3% and 91%. Utilising only velocity decline calculations that include differences between two repetitions (either first to last or fastest to slowest) may lead to misleading interpretations of the true reflection of the demands of the training session as the other 16 repetitions are not accounted for. Further investigation is needed to determine if reporting decline or maintenance metrics is the most appropriate method to inform practitioners.

Although not a primary aim in this study, utilising a velocity decline from the first to last repetition indicated noteworthy trends. Seven subjects showed a decrease in velocity during the TS (range -5 to 14%) during the TS structure, with 13 showing an increase (range 1% to 20%). For the RR_{45} protocol, 11 subjects increased velocity (range 1-28%), whilst 8 decreased (-3 to -14%). Similarly, during the RR_{72} 12 subjects showing an increase across a range of 2-13%, and 7 subjects showing a decrease of -2 to -19%. This highlights practical implications that individual responses may be preferential when reporting the efficacy of PV decrements, due to the differences observed between subjects, and thus the PVD of first to last repetition should not be implemented.

Rating of Perceived Exertion across entire set-protocols was also not significantly different in RR protocols compared to TS across the entire testing session. This is not surprising given that there were no significant differences between TS and RR configuration on kinetics or kinematics, except for significantly greater PV during the RR_{72} protocol compared to RR_{45} protocol, although the highest RPE was reported during the TS protocol, and lowest in the RR_{72} protocol. Although there are minimum differences in kinetics and kinematics between sets, there were significant differences between all sets for RPE in all configurations. Practitioners should be mindful of this when prescribing supramaximal HP throughout different phases of a training cycle due to the increasing RPE value, particularly during key competition phases.

Our results indicate that despite the TS protocol having greater RPE than RR protocols, RR resulted in similar PF, MF, MV, IMP, propulsion duration, PVD, PVM, and RPE across multiple sets. This contrasts with various studies which demonstrated that more frequent rest periods allowed for better velocity maintenance (255, 257, 330), although these results were during the back squat. Although direct comparisons between studies are challenging due to various resistance training protocols, exercise selection, and subject characteristics, previous researchers demonstrated that configurations with fewer repetitions per set result in lower RPE during back squats at 70% of 1-RM when compared to TS protocols of 30 total repetitions (175). In this study, 18 repetitions at 140% 1-RM PC were prescribed, whilst (255, 257) prescribed 4x10 (40 repetitions) at 70% 1-RM and (330) prescribed 3x12 (36 repetitions) at 60% 1-RM during the back squat. Conflicting findings could be partially explained by the number of repetitions and range of motion in the TS sets, as subjects may experience more fatigue during the back squat and/or bench press due to the possibility of being under tension for longer across a larger range of motion compared to the HP and given the fact that the 140% in this study is based upon a 1-RM PC and not the same exercise.

Significant and moderate to large differences were observed between sets for RPE for TS, RR_{45} and RR_{72} (Table 8.2) and showed a progressively greater RPE with an increase in sets, and therefore total repetitions in line with previous research during TS, albeit during the PC (140). This increase was not consistently evident in the kinetics and kinematics variables, with set 3 eliciting the peak values in many variables (Table 8.2). This potentially questions the appropriateness of utilising RPE scores to represent changes in kinetic and kinematic changes during the HP due to the minimal meaningful or significant differences observed between sets and protocols (Table 8.1 & Table 8.2; Appendix 10.8.4).

In contrast to this study, Jukic and Tufano (176) reported significantly lower RPE during the RR protocols compared to TS regardless of whether RR or TS configurations were performed, and showed that RPE increased across sets at all loads, demonstrating that RR was perceptually easier compared to TS, even though previous authors have suggested that the number of sequential repetitions may have an important role in RPE response (216). Previously, researchers have also shown that configurations with fewer repetitions per set result in lower RPE (174, 176, 216). Differences between this study and other studies may be a result of the different exercises and intensities performed, but more importantly, exercises with a much greater movement displacement (i.e., parallel squat and clean pull).

Although the RPE is similar across the 18 repetitions, the lowest RPE was reported within the RR_{72} protocol. It is also worth considering that the barbell was placed on the safety rack after each set. During TS, the bar was un-racked for 3 sets, the 9 sets for RR_{45} and 6 sets during RR_{72}, which may have contributed to the overall fatigue and subsequent RPE ratings. As RPE did not differ between protocols, the HP may in fact not be a physically demanding exercise, even at loads of 140% 1-RM PC. Although it is likely that the lower PV obtained during RR_{45} compared to RR_{72} (Table 8.1) is likely a result of un-racking the barbell more often in that protocol. Due to the ability to tolerate higher repetitions at 140% 1-RM PC, if RR and TS set structures are performed using identical training intensities, it is possible that the TS group may have reported increased perception of fatigue due to the highest RPE reported, however this did not coincide with a decrease in kinetic and kinematic variables as may be expected with a higher RPE reporting (Table 8.1).

The findings of this study are not without their limitations. Whilst this study and many previous studies have investigated force-time characteristics of weightlifting pulling derivatives using loads that have been calculated from the 1-RM of a weightlifting catching variation (126, 174, 176, 230, 232), the authors acknowledge that it likely impractical to perform 1-RM tests for certain pulling derivatives. Given the multiple sport cohort in this study, these findings should be interpreted with caution as assessing proficient weightlifters may yield different conclusions. As 3x6 repetitions did not result in any significant differences between sets for kinetic or kinematic variables, it may be possible for athletes to perform > 6 repetitions per set at 140% 1-RM PC, which may allow for higher repetition loading and a higher volume of work in the HP, and this warrants further investigation. Additionally, although not measured in this study, investigating the additional measurement of barbell displacement may also determine any differences in work if the inclusion of RR allows for greater barbell displacements over the duration of each protocol at loads of 140% 1-RM PC. Researchers should consider replicating this this study with cluster sets to establish if cluster sets utilising short (e.g., 15-45 s) intra-set rest periods in addition to longer (e.g., > 1 min) inter-set rest periods are a superior method to maintain kinetics and kinematics in the HP.

8.9. PRACTICAL APPLICATIONS

The results of this study demonstrated that a lack of differences in velocity and force output (and likely power) may have been due to the lack of high levels of fatigue during TS, potentially due to the minimal displacement of the HP. Implementing RR periods to create shorter, but more frequent sets may only result in a significant occurrence when a comparative TS structure is highly fatiguing, or when a larger range of motion is performed, (e.g. clean pulls) (126). From a practical perspective, having athletes perform RR protocols should allow practitioners give more frequent technical feedback, but consideration should be paid to the frequency of un-racking and re-racking the barbell as this may contribute to overall fatigue.

Chapter 9: Thesis Summary and Recommendations for Future Research

9.1. SUMMARY AND CONCLUSIONS

The overarching aim of the thesis was to investigate if differences exist in kinetics and kinematics between specific weightlifting pulling derivatives across a spectrum of loads, the effects of inclusion of a countermovement and set configuration (effects of rest-redistribution), to provide greater context and exercise prescription guidelines regarding practical applications of these exercises, and how they may be implemented into training programmes. Fundamentally, S&C practitioners must select, teach, coach, and implement the most appropriate exercise, intensities (relative loads) and training volumes, throughout a training plan to improve athletes' physical capability.

The results from the thesis bridge the gap between the laboratory and performance setting by providing a better understanding of the effect of load during weightlifting pulling derivatives across a spectrum of loads, which can be used to inform appropriate exercise selection. To investigate these aims however, it was important to establish differences in key exercises to determine the direction of the objectives outlined. The results from Chapter 3 adds to the body of literature surrounding the previously examined MTP research (52, 55) and provide novel findings highlighting that the CMS appears to be a superior exercise to acutely maximise kinetic and kinematic variables in this sample population, with athletes from multiple sports. Similarly, the published findings obtained from Chapter 4 indicate that the HP appears to be a more appropriate exercise for acutely maximising kinetic and kinematics compared to the PFK, particularly at loads ≥100% 1-RM PC. However, it may appropriate to sequence training logically, so the athletes can establish sufficient postural strength before adding initiating the countermovement. As a result of the enhanced variables, this might enable greater ‘buy in’ from athletes and sports coaches involved in the training programme, due to the enhanced kinetics and kinematics, which is likely attributed to the utilisation of the SSC during both the CMS and HP. It is likely that in an applied S&C environment, athletes perform 2-3 resistance training session per week, so selecting the most appropriate exercises is critical for performance improvement.

The findings from chapter’s 3 and 4 add a new insight to previously published work by Suchomel, Comfort and Lake (301) in which the authors highlighted force and velocity characteristics of weightlifting derivatives. However, the authors suggested that the static variations may result in greater forces and velocities than countermovement variations (Figure 9.1), likely due to the loads being too heavy to move quickly with loads >1-RM, potentially limiting the utilisation of the SSC which is sensitive to the rate of change in length of a muscle. However, the findings in this thesis demonstrates that use the HP and CMS elicit greater forces and power compared to the PFK and MTP. As a result, the findings of this study provide an updated force-velocity (power) curve highlighted in Figure 9.2.

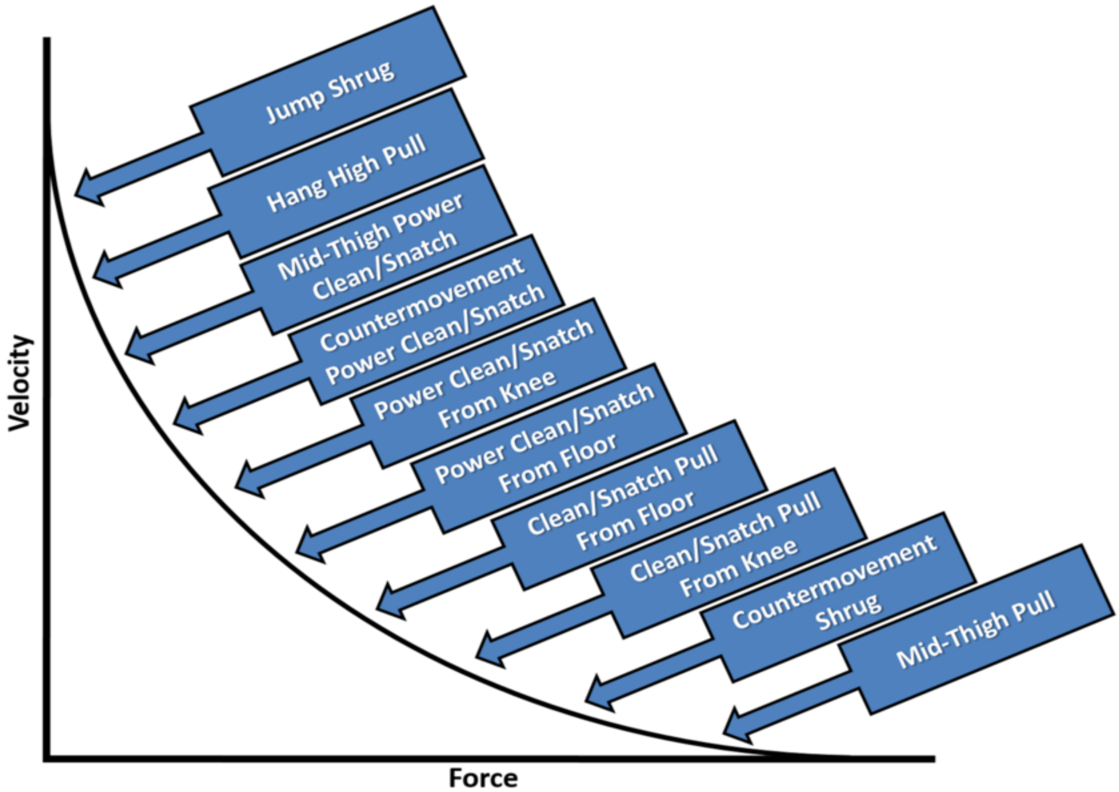


Figure 9.1-Force–velocity (power) curve with respect to weightlifting derivatives. Suchomel, Comfort and Lake (301)

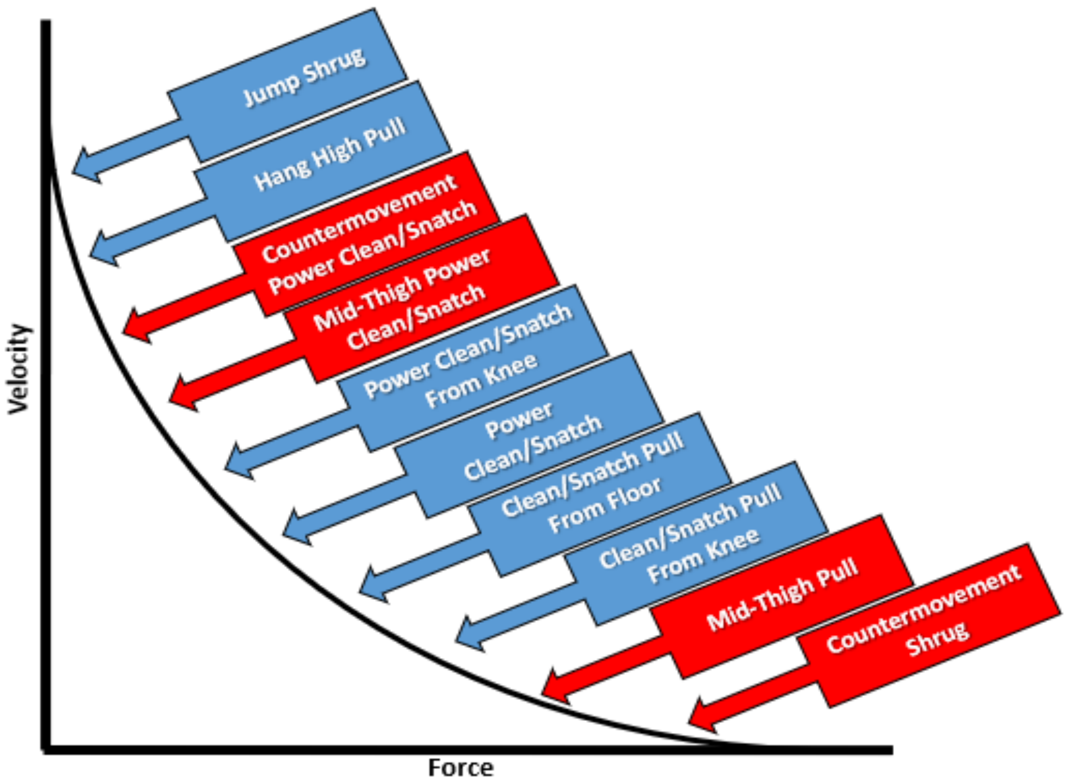


Figure 9.2-Modified force–velocity (power) curve with respect to weightlifting derivatives, illustrating that the addition of a countermovement increases force and velocity. Adapted from Suchomel, Comfort and Lake (301)

Following on from Chapters 3 and 4 which identified that acute differences in kinetics and kinematics exist between the CMS and MTP and the PFK and HP, a further aim of this thesis was to investigate the effects of load on temporal phase characteristics during the CMS and HP, to provide a more detailed and comprehensive analysis of these exercises. The third and fourth investigations (Chapters 5 and 6) are the first studies to include the effect of load, via SPM analysis, across biomechanical time series data in weightlifting pulling derivatives, and provide new insights resulting in novel findings in both the magnitude of differences, but importantly where these differences occur across the entire continuous time-series. These are also the first studies in which a broad spectrum of loads have been compared in this way, with researchers previously examining one load (70% 1-RM HPC) (185). Results show that as load increases, the unweighting phase duration becomes shorter, whilst the propulsion phase become longer, therefore, direct phase comparisons (unweighting, braking and propulsion) cannot be made when assessing the effect of load, due to a misalignment of phases (Figure 5.4). The change in unweighting phase percentage is likely due to the increased in load, as the braking and propulsion phases generally become greater with an increase in load. Similarly, as absolute movement time increases with load, absolute durations of unweighting, braking and propulsion also increase.

These findings offer greater insight to the demands of each load during both the CMS and HP. During the CMS, as load increases, the overall durations of each sub-phase and total movement durations increases. Therefore, as load increase, the subjects are braking for longer, with absolute braking duration at 140% 1-RM 28% greater than 40% 1-RM. Similarly, the propulsion phase is 18% greater and the total movement duration 14% greater at 140% 1-RM compared to 40% 1RM. Additionally, due to the greater ROM during the HP compared to the CMS, when compared to 40% 1-RM, the braking phase duration was 33% greater at 140% 1-RM, with propulsion phase being 23% longer at 140% 1-RM and the total movement duration being 16% longer. Practically, as the increased loads result in an increased TUT, these findings provide S&C practitioners further detailed insight into optimal exercise selection when selecting load prescription during these exercises, particularly important during competition or rehabilitation and peaking / tapering phases when TUT must be considered. Researchers need to consider normalising these individual phases then making direct phase comparisons. The results also demonstrate where differences exist outside peak values, highlighting that load selection will result in differences throughout the movement (i.e., late propulsion phase), which may affect exercise selection.

The primary aim of Chapter 7 was to follow up the preliminary findings of Chapter 3 to determine if differences in kinetic and kinematics exist between TS structures and RR during the CMS at 140% 1-RM PC as this was the heaviest load examined, and therefore the likely most fatiguing. Previous findings demonstrated that the inclusion of RR and CLU protocols might allow for lower perceptual fatigue (176), and increased barbell kinematics (126) when performing the clean pull from the floor. Mitigating a decrease in kinetics and kinematics, would likely result in greater velocity, power enhancement and work over a greater ROM, and potentially better adaptation to training. However, when performing the, CMS, RR is not required during sets of 6 repetitions of at 140% 1-RM PC, as a TS structure did not result in a meaningful decrease in force, velocity, or impulse, likely due to low exercise complexity, limited displacement, and therefore work performed. Further, previous research has shown that the 1st pull contributes to ~ approximately 66-71% of the total repetition duration during the clean in both elite and non-elite weightlifters, whilst the 2nd pull accounts 13% (178), thus highlighting the 2nd pull may not be as fatiguing as the 1st pull.

To our knowledge no researcher has investigated > 6 TS repetitions during a weightlifting pulling derivative, therefore in the future researchers should examine an upper limit of TS repetitions for supramaximal loading with a reduced range of motion, as it is possible more repetitions can be performed, without a detrimental effect on kinetics, kinematics and RPE during the CMS. Practically, it could be hypothesised that the CMS could be selected as an appropriate method of reducing training volume. It seems plausible that reducing the overall displacement and therefore work allows for coaches to switch to exercises that have a limited displacement during tapers and may represent a more accurate representation of loading (157).

As a result of the findings from studies 2 and 5, a further aim was established in determining kinetic and kinematics exist between TS structures and RR during the HP at 140% 1-RM PC, which has a greater range of motion than the CMS, and therefore, likely more difficult to perform across multiple sets at supramaximal loads. The findings show a higher PV during RR_{72} compared to RR_{45} for the average of 18 repetitions Further, a main effect for set configuration was evident on PF, PV, and impulse during RR_{72} compared to RR_{45}. Set configuration showed a main effect on PVD, with greater PVD during RR_{45} compared to TS and RR_{72} and PVM, with PVM for RR_{72} compared to RR_{45}. Whilst no significant or meaningful differences existed between RR and TS protocols, performing RR_{72} appears to be a better RR protocol compared to RR_{45} in maximising PF, PV, impulse and PVM, whilst minimizing PVD. This is likely due to the un-racking and re-racking between protocols. Practitioners should be mindful of the selecting the most appropriate set configuration. Importantly, these findings offer further practical application during these exercises. As a result of the subjects not demonstrating reduced kinetic and kinematic output at 140% 1-RM PC, practitioners can therefore be confident that if prescribing these exercises across multiple sets and repetitions, then TS structures will not result in decrement in kinetics or kinematics, and in fact, allows the practitioner to prescribe repeated supramaximal loaded pulls to target force development. However, during the overall training session, RR might allow for more frequent feedback, particularly to novice athletes.

Practically, the results of the studies contained in this thesis conclude that practitioners should select exercises that emphasis force or velocity of movement and not power. Moreover, the inclusion of a prior countermovement is more appropriate to emphasise force and velocity, Moreover, if subjects possess sufficient technique during the CMS or HP, RR protocols are not needed to maintain kinetics or kinematics during these exercises. Finally, as the loads > 100% 1-RM PC results in increased propulsion phase duration and force, regularly performing the CMS and HP may provide an excellent stimulus for high load ballistic force production due to higher forces and increased TUT.

9.2. LIMITATIONS AND RECOMMENDATIONS

A strength of this thesis is the direct application of these findings into applied S&C that practitioners can implement. Firstly, it is more appropriate to emphasise force production or movement velocity and not power as performing combined methods of training allows for a more complete adaptation to occur across the entire force-velocity curve. Results from this study show that derivatives that are performed with a prior countermovement elicit greater force and velocity across loads of 40-140% 1-RM PC if technique is competent.

Moreover, assuming that the technique is competent, there does not seem to be any real benefit in performing RR set configurations over TS configurations on kinetics and kinematics at 140%

1-RM PC, whilst lastly, the increased propulsion phase duration and force during loads of > 100% 1-RM PC may provide an excellent stimulus for high load ballistic force production due to the higher forces and time under tension. The present thesis is not without its limitations. Limitations for each study have been presented in their respective chapters; thus, the main limitations and considerations of the thesis will be discussed in this section. Subjects in this study were recruited from various sports, which allows for the results obtained in this thesis to be generalised across sports and strength-matched individuals all with different technical competency in the PC (particularly the proficiency of the catch phase), CMS, and HP and were all male. Thus, caution is advised in applying the results from this thesis with weightlifters who are substantially more competent in these lifts. Further, due to these subjects being recruited from the Hong Kong Sports Institute athlete population, all were performing concurrent sports specific training throughout the training week, and therefore various frequencies and intensities, however, logistically, it was not possible to control for this. However, subjects had at least 48 hours with no intensive training prior to participation. The methodological of data collection via the FP is also a limitation. With regard to optimal sampling frequency, recommendations are based on the Nyquist– Shannon sampling theorem, which states that the critical sampling frequency must be a minimum of two times the highest frequency in the signal of interest to obtain all the information found in the original signal (78, 130, 229). Sampling at rates below the critical frequency run the risk of aliasing (i.e., distortion) and losing critical pieces of the original signal (130, 229). In this thesis, all data was collection on a force plate sampling at 600 Hz only (As this is the only available option). It is recommended when rate dependent variables are included sampling frequencies should be much larger (1000–2500 Hz) (229). Therefore, sampling at a higher frequency may yield different or more accurate findings.

9.3. FUTURE DIRECTIONS OF RESEARCH

Whist several gaps in the literature and practical implications have been addressed in this thesis, there remains scope for future research.

- Perform further investigations to determine similar differences are observed in elite weightlifters (studies 1 & 2), as their clean and power clean maximums are likely more accurate due to technical mastery in those derivatives.
- Due to the paucity of kinetic and kinematic data during snatch derivatives, further research should investigate kinetic and kinematic differences during the snatch derivatives.
- As a result of non-alignment of phases during the biomechanical time series data during the CMS and HP with an increase in load, researchers should consider normalising movement phases (and not overall movement time) to determine if any true differences occur between phases.
- As RR did not result in significantly greater kinetics or kinematics during the HP or CMS compared to TS, it is worth exploring if significant differences occur in an elite weightlifting population.
- Due to the reduced range of motion during the CMS and HP, future investigations should identify the upper limit repetition range for supramaximal loaded pulls at 140% and 3x6 is not extremely fatiguing, and it may be possible to perform > 6 repetitions, without the detrimental effect of kinetic and kinematic output.
- Longitudinal studies involving the CMS and HP are recommended to determine if different loading paradigms result in different adaptations, and if training with a specific exercise improves athletic performance over another exercise, even if one exercise is associated with greater kinetics and kinematics as shown in this thesis.

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Appendices

10.1. APPENDIX 1- PARTICIPANT INFORMATION SHEET

Athletes wanted for PhD Research in Olympic Weightlifting Derivatives

- **High quality testing of force and power in key exercises**
- **Undertaken at the elite S&C facility at the Hong Kong Sports Institute**
- **Supervised by an elite strength and conditioning coach**
- **If you are aged 18-35 and are uninjured then you may be eligible**

For more information contact

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10.2. APPENDIX 2- EXAMPLE CONSENT FORM

CONSENT FORM

Title of study: A comparison of kinetic and kinematic variables during the mid-thigh pull and pull from the knee, with and without countermovement, across loads

Name of Researcher: DM
[Anonymise for initial approval]

Please complete and sign this form **after** you have read and understood the study information sheet. Read the statements below and yes or no, as applicable in the box on the right-hand side.

1.	I confirm that I have read and understand the study information sheet version 1, dated December 2016, for the above study. I have had opportunity to consider the information and ask questions which have been answered satisfactorily.	Yes/No
2.	I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without my rights being affected.	Yes/No
3.	If I do decide to withdraw I understand that the information I have given, up to the point of withdrawal, may be used in the research. The timeframe for withdrawal is 4 weeks after data has been collected.	Yes/No
4.	I agree to participate by undertaking the physical activity that has been described in the participation information sheet.	Yes/No
5.	I understand that my personal details will be kept confidential and not revealed to people outside the research team -However, your results may be shared with your coach to aid in training development. I am aware that if I reveal anything related to criminal activity and/or something that is harmful to self or other, the researcher will have to share that information with the appropriate authorities].	Yes/No
6.	I understand that my anonymised data will be used in DM thesis/ research report and other academic publications and conferences presentations.	Yes/No
7.	I agree to take part in the study:	Yes/No

______________________ ______________________ ______________________

Name of participant **Date** **Signature**

Name of person taking consent **Date** **Signature**

10.3. APPENDIX 3- ETHICAL APPROVAL

10.3.1. Ethical Approval (Chapter's 3-6)

University of Salford
MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

Research Centres Support Team
G0.3 Joule House
University of Salford
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk/

22 February 2017

Dear David,

RE: ETHICS APPLICATION–HSR1617-60–'A comparison of kinetic and kinematic variables during the mid thigh pull and pull from the knee, with and without counter movements, across loads..'

Based on the information you provided I am pleased to inform you that application HSR1617-60 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

10.3.2. Ethical Approval 2 (Chapter 7)

University of Salford MANCHESTER

Research, Enterprise and Engagement
Ethical Approval Panel

Doctoral & Research Support
Research and Knowledge Exchange,
Room 827, Maxwell Building,
University of Salford,
Manchester
M5 4WT

T +44(0)161 295 2280

www.salford.ac.uk

11 August 2020

Dear David,

RE: ETHICS APPLICATION–HSR1920-102 – The effect of rest redistribution of kinetic and kinematic variables during the countermovement shrug, across loads.

Based on the information that you have provided, I am pleased to inform you that application HSR1920-102 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Professor Andrew Clark
Chair of the Research Ethics Panel

10.3.3. Ethical Approval Amendment (Chapter 8)

University of Salford MANCHESTER

Amendment Notification Form

<table>
<tr><td colspan="3">Title of Project:</td></tr>
<tr><td colspan="3">The effect of rest redistribution of kinetic and kinematic variables during the countermovement shrug (part A) and hang pull (part B), across loads</td></tr>
<tr><td>Name of Lead Applicant:</td><td colspan="2">School:</td></tr>
<tr><td>David Meechan</td><td colspan="2">Health & Society</td></tr>
<tr><td colspan="2">Are you the original Principal Investigator (PI) for this study?</td><td>Yes</td></tr>
<tr><td colspan="3">If you have selected ‘NO’, please explain why you are applying for the amendment:</td></tr>
<tr><td>Date original approval obtained:</td><td>Reference No:</td><td>Externally funded project?</td></tr>
<tr><td>11/08/2020</td><td>HSR1920-102</td><td>No</td></tr>
<tr><td colspan="3">Please outline the proposed changes to the project. NB. If the changes require any amendments to the PIS, Consent Form(s) or recruitment material, then please submit these with this form highlighting where the changes have been made:</td></tr>
<tr><td colspan="3">We seek to make an amendment to the above project. As part of this research, we would also like to investigate ‘The effect of rest redistribution of kinetic and kinematic variables during the hang pull, across loads. From a methodological standpoint, all methods of data collection, subjects, data protection will be the same, with the only difference being the addition of a different exercise derivative which has a larger barbell displacement. This has been highlighted in yellow in the previous approval letter as part A and part B. Attached is the amended ethical application form.</td></tr>
<tr><td colspan="3">Please say whether the proposed changes present any new ethical issues or changes to ethical issues that were identified in the original ethics review, and provide details of how these will be addressed:</td></tr>
<tr><td colspan="3">They do not present any new ethical issue</td></tr>
</table>

Amendment Approved:	**YES**	***Date of Approval:***	**19/11/2021**

Chair's Signature:

Once completed you should submit this form and any additional documentation to the RKE Ethics Team at ethics@salford.ac.uk

Version 3.1 – July 2020

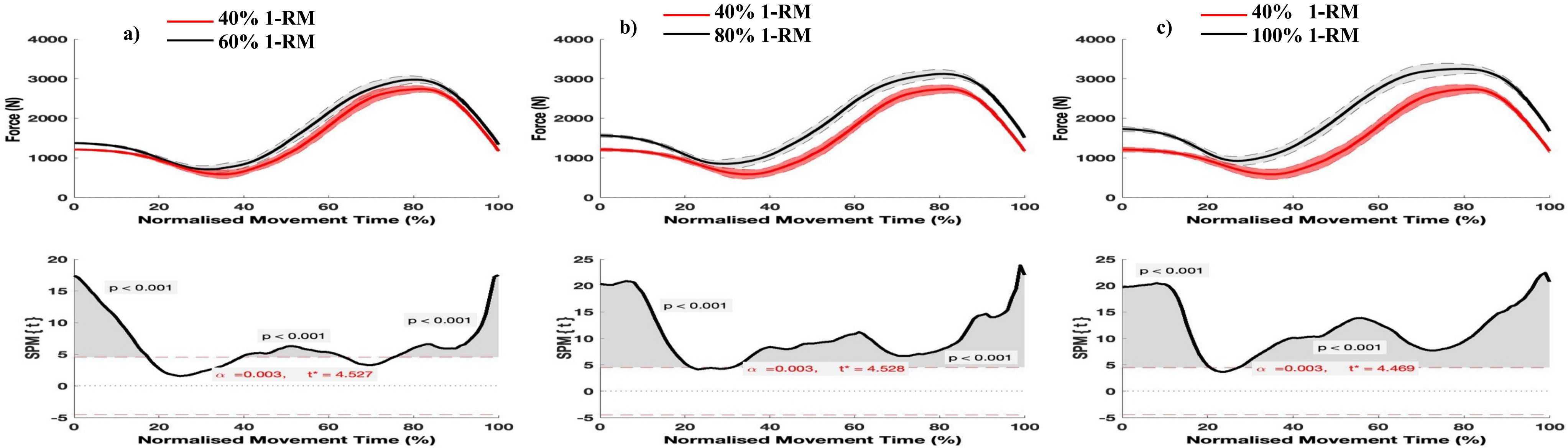
10.4. APPENDIX 4- BACKGROUND TO FORCE PLATE TECHNOLOGY

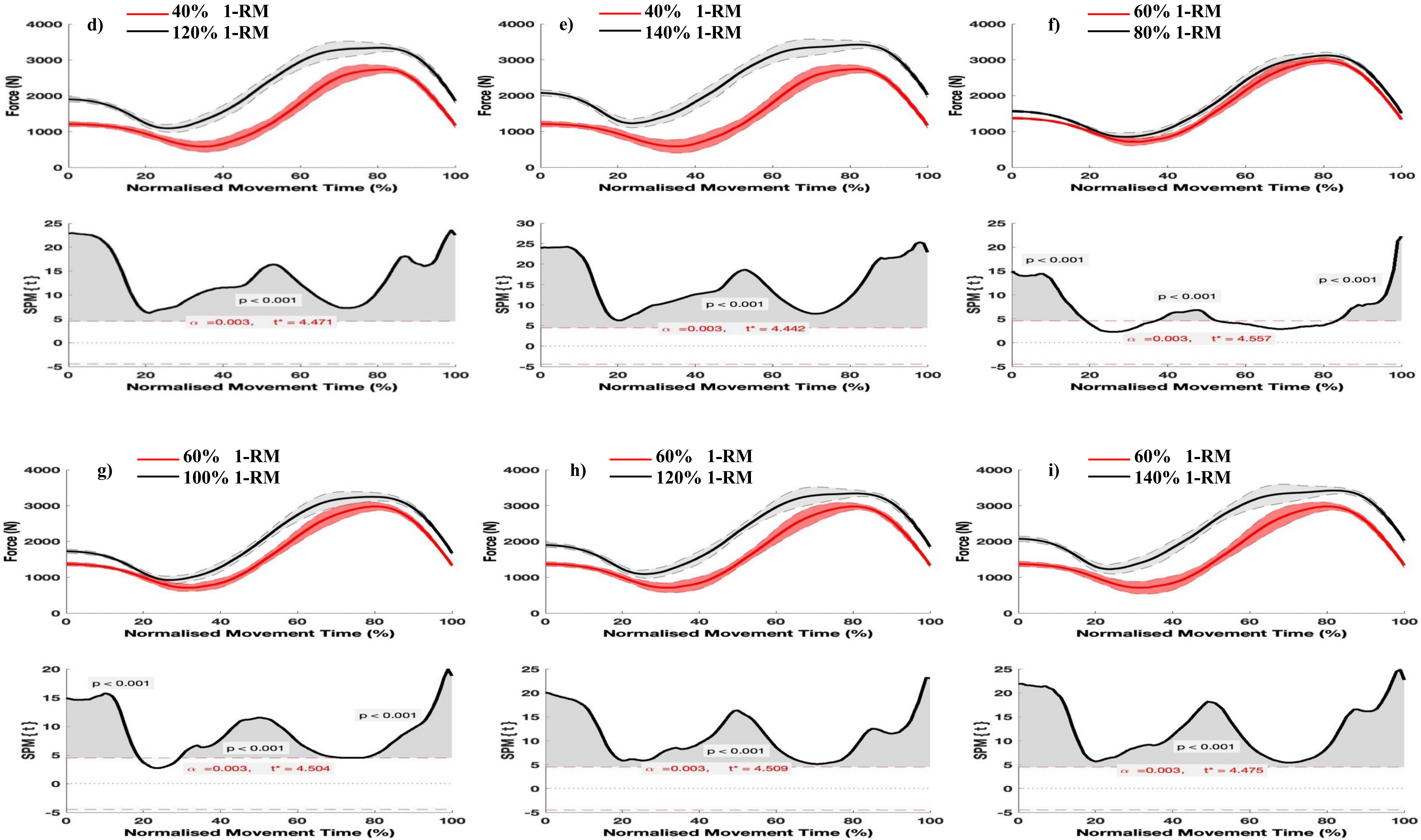
Force platforms or force plates (FP) are rectangular plates, generally either metal or plastic, depending on design and brand and are typically approximately 0.4 m x 0.6 m (205). Force platforms measure the force exerted over time by the subject, which in accordance with Newton's third law, is equal in magnitude and opposite in direction of the force being applied to the FP (205). These forces are measured via an internal force transducer and this either converts or transduces the force in measurable voltage called load cells, in which the common load cells are strain gauges, piezoelectric and beam load cells (25). A FP usually has four load cells, one positioned at each corner, that are constructed either using piezo-electric technology or with strain gauges (203) with many FP capable of measuring force in three planes; vertical, anterior-posterior and medial-lateral (25). Piezo electric cells operate when a force is applied to a piezo electric material, a charge equal to the force appears on the surface material (25). Further, strain gauge and load beam cells operate when a deformation of a semiconductor occurs. All of the above devices all have an excitation voltage that runs through them, with the initial input voltage known. Monitoring the changes in voltage with applied force allows for calculation of the force applied to the device (25). In human movements such as jumping and sprinting which apply force to the ground, this force is commonly referred to as the 'ground reaction force' (GRF), with both peak force (PF) and mean force (MF) commonly reported (205).

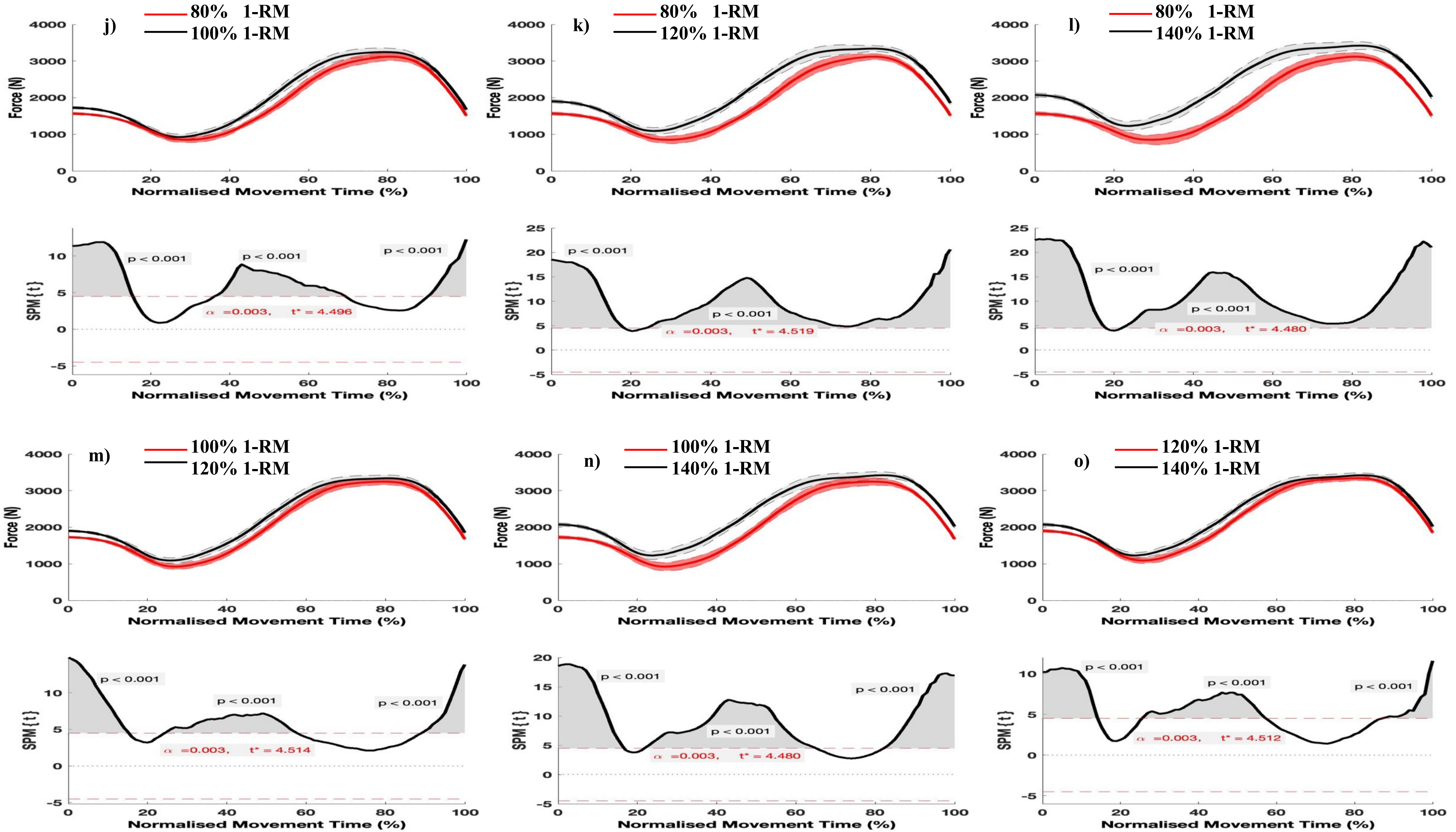
Laboratory FP's are typically housed into a concrete floor to reduce the external vibrations and to ensure the landing surface is even with the laboratory floor (33, 340). Furthermore, laboratory FPs are very sensitive to extraneous vibrations and are usually mounted to the manufacturers specifications to preserve the signal integrity (73). One previous limitation with laboratory FPs was that they were limited to a laboratory setting, and thus inaccessible for most testing sessions where athletic performance training is performed (33, 340). However, through advancement of FP technology, FPs with high sampling frequency and portability can now be used in field-based settings due to smaller dimensions with lower financial cost.

10.5. APPENDIX 5- SUPPLEMENTARY DIGITAL CONTENT (CHAPTER 5, STUDY 3)

10.5.1. SPM T-tests (Force)

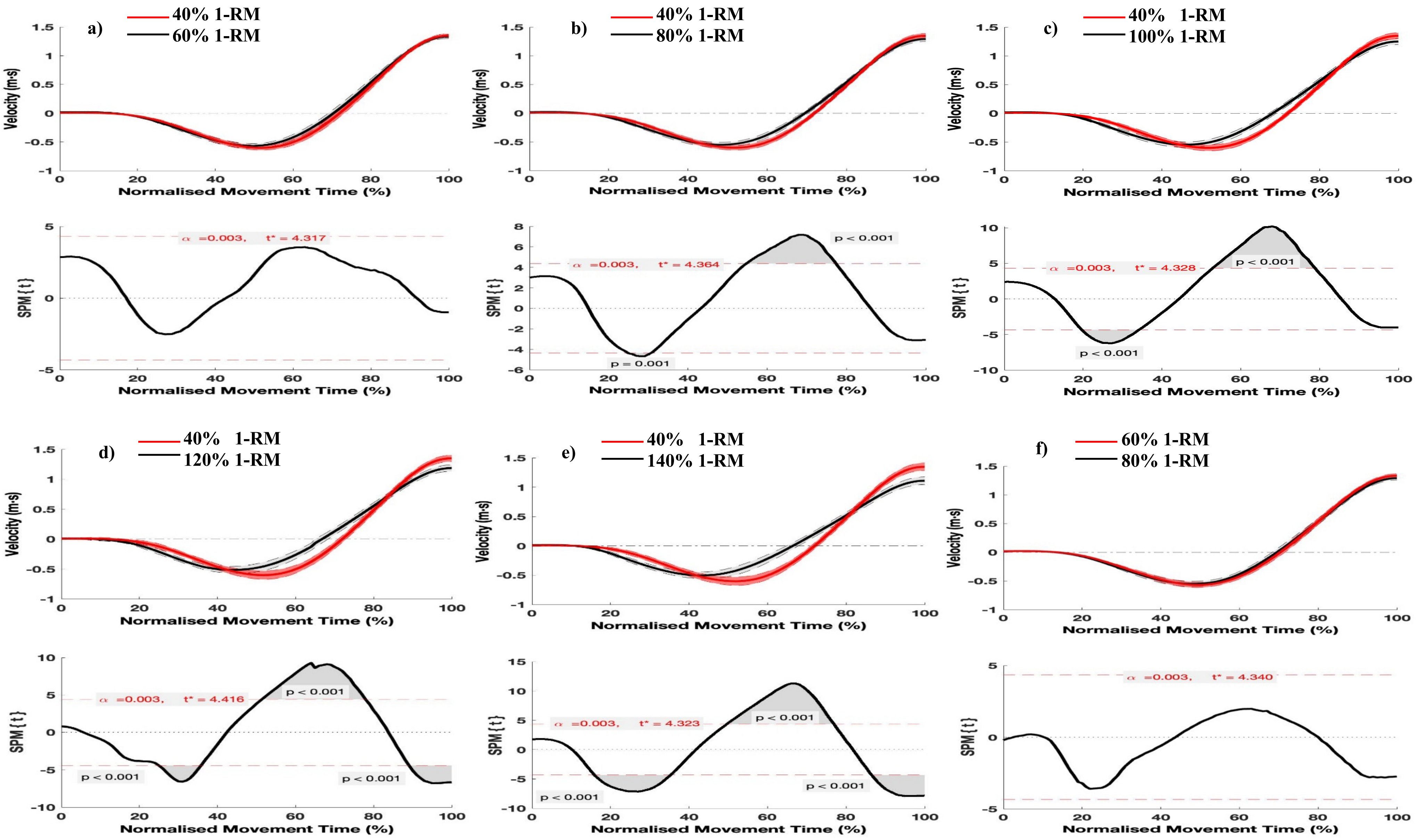


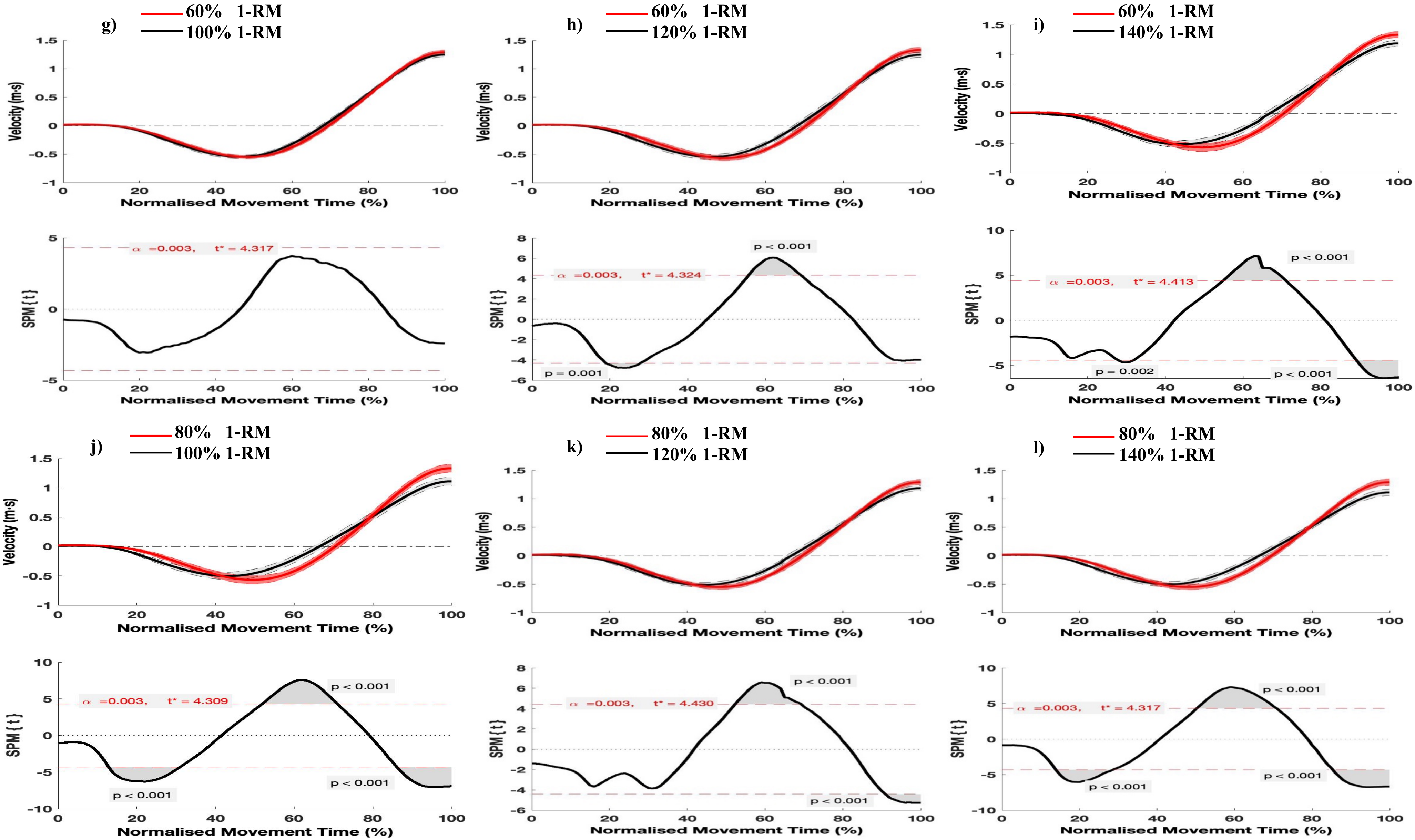

d)
40% 1-RM
120% 1-RM
Force (N)
Normalised Movement Time (%)
SPM{t}
p < 0.001
α =0.003, t* = 4.471
e)
40% 1-RM
140% 1-RM
Force (N)
Normalised Movement Time (%)
SPM{t}
p < 0.001
α =0.003, t* = 4.442
f)
60% 1-RM
80% 1-RM
Force (N)
Normalised Movement Time (%)
SPM{t}
p < 0.001
p < 0.001
p < 0.001
α =0.003, t* = 4.557
g)
60% 1-RM
100% 1-RM
Force (N)
Normalised Movement Time (%)
SPM{t}
p < 0.001
p < 0.001
p < 0.001
α =0.003, t* = 4.504
h)
60% 1-RM
120% 1-RM
Force (N)
Normalised Movement Time (%)
SPM{t}
p < 0.001
α =0.003, t* = 4.509
i)
60% 1-RM
140% 1-RM
Force (N)
Normalised Movement Time (%)
SPM{t}
p < 0.001
α =0.003, t* = 4.475



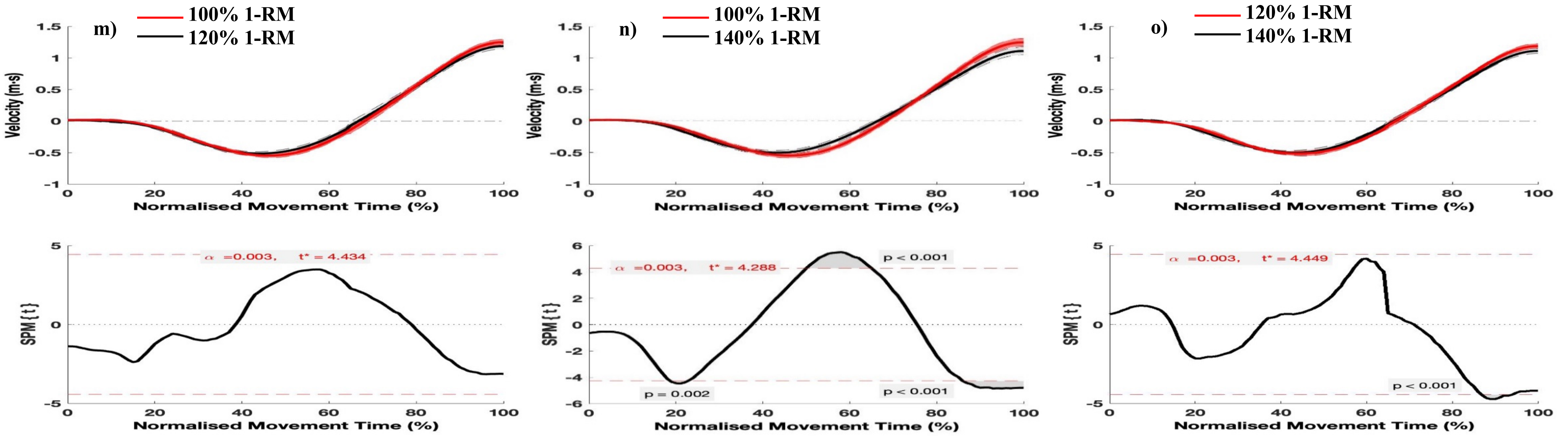
(a-o)- Top- Mean and 95% confidence intervals [95% CI] for time-normalised force. Bottom- Statistical parametric mapping [SPM] t-test- inference curve with suprathreshold clusters (shaded), critical threshold (t statistic) as a function of time represents a significant difference between those timepoints.

10.5.2. SPM T-tests (Velocity)



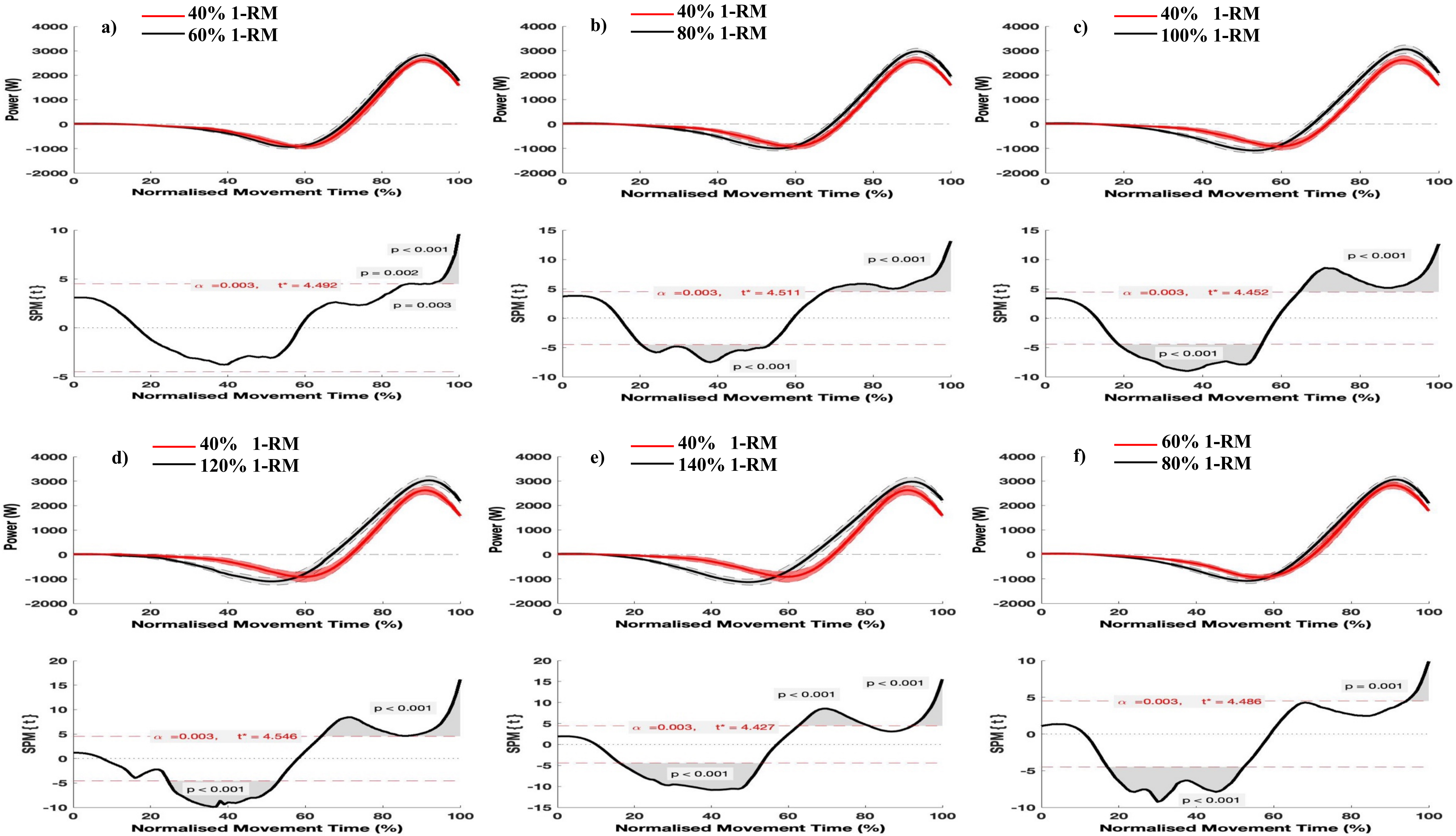


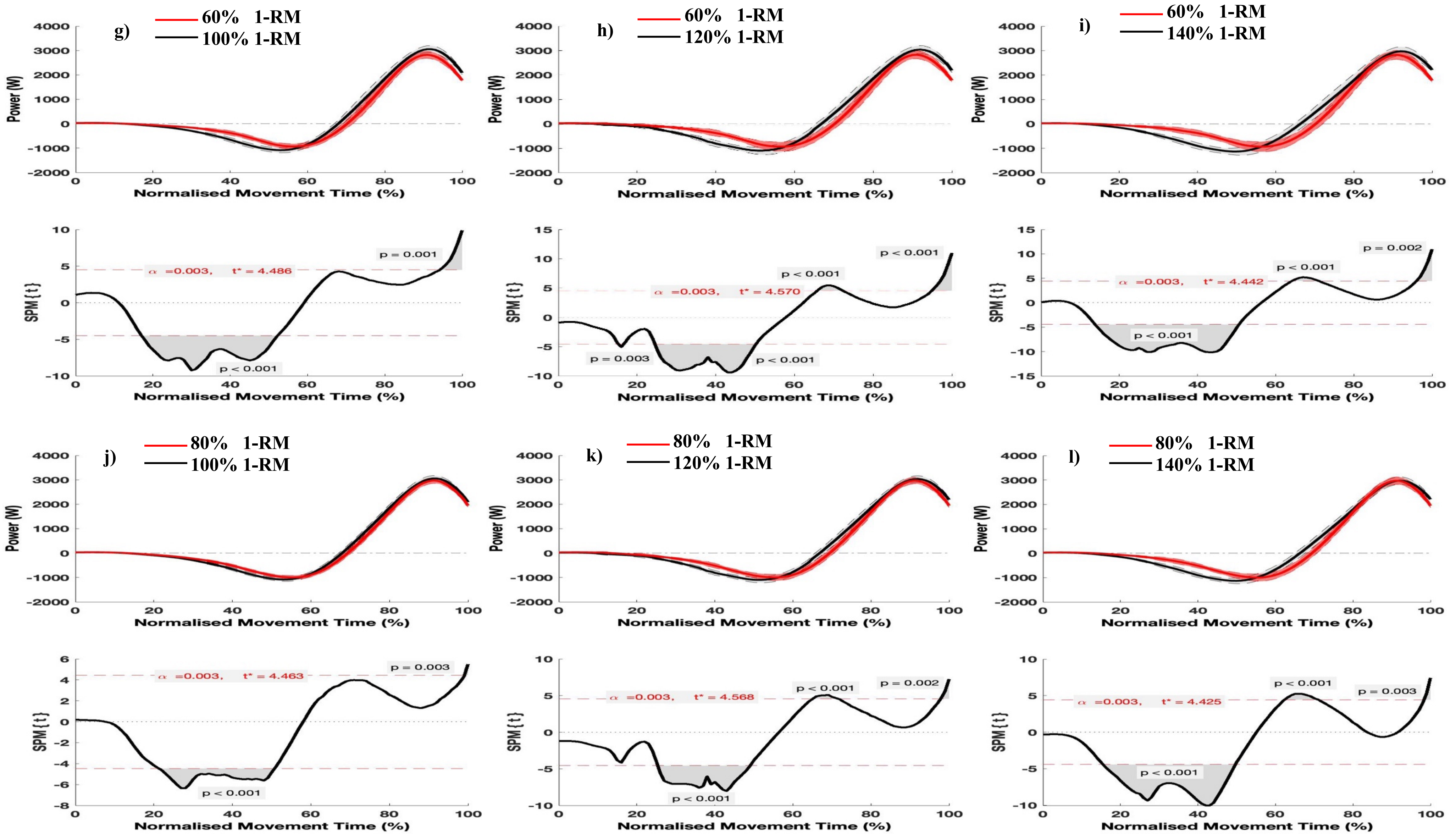
g)
60% 1-RM
100% 1-RM
Velocity (m·s)
Normalised Movement Time (%)
SPM{t}
α =0.003, t* = 4.317
h)
60% 1-RM
120% 1-RM
α =0.003, t* = 4.324
p < 0.001
p = 0.001
i)
60% 1-RM
140% 1-RM
α =0.003, t* = 4.413
p < 0.001
p = 0.002
p < 0.001
j)
80% 1-RM
100% 1-RM
α =0.003, t* = 4.309
p < 0.001
p < 0.001
p < 0.001
k)
80% 1-RM
120% 1-RM
α =0.003, t* = 4.430
p < 0.001
p < 0.001
l)
80% 1-RM
140% 1-RM
α =0.003, t* = 4.317
p < 0.001
p < 0.001
p < 0.001



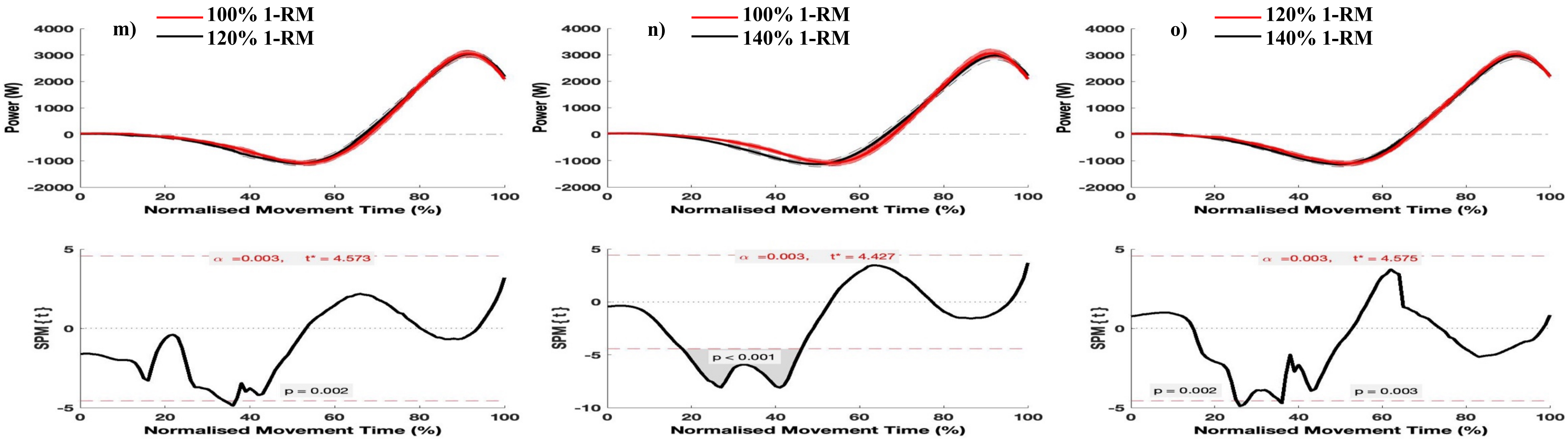
(a-o)- Mean and 95% confidence intervals [95% CI] for time-normalised velocity. Unweighted phase = Initial decrease velocity, to the lowest point (greatest negative velocity), Braking phase = greatest negative velocity until zero velocity, Propulsion phase = Above zero velocity. Statistical parametric mapping (SPM) t-test- inference curve as a function of time, with suprathreshold clusters (shaded), critical threshold for SPM[t] statistic (Dashed Line) indicating the random field theory critical thresholds for significance (α = 0.003), and p-values

10.5.3. SPM T-tests (Power)





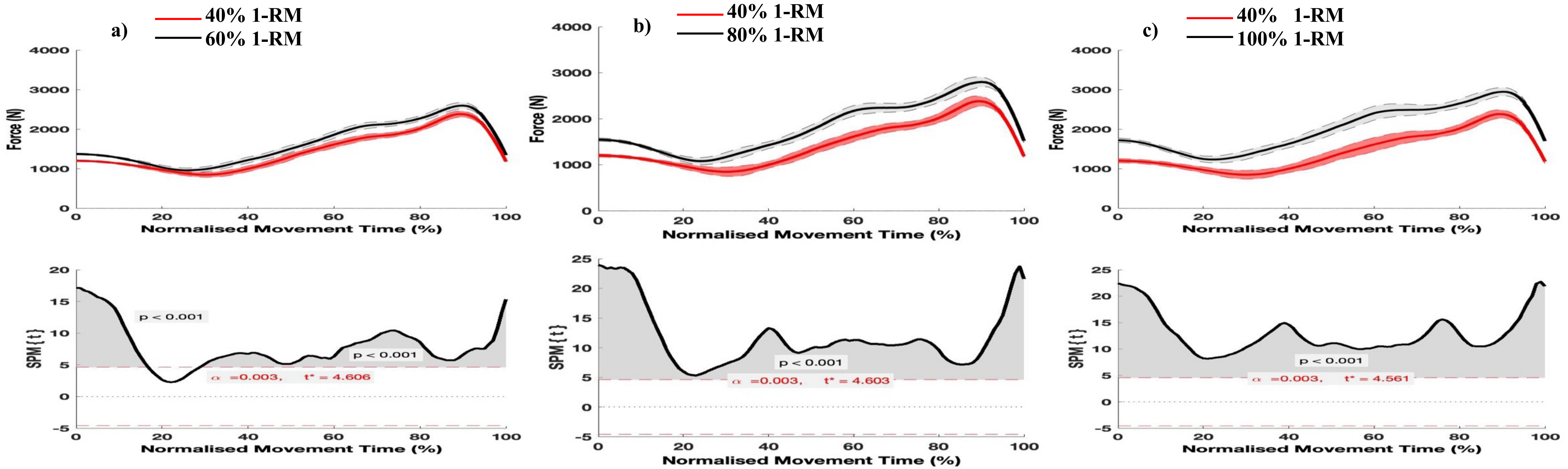
g)
60% 1-RM
100% 1-RM
Power (W)
Normalised Movement Time (%)
SPM{t}
α =0.003, t* = 4.486
p = 0.001
p < 0.001
h)
60% 1-RM
120% 1-RM
α =0.003, t* = 4.570
p < 0.001
p < 0.001
p = 0.003
p < 0.001
i)
60% 1-RM
140% 1-RM
α =0.003, t* = 4.442
p = 0.002
p < 0.001
p < 0.001
j)
80% 1-RM
100% 1-RM
α =0.003, t* = 4.463
p = 0.003
p < 0.001
k)
80% 1-RM
120% 1-RM
α =0.003, t* = 4.568
p < 0.001
p = 0.002
p < 0.001
l)
80% 1-RM
140% 1-RM
α =0.003, t* = 4.425
p < 0.001
p = 0.003
p < 0.001

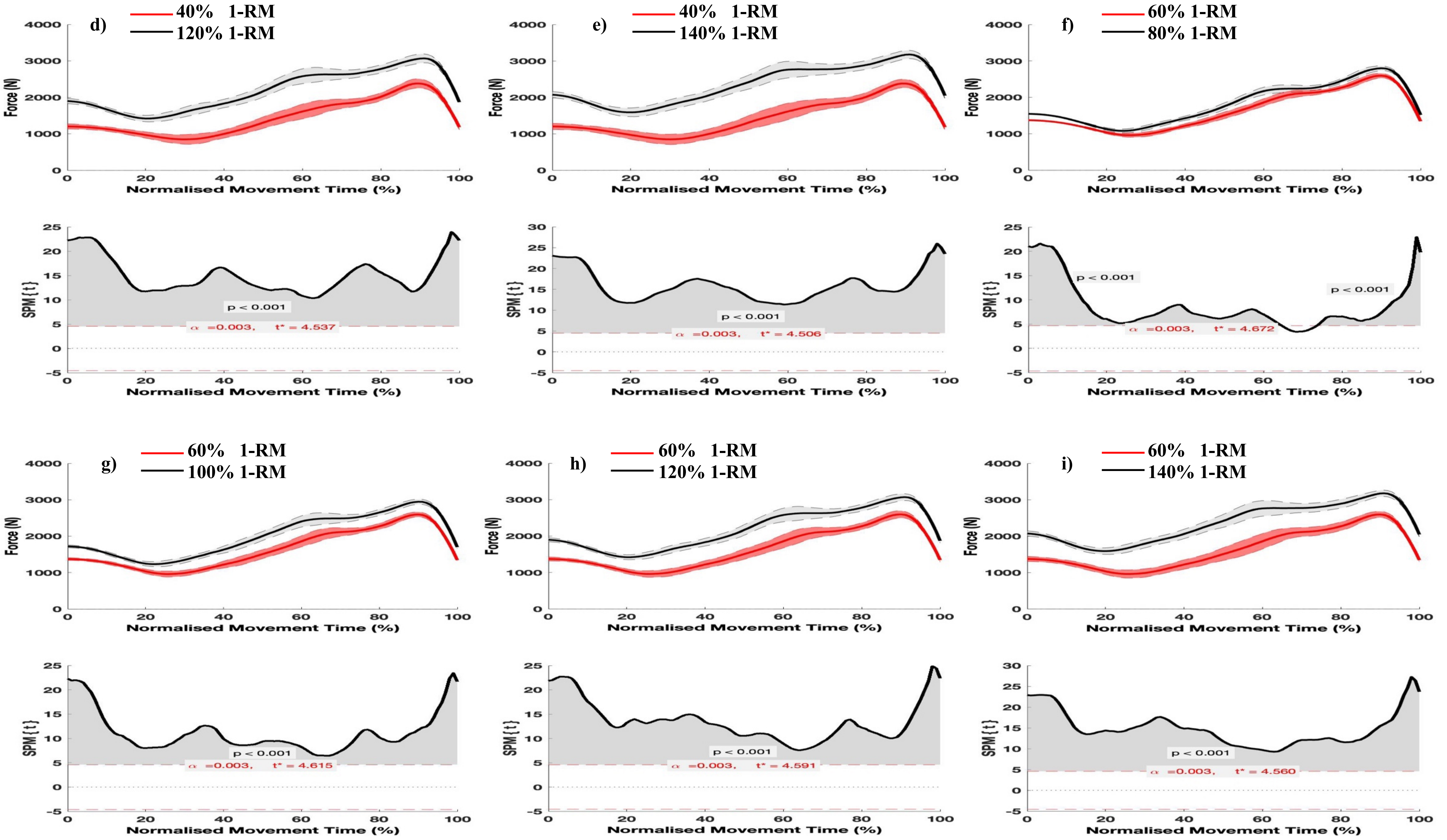


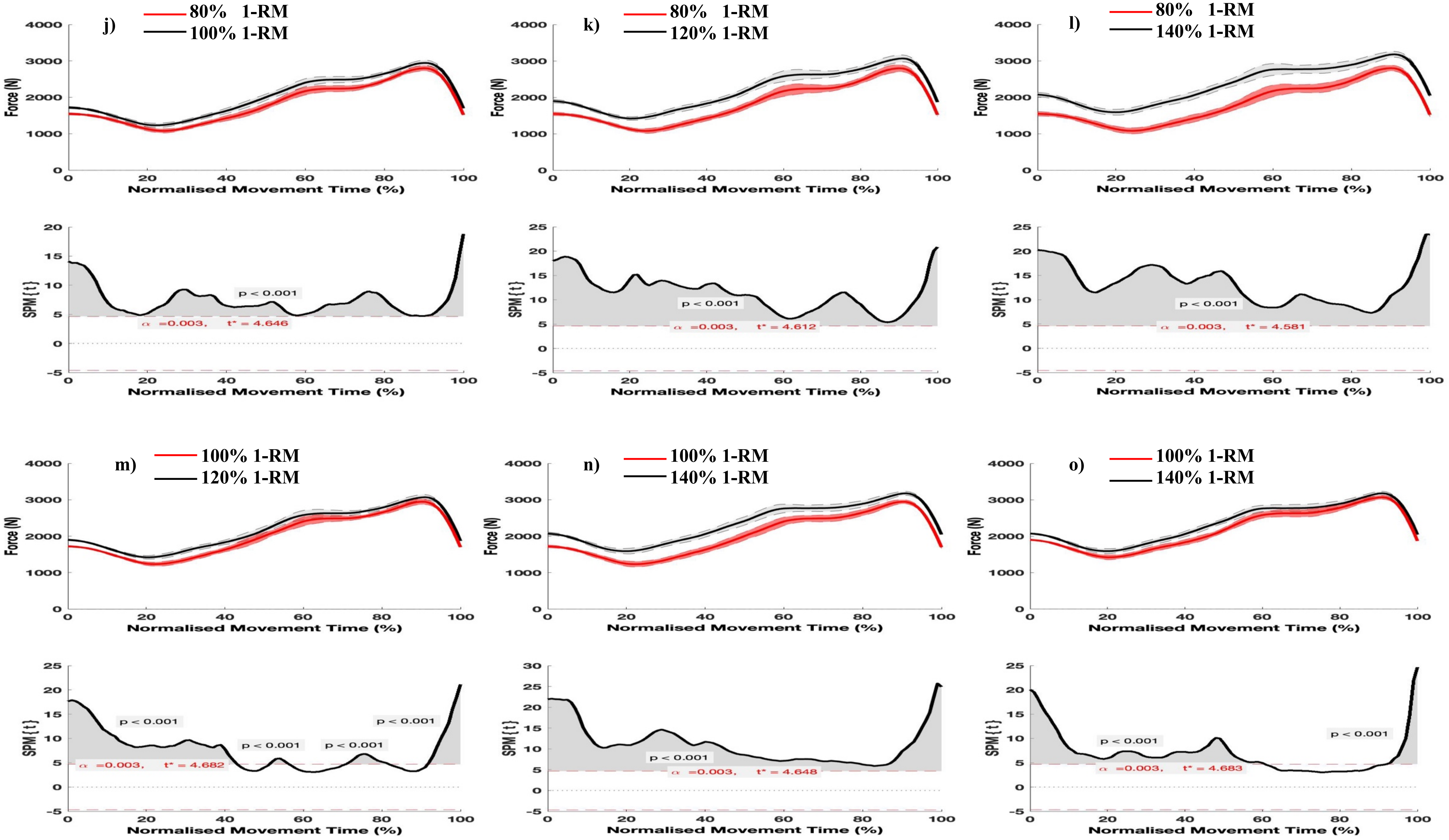
(a-o)- Top- Mean and 95% confidence intervals [95% CI] for time-normalised power. Bottom- Statistical parametric mapping [SPM] t-test- inference curve with suprathreshold clusters (shaded), critical threshold (t statistic) as a function of time represents a significant difference between those timepoints.

10.6. APPENDIX 6- SUPPLEMENTARY DIGITAL CONTENT (CHAPTER 6, STUDY 4)

10.6.1. SPM T-Tests (Force)

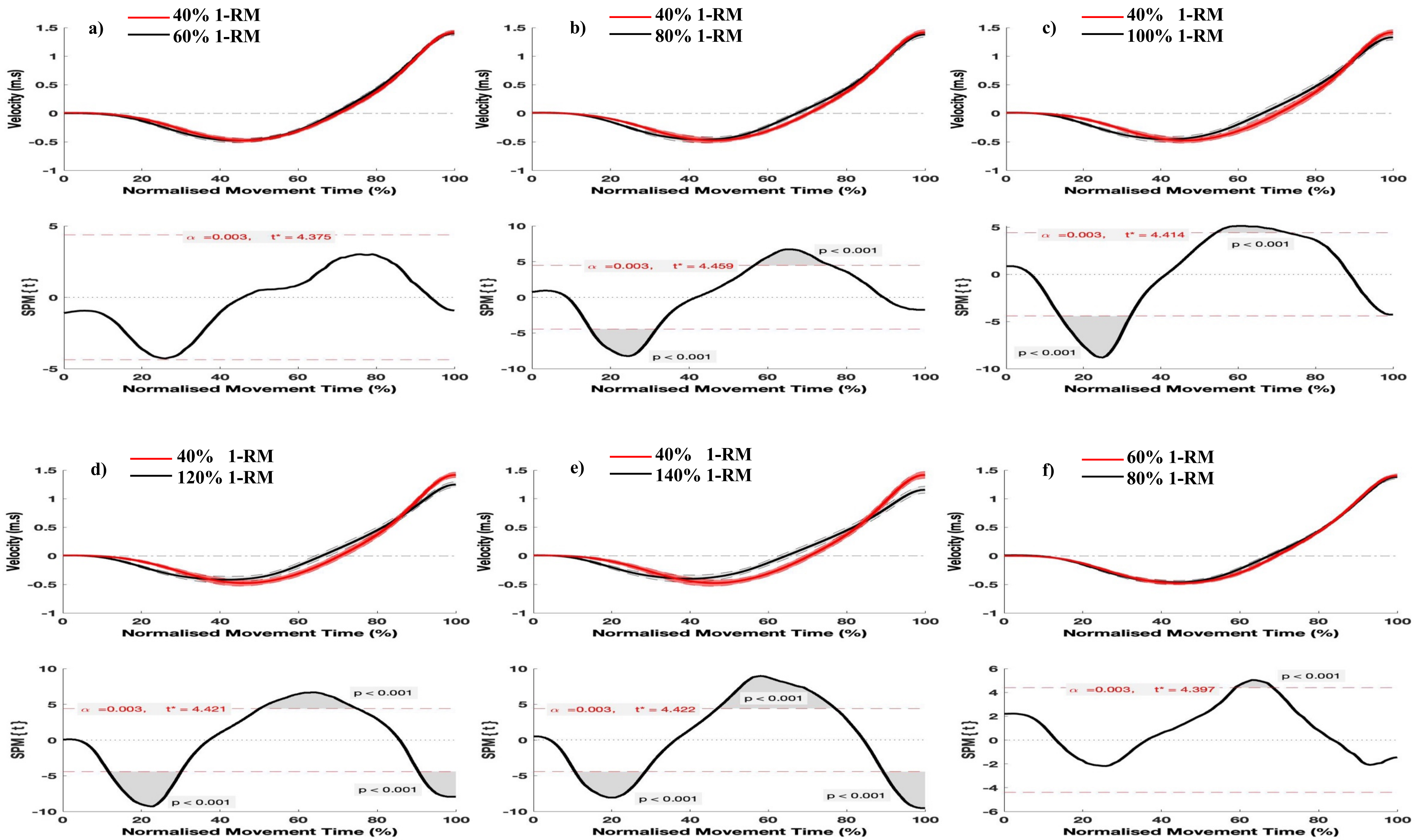


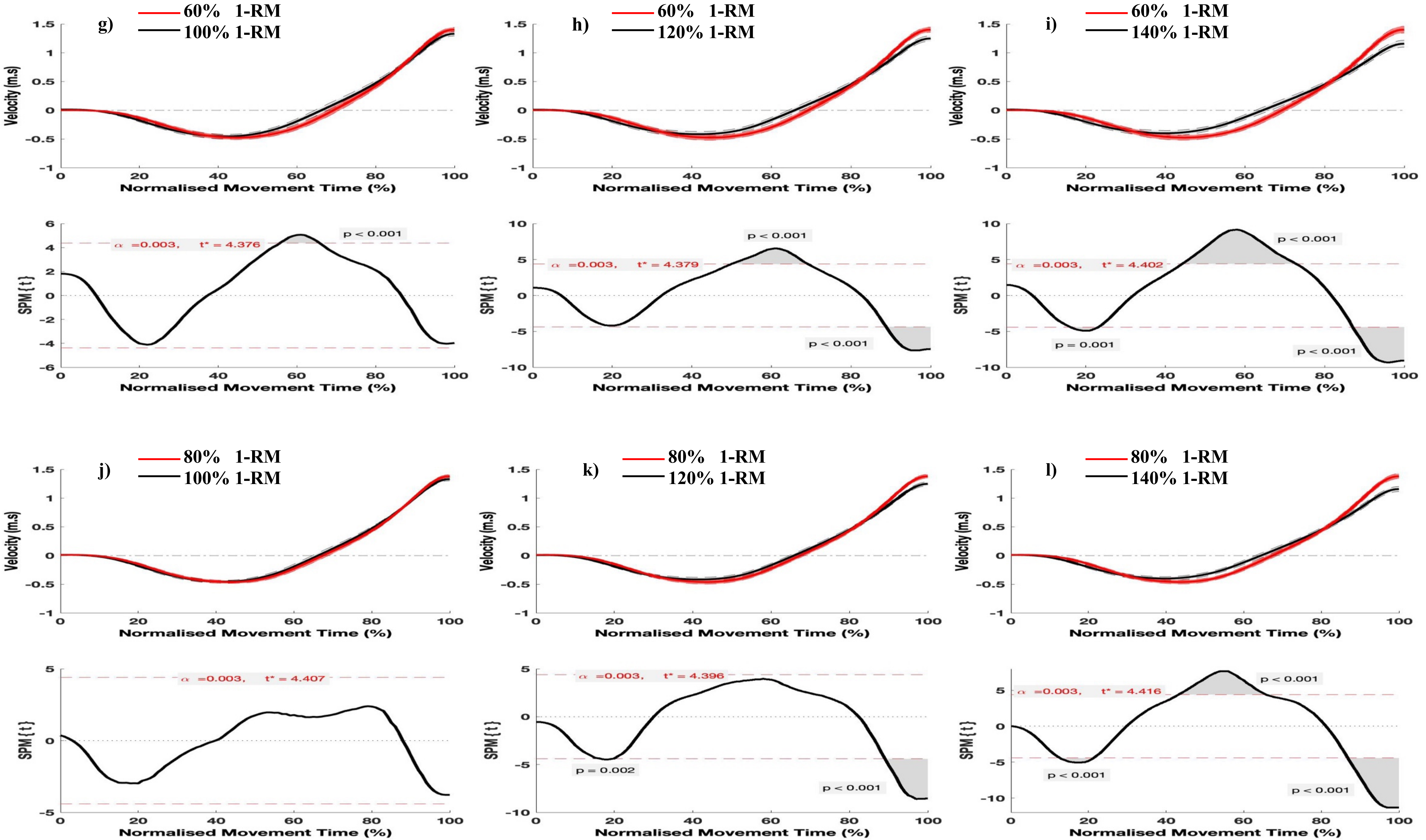

d)
40% 1-RM
120% 1-RM
e)
40% 1-RM
140% 1-RM
f)
60% 1-RM
80% 1-RM
g)
60% 1-RM
100% 1-RM
h)
60% 1-RM
120% 1-RM
i)
60% 1-RM
140% 1-RM
Force (N)
SPM{t}
Normalised Movement Time (%)
p < 0.001
α =0.003, t* = 4.537
α =0.003, t* = 4.506
α =0.003, t* = 4.672
α =0.003, t* = 4.615
α =0.003, t* = 4.591
α =0.003, t* = 4.560



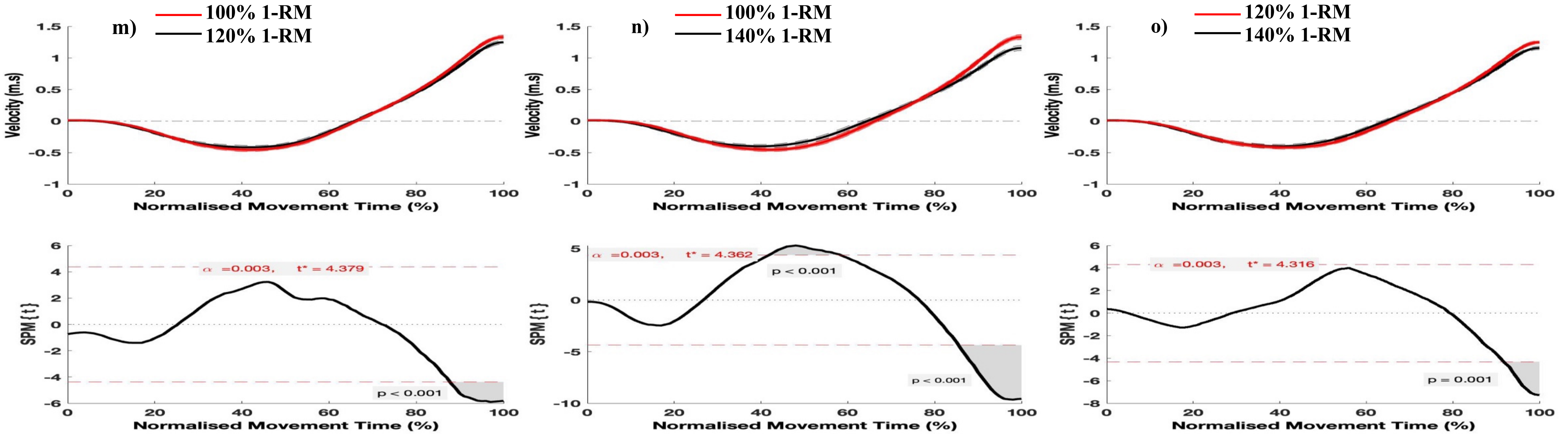
(a-o)- Top- Mean and 95% confidence intervals [95% CI] for time-normalised force. Bottom- Statistical parametric mapping [SPM] t-test- inference curve with suprathreshold clusters (shaded), critical threshold (t statistic) as a function of time represents a significant difference between those timepoints.

10.6.2. SPM T-Tests (Velocity)



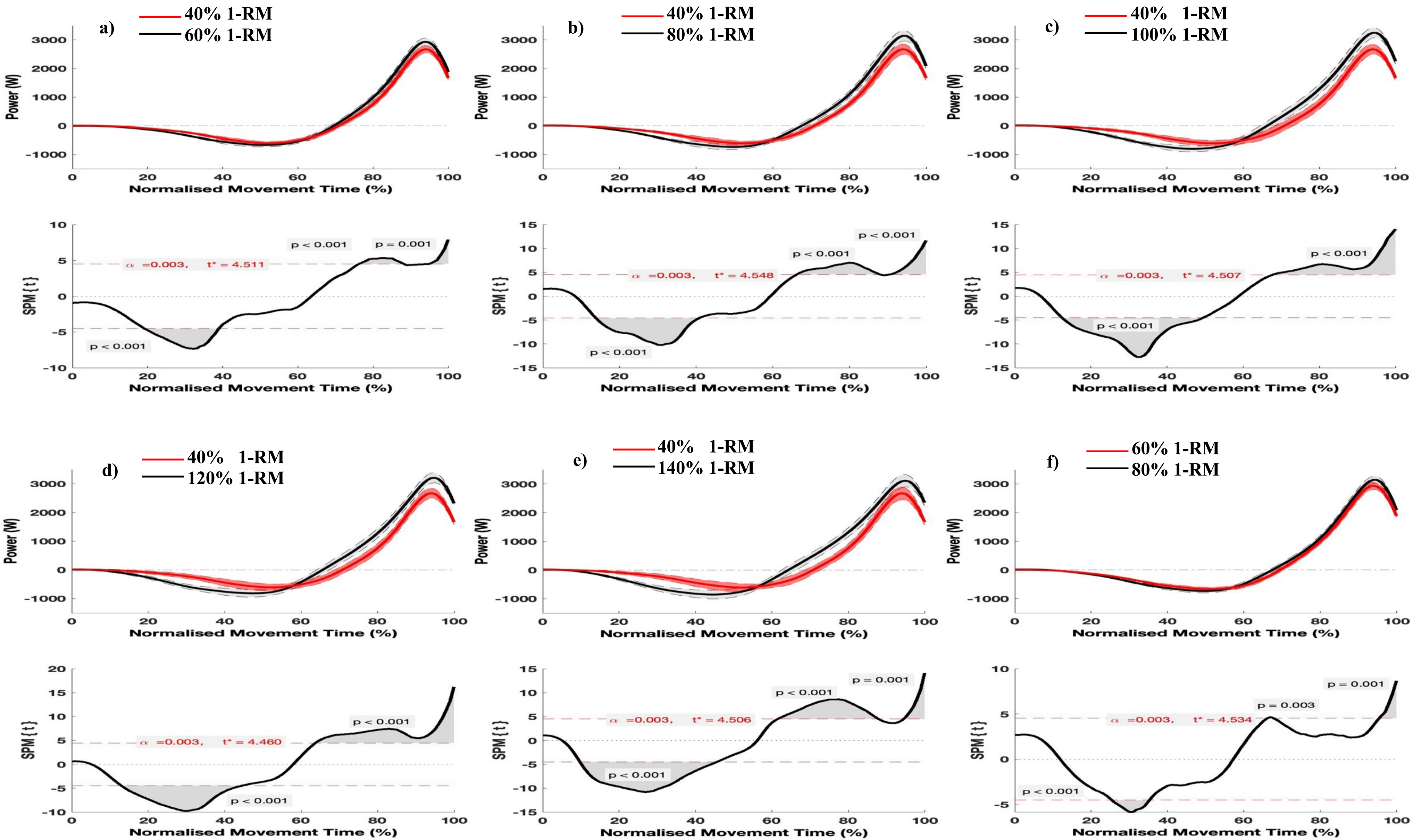


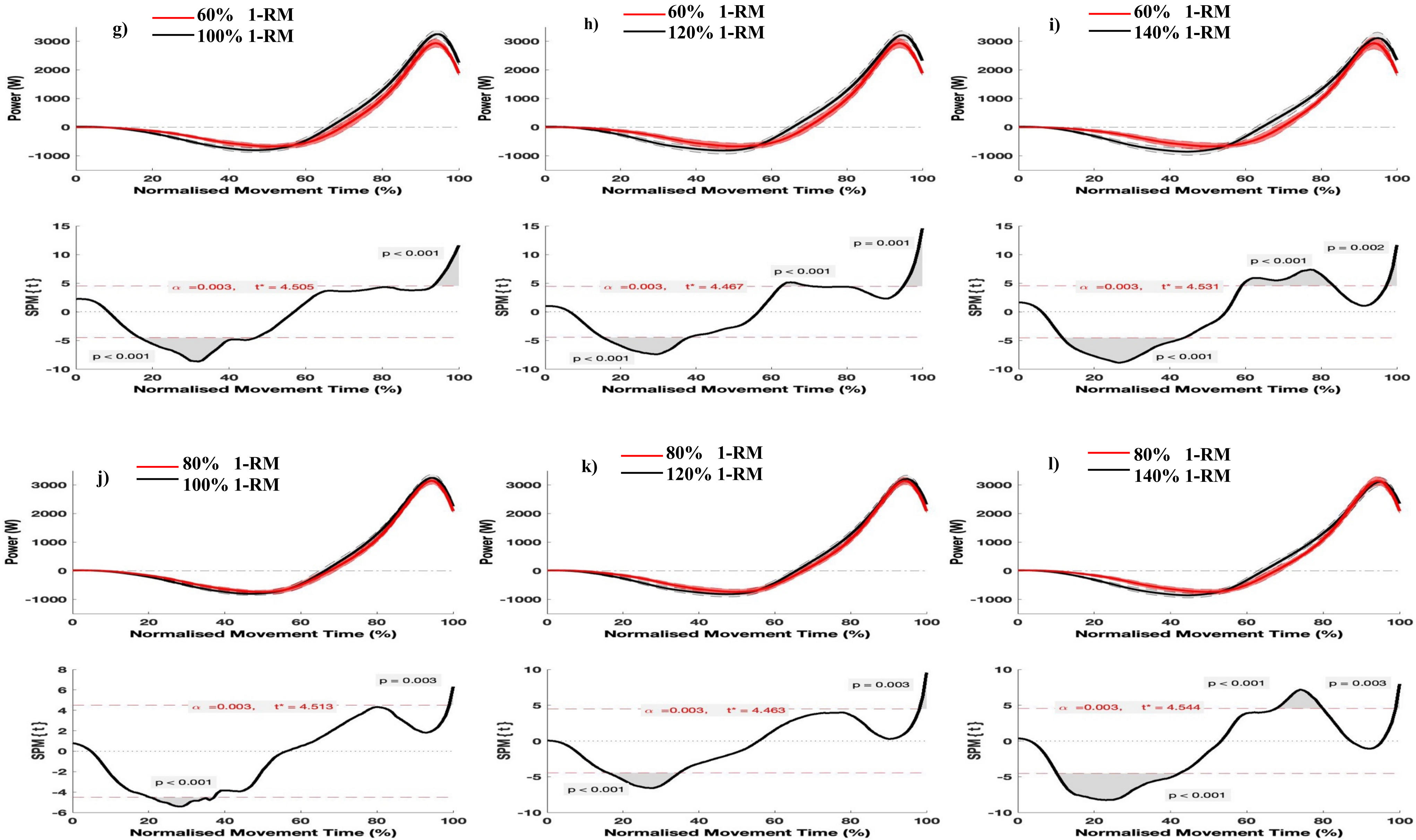
g)
60% 1-RM
100% 1-RM
h)
60% 1-RM
120% 1-RM
i)
60% 1-RM
140% 1-RM
j)
80% 1-RM
100% 1-RM
k)
80% 1-RM
120% 1-RM
l)
80% 1-RM
140% 1-RM
Velocity (m.s)
SPM{t}
Normalised Movement Time (%)
α =0.003, t* = 4.376
p < 0.001
α =0.003, t* = 4.379
p < 0.001
p < 0.001
α =0.003, t* = 4.402
p < 0.001
p = 0.001
p < 0.001
α =0.003, t* = 4.407
α =0.003, t* = 4.396
p = 0.002
p < 0.001
α =0.003, t* = 4.416
p < 0.001
p < 0.001
p < 0.001



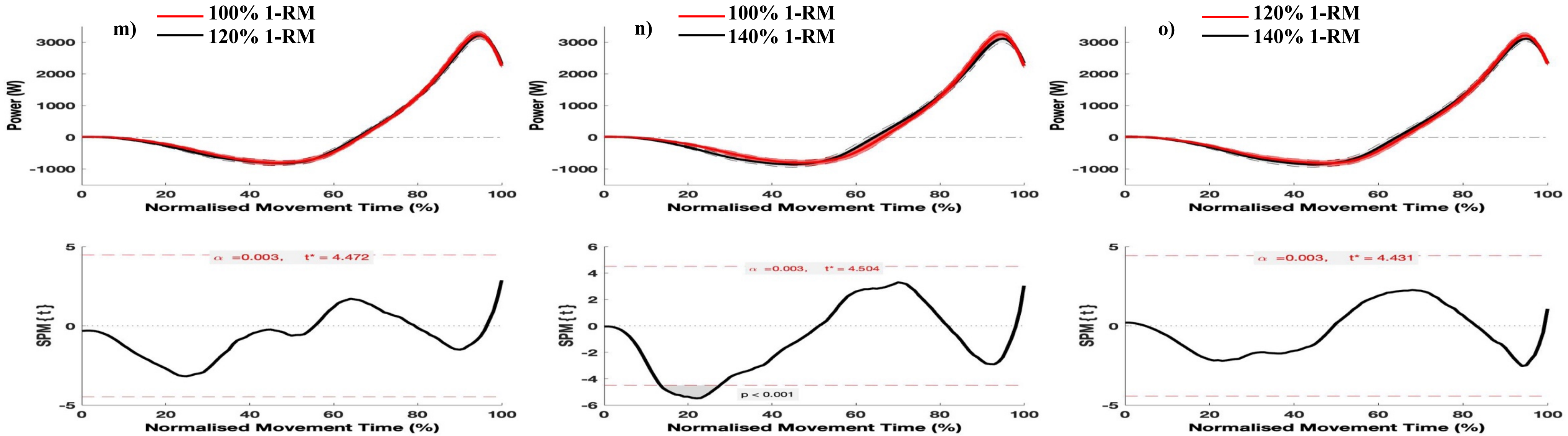
(a-o)- Mean and 95% confidence intervals [95% CI] for time-normalised velocity. Unweighted phase = Initial decrease velocity, to the lowest point (greatest negative velocity), Braking phase = greatest negative velocity until zero velocity, Propulsion phase = Above zero velocity. Statistical parametric mapping (SPM) t-test- inference curve as a function of time, with suprathreshold clusters (shaded), critical threshold for SPM [t] statistic (Dashed Line) indicating the random field theory critical thresholds for significance (α = 0.003), and p-values

10.6.3. SPM T-Tests (Power)





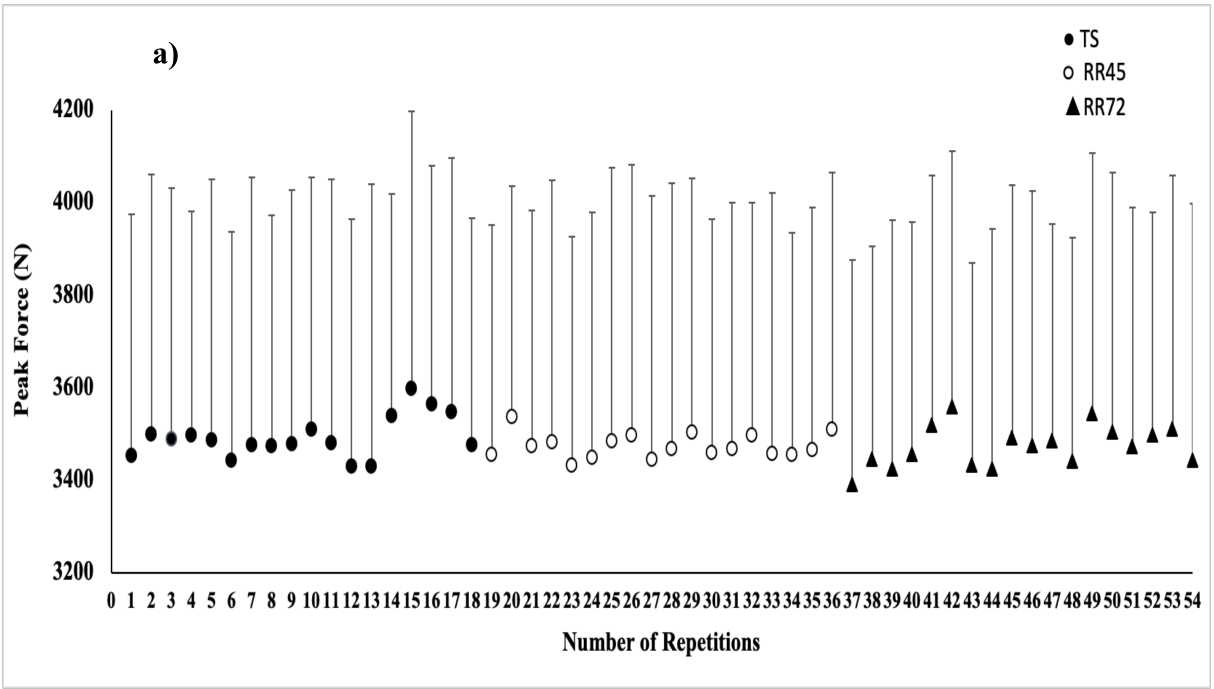
g)
60% 1-RM
100% 1-RM
h)
60% 1-RM
120% 1-RM
i)
60% 1-RM
140% 1-RM
Power (W)
Normalised Movement Time (%)
SPM{t}
α =0.003, t* = 4.505
α =0.003, t* = 4.467
α =0.003, t* = 4.531
p < 0.001
p = 0.001
p = 0.002
j)
80% 1-RM
100% 1-RM
k)
80% 1-RM
120% 1-RM
l)
80% 1-RM
140% 1-RM
α =0.003, t* = 4.513
α =0.003, t* = 4.463
α =0.003, t* = 4.544
p = 0.003



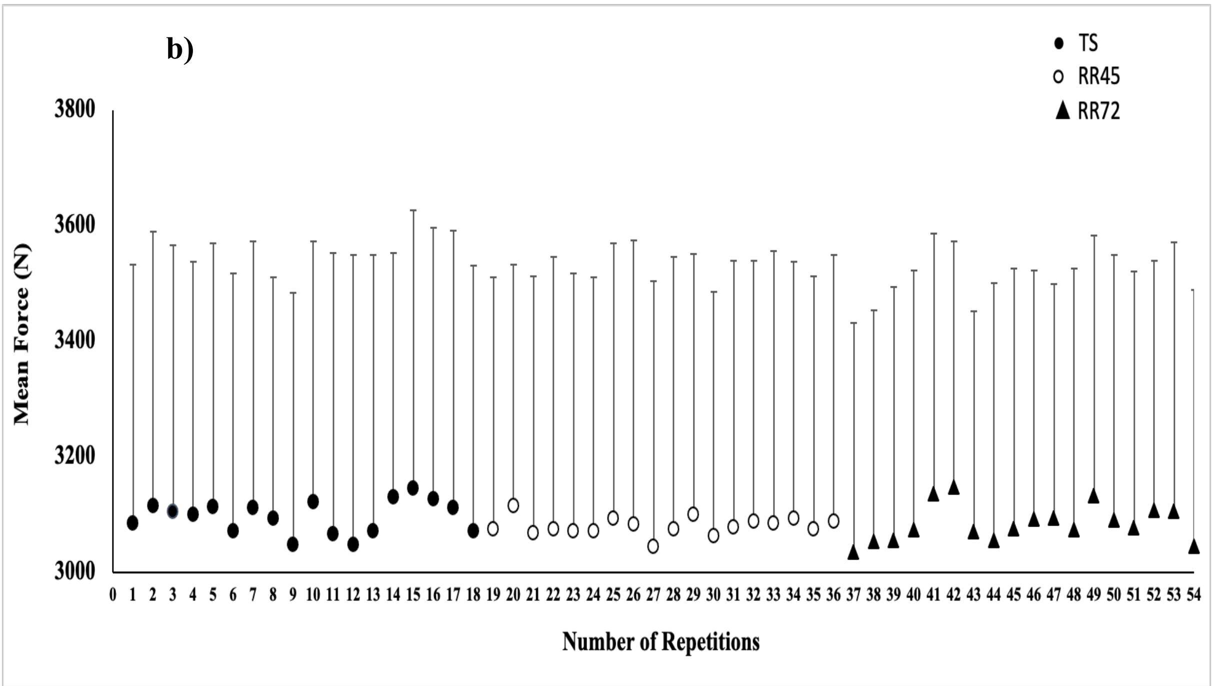
(a-o)- Top- Mean and 95% confidence intervals [95% CI] for time-normalised power. Bottom- Statistical parametric mapping [SPM] t-test- inference curve with suprathreshold clusters (shaded), critical threshold (t statistic) as a function of time represents a significant difference between those timepoints.

10.7. APPENDIX 7- SUPPLEMENTARY DIGITAL CONTENT (CHAPTER 7, STUDY 5)

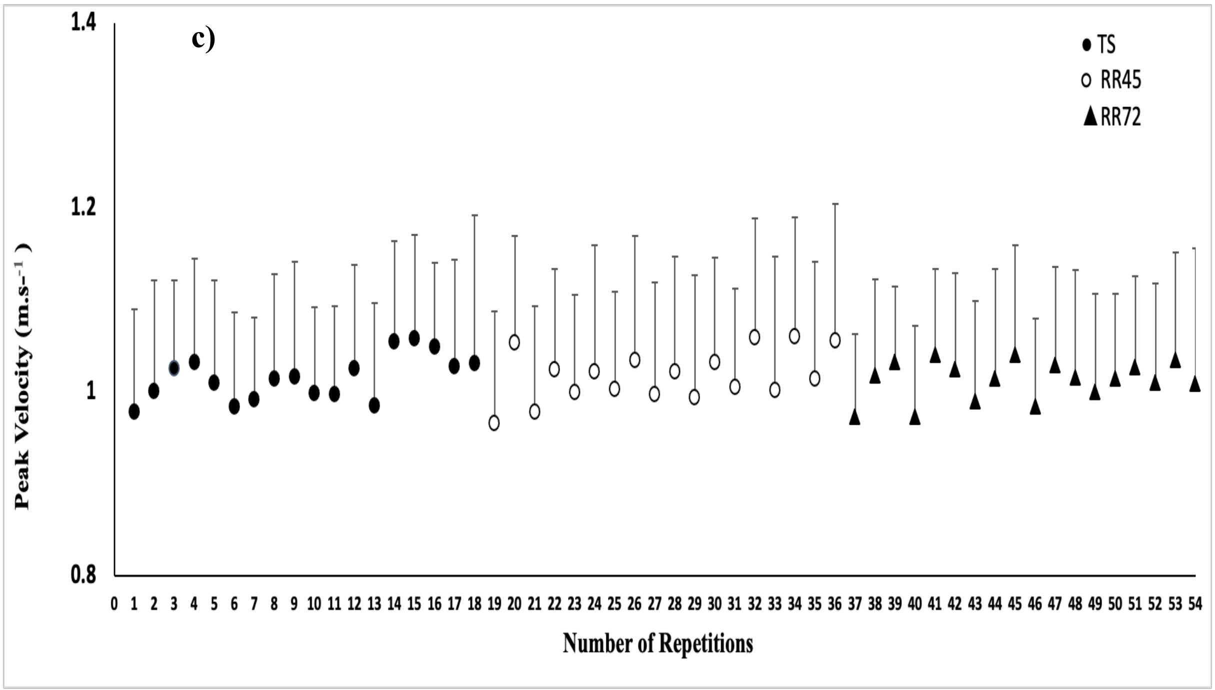
10.7.1. Kinetics and Kinematics Comparison between Protocols across 18 Repetitions



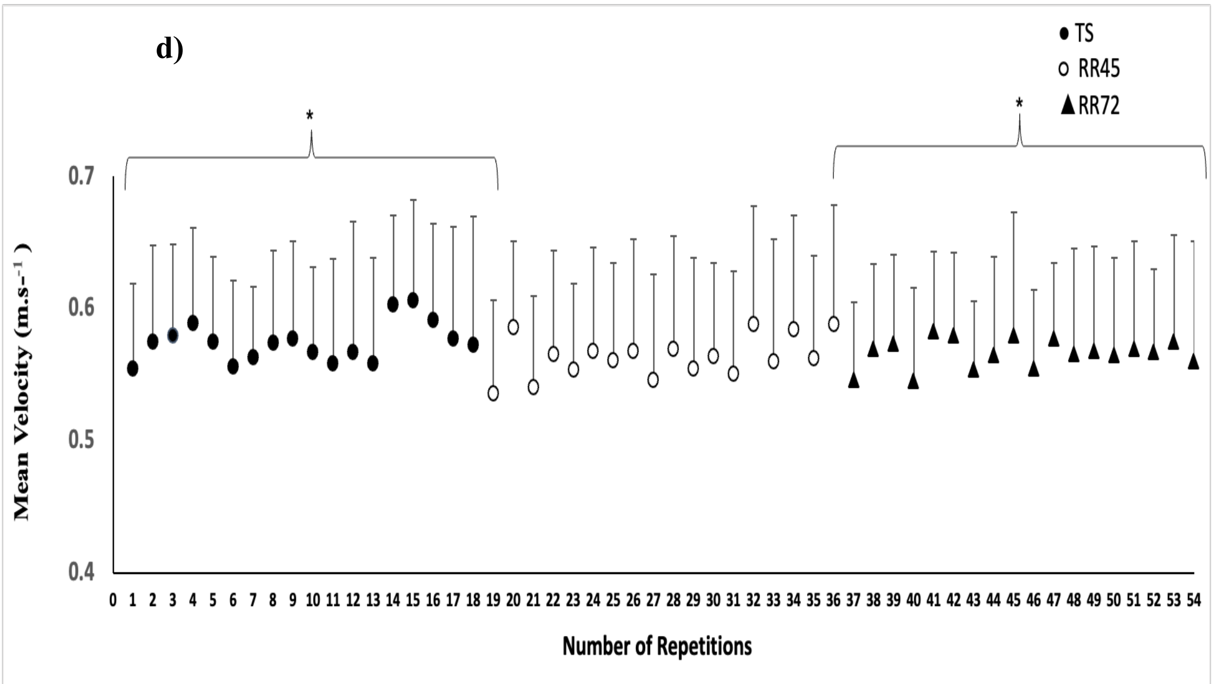
No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions



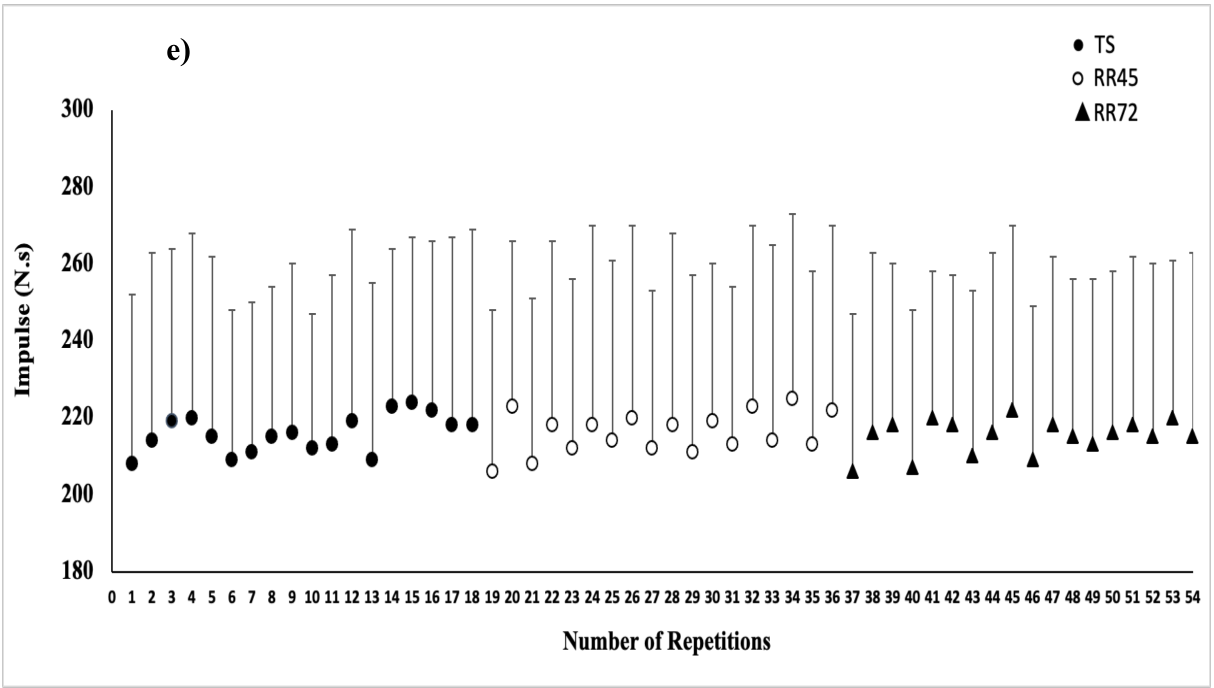
No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions



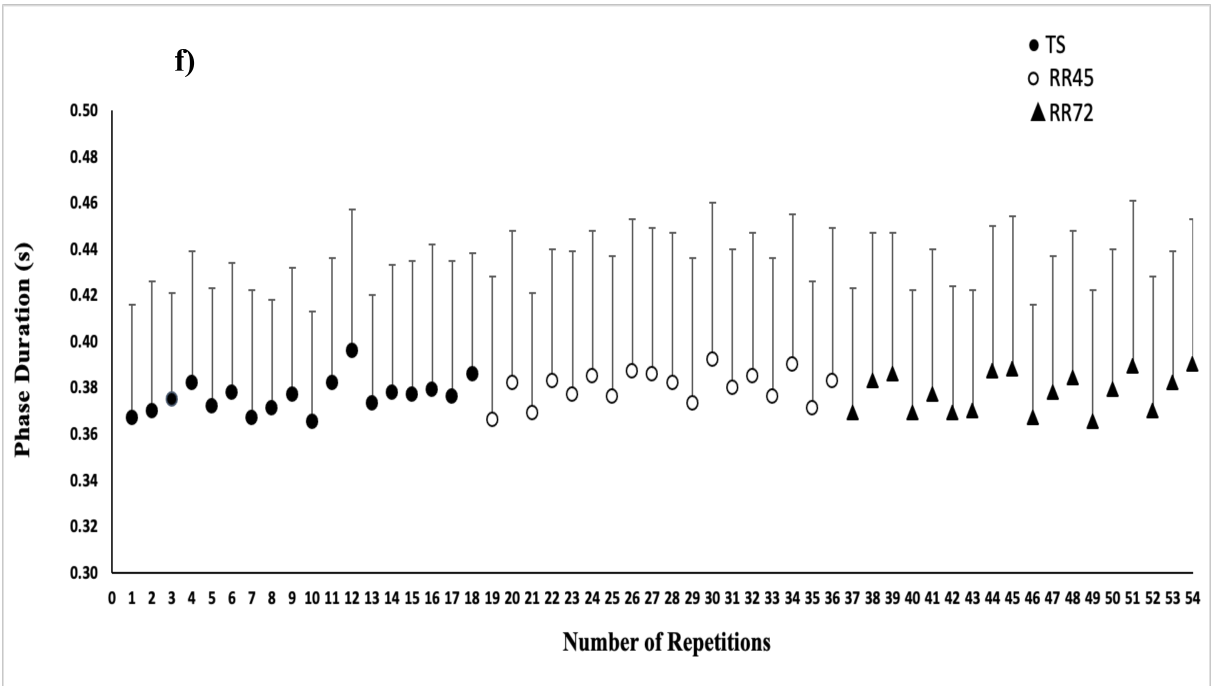
No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions



No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions * Significantly greater MV for TS compared to RR_{72} for configuration ($p = 0.034$)

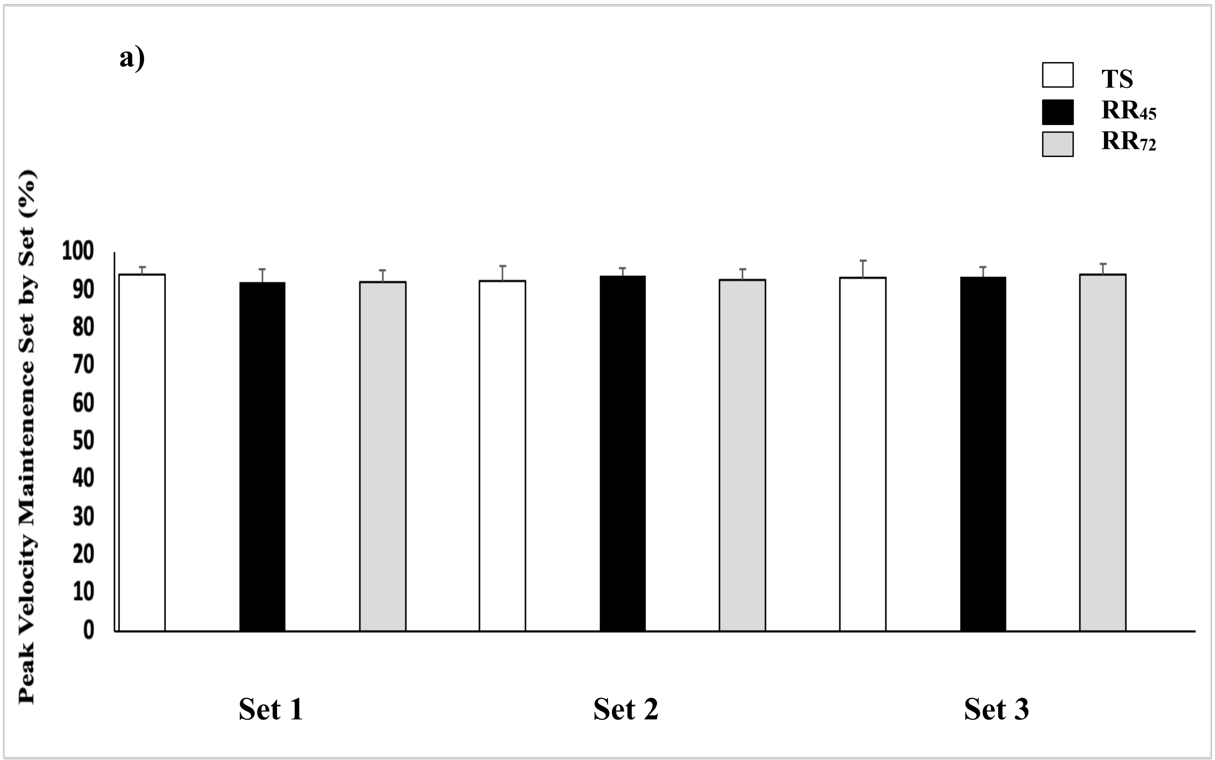


No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions

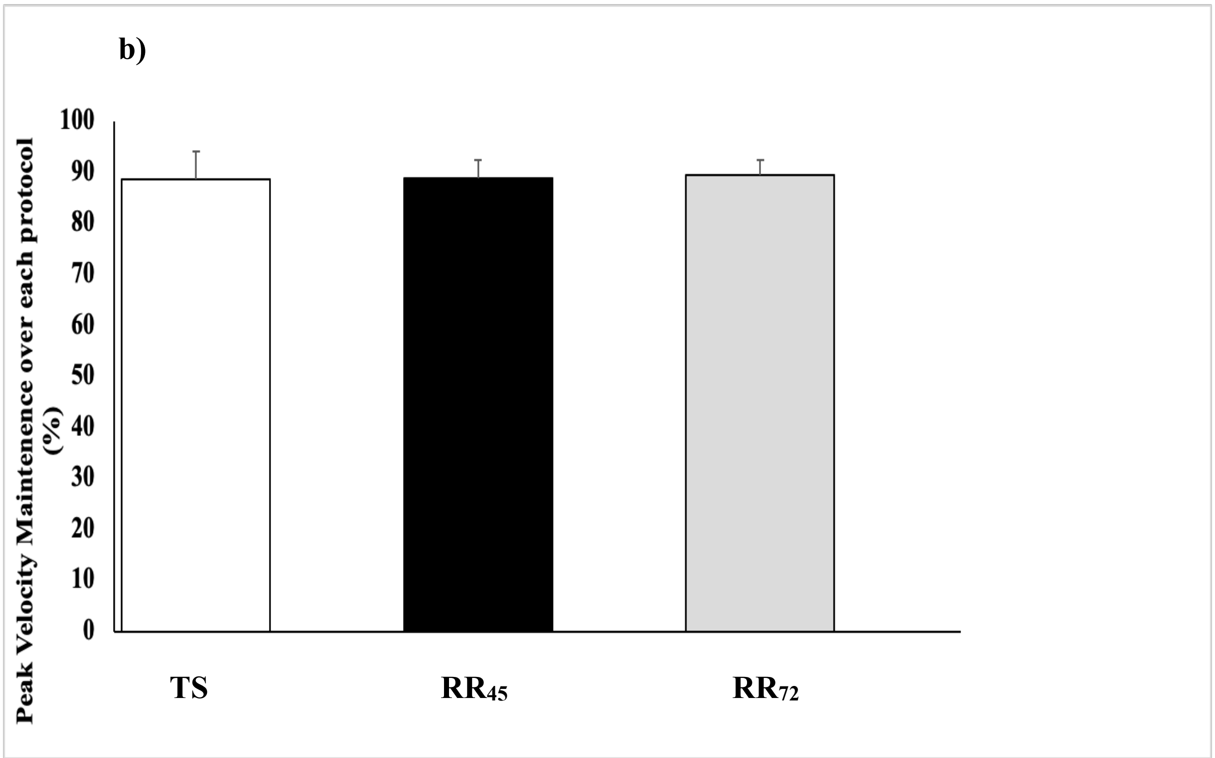


(a-f)-Kinetics and Kinematics Comparison between Protocols across 18 Repetitions. No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions. Mean and standard deviation across 18 repetitions for the countermovement shrug at 140% 1-RM PC for traditional sets (Black circles), Rest Redistribution (Open circles) with 45 s inter-repetition rest (RR_{45}) and 72 inter-repetition rest (Black triangles) (RR_{72}).

10.7.2. Peak Velocity Maintenance

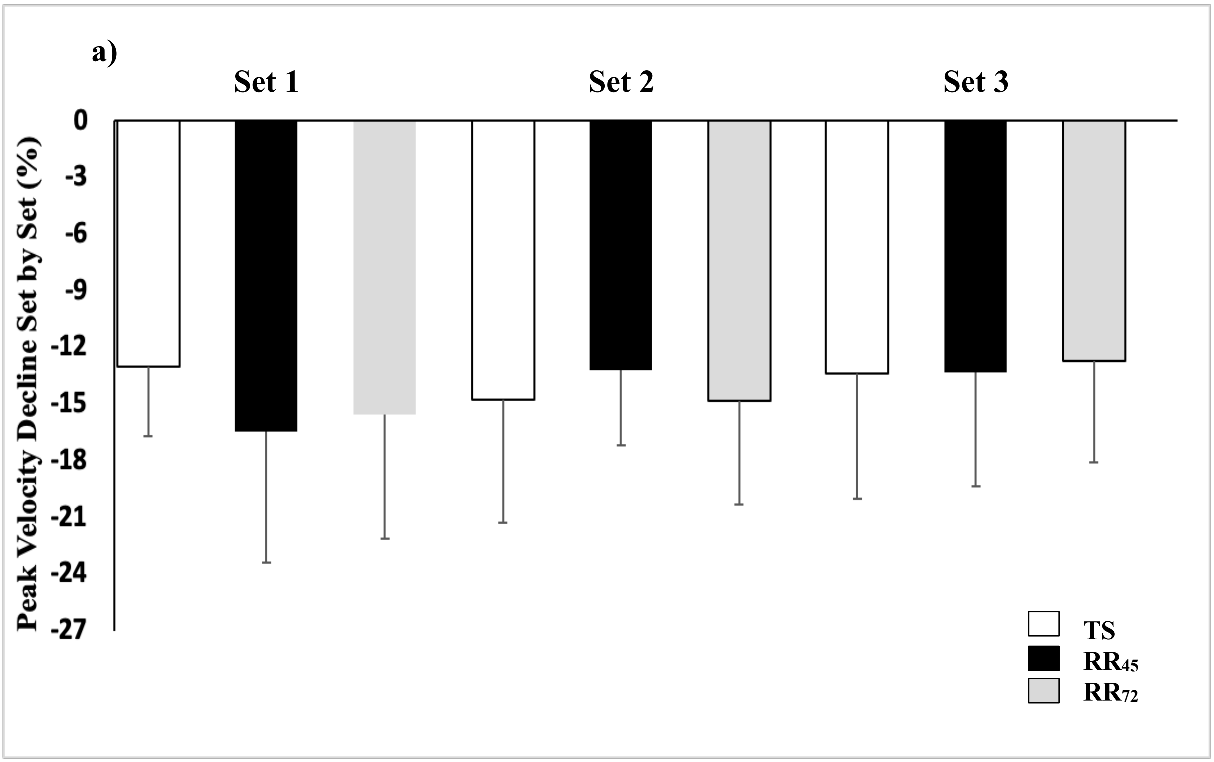


Maintenance of peak velocity for 3 sets of 6 repetitions. No significant differences ($p > 0.05$)

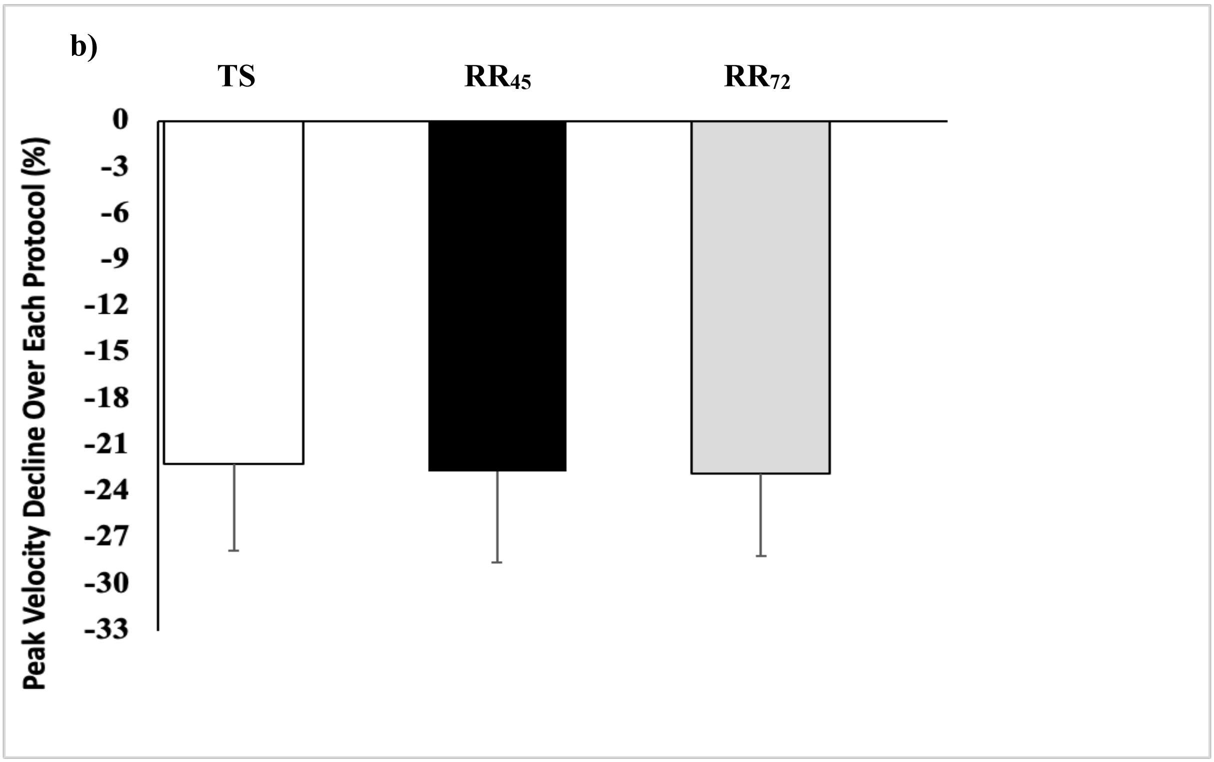


Maintenance of peak velocity for all entire protocols. No significant differences ($p > 0.05$)

10.7.3. Peak Velocity Decline

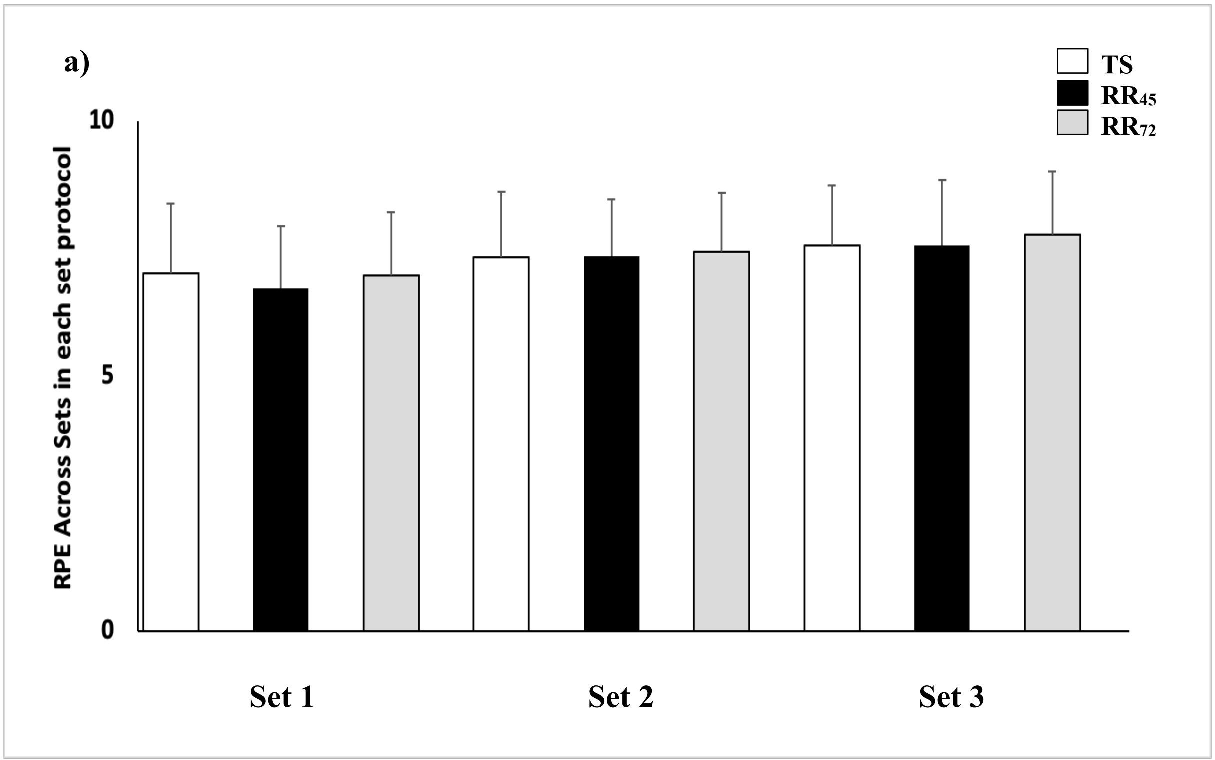


Peak velocity percentage decline for all 3 sets of 6 repetitions. No significant differences ($p >$ 0.05)

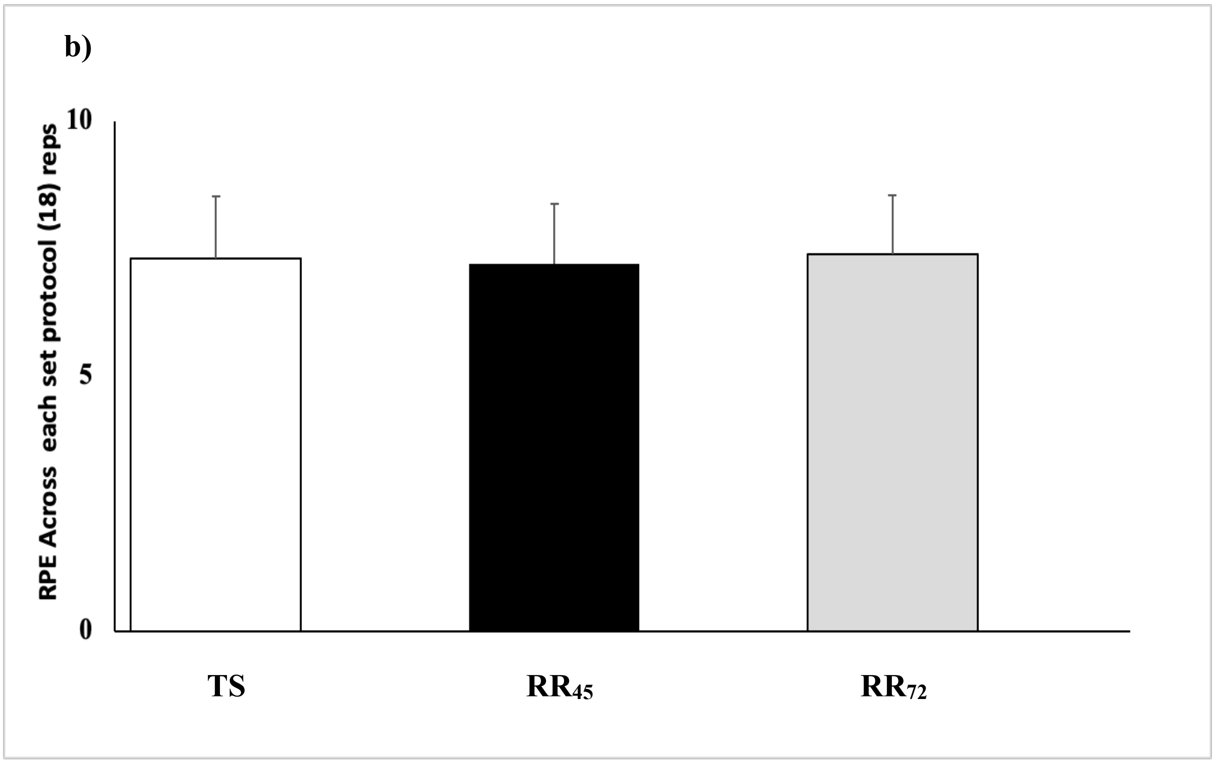


Percentage decline for peak velocity for entire protocols. No significant differences ($p > 0.05$)

10.7.4. RPE Scores



RPE for all 3 sets of 6 repetitions. No significant differences ($p > 0.05$)

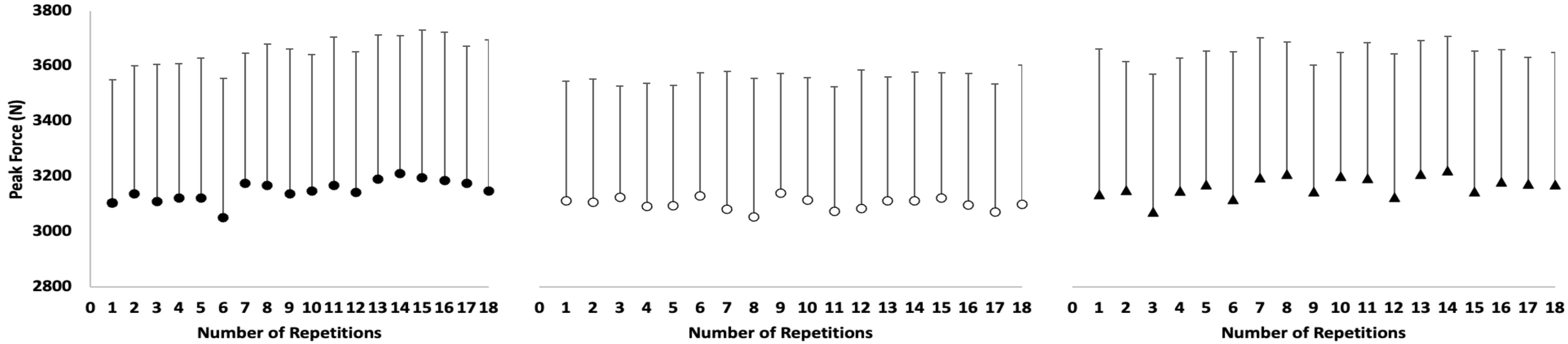


RPE for each set protocol across all repetitions. No significant differences ($p > 0.05$)

10.8. APPENDIX 8- SUPPLEMENTARY DIGITAL CONTENT (CHAPTER 8, STUDY 6)

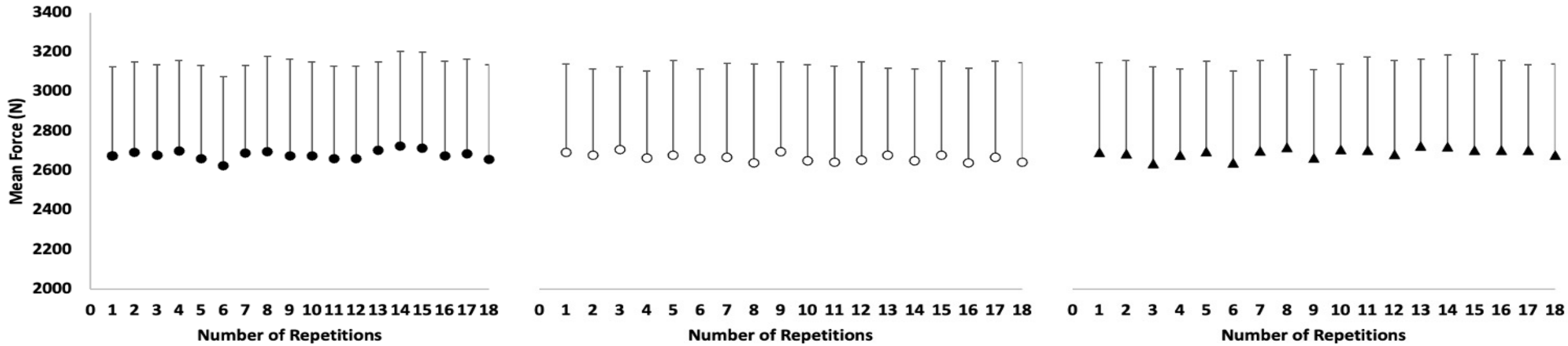
10.8.1. Kinetics and Kinematics Comparison between Protocols across 18 Repetitions

a) TS (3x6) RR$_{45}$ (9x2) RR$_{72}$ (6x3)

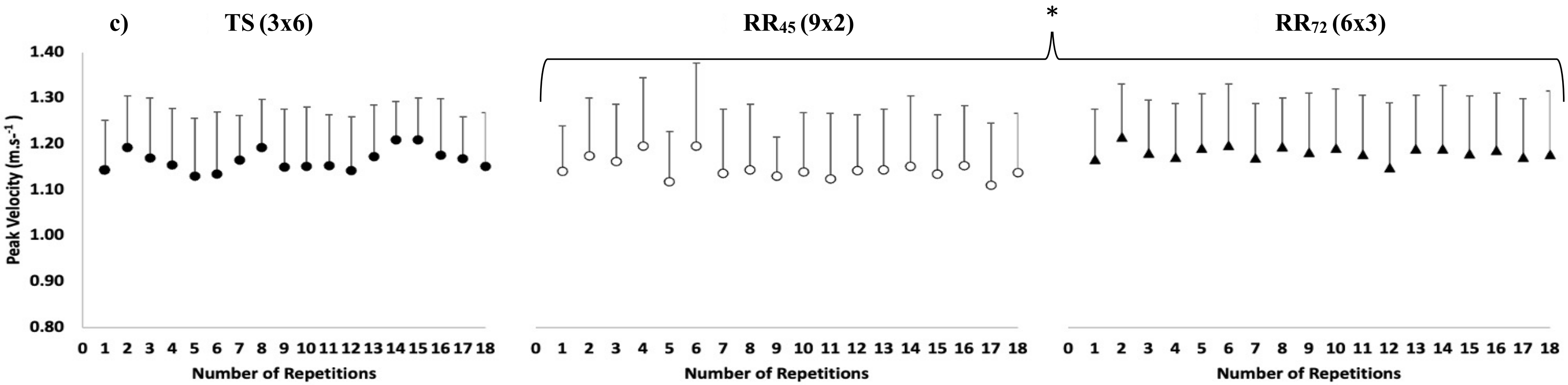


No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions

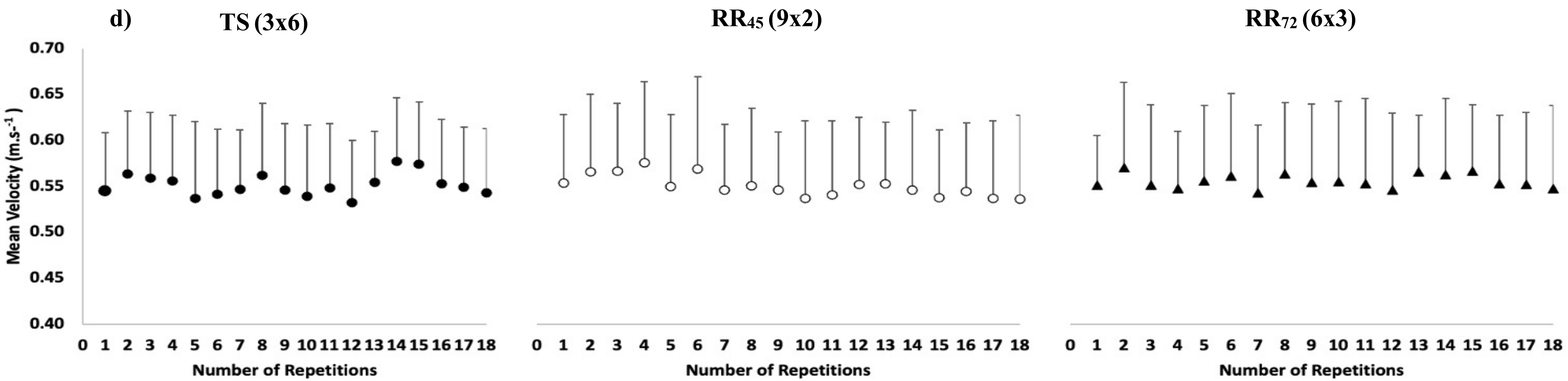
b) TS (3x6) RR$_{45}$ (9x2) RR$_{72}$ (6x3)



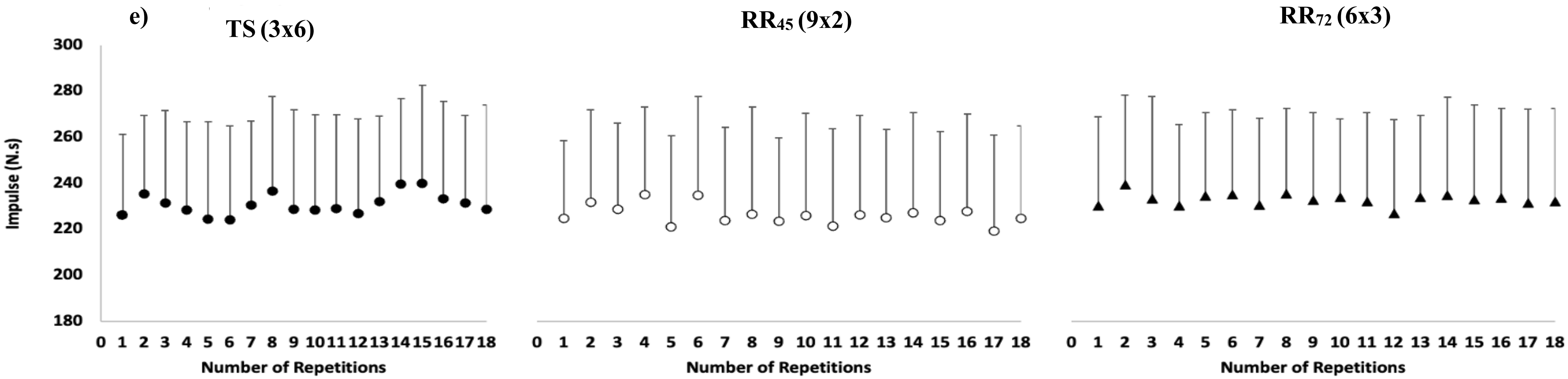
No significant ($p > 0.05$) differences between protocols across the average of 18 repetitions



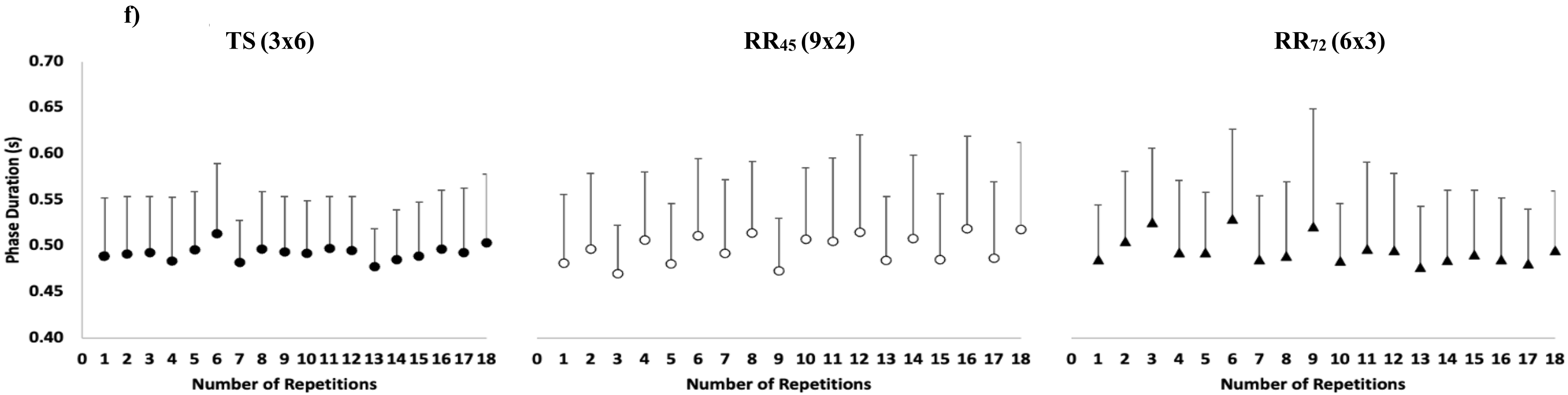
∗ Significantly (p = 0.025) greater PV for RR_{72} compared to RR_{45} for configuration



No significant (p > 0.05) differences between protocols across the average of 18 repetitions

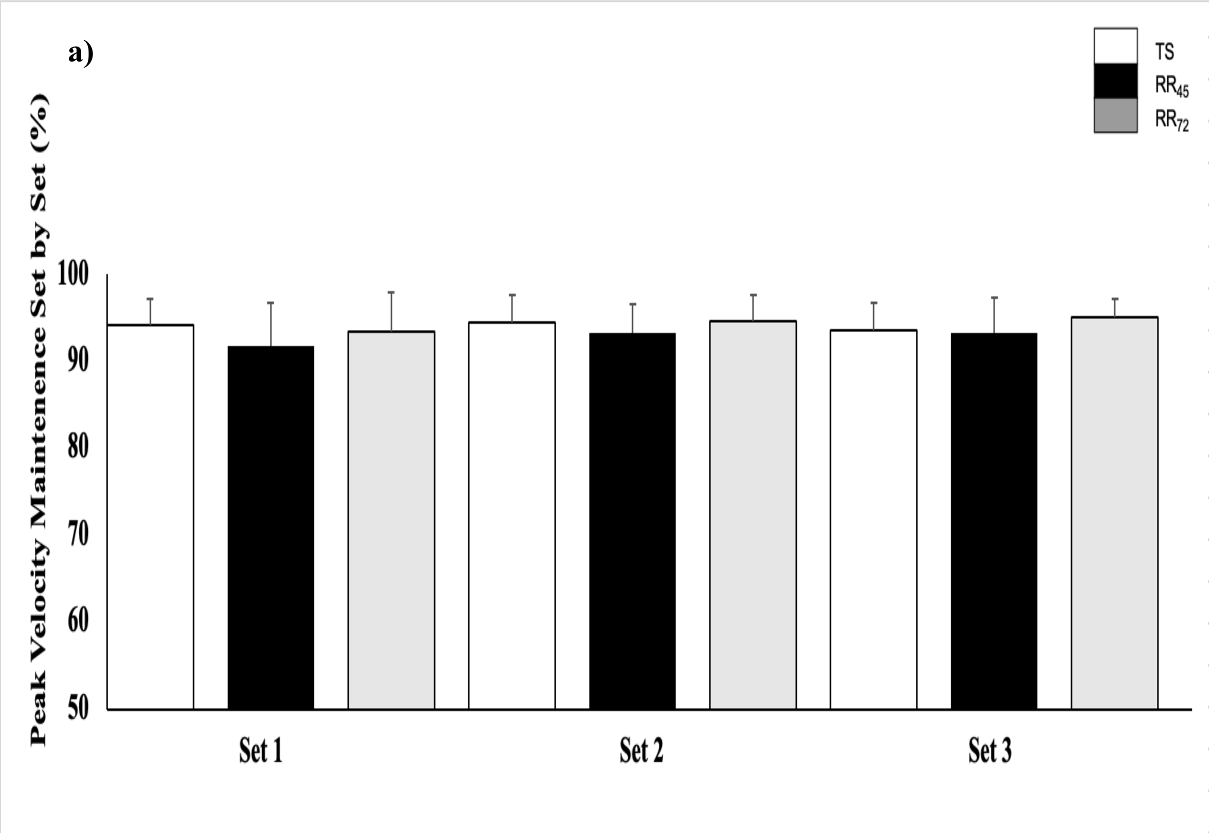


No significant (p > 0.05) differences between protocols across the average of 18 repetitions

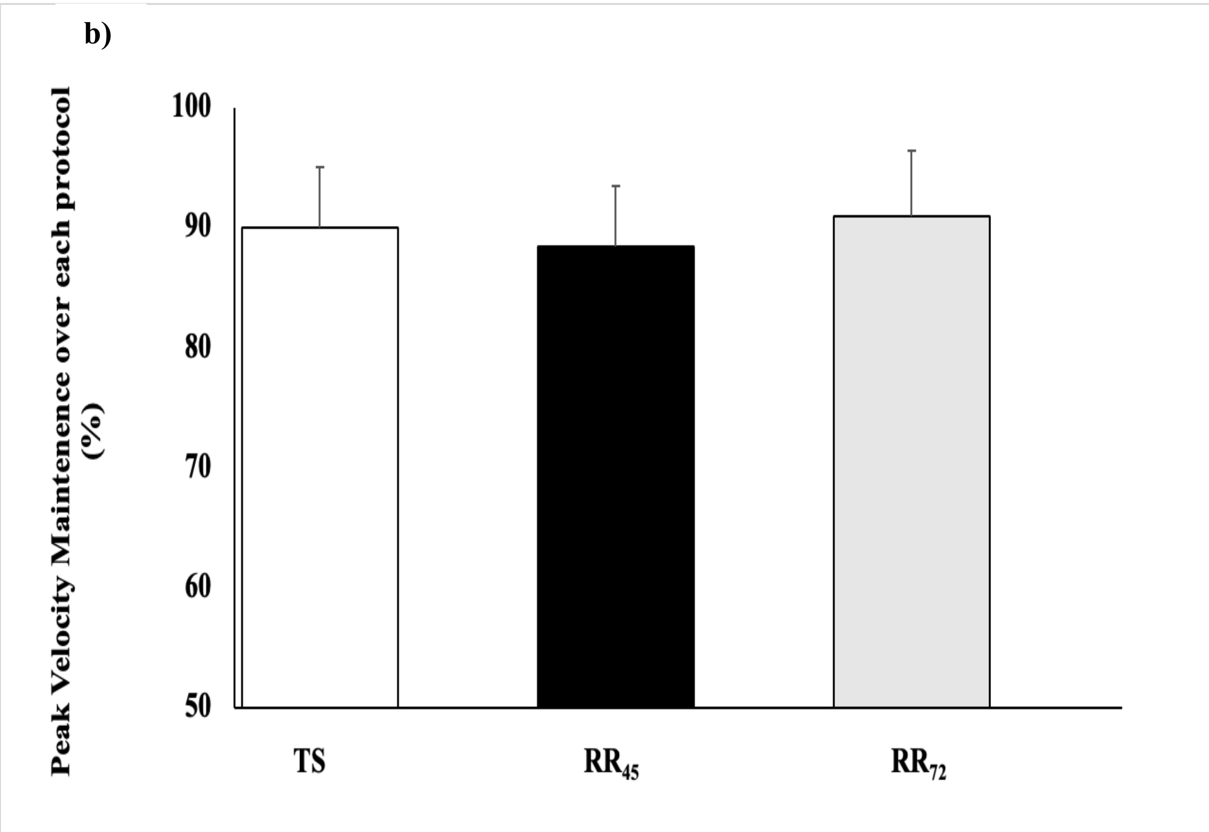


No significant (p > 0.05) differences between protocols across the average of 18 repetitions

10.8.2. Peak Velocity Maintenance

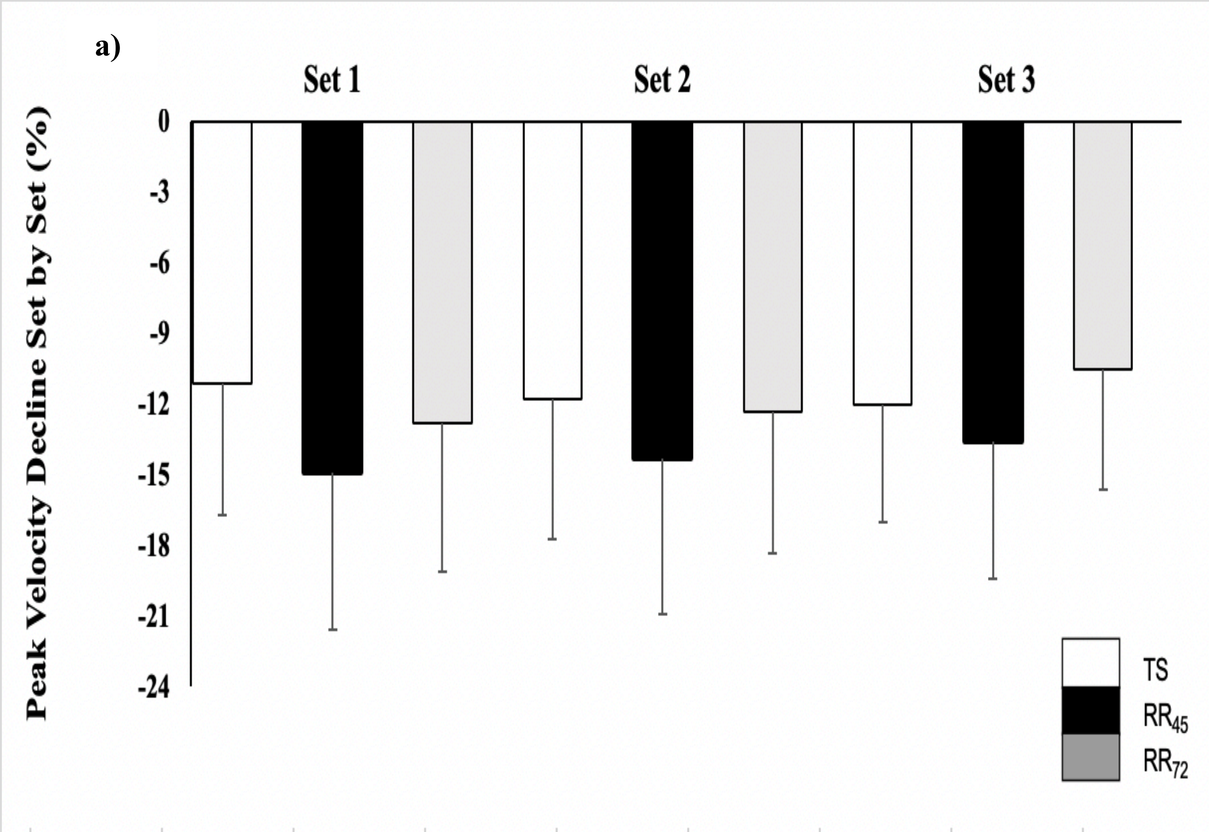


Maintenance of peak velocity for 3 sets of 6 repetitions. No significant ($p > 0.05$) differences

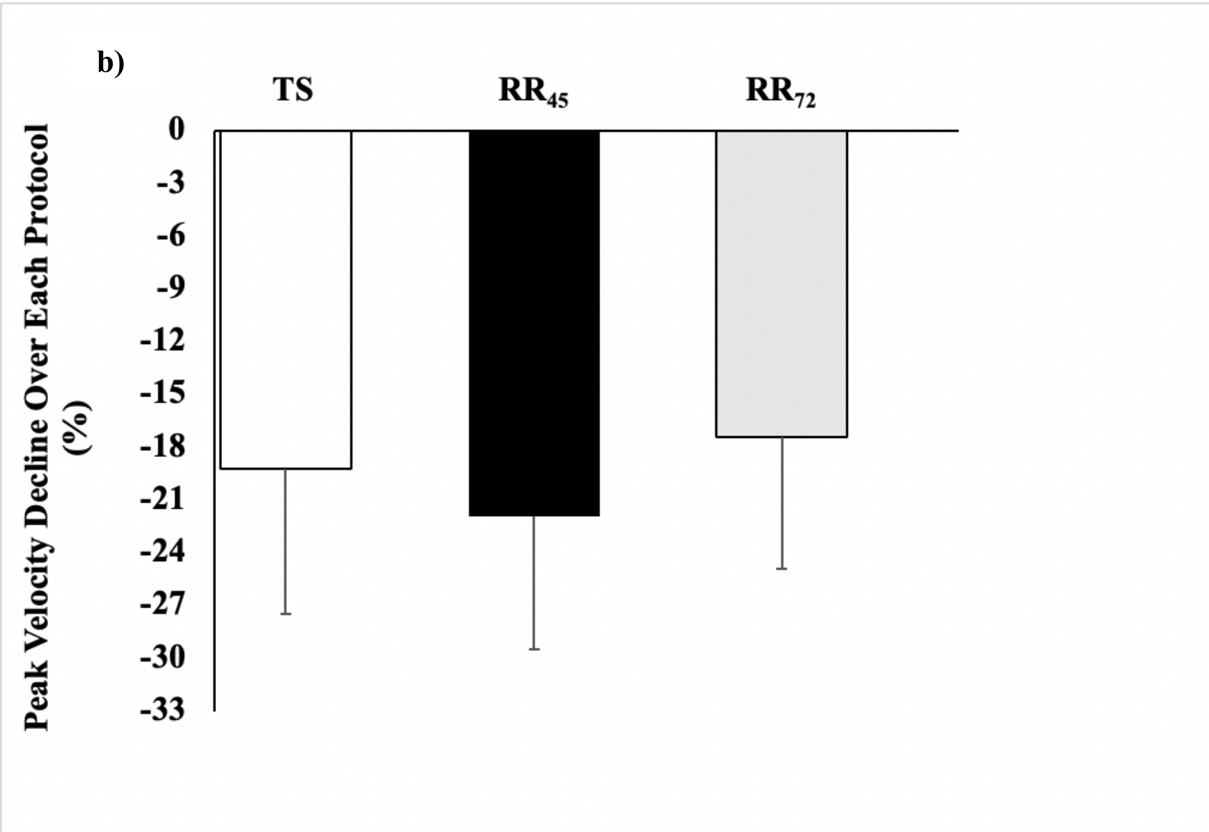


Maintenance of peak velocity for all entire protocols**.** No significant ($p > 0.05$) differences

10.8.3. Peak Velocity Decline

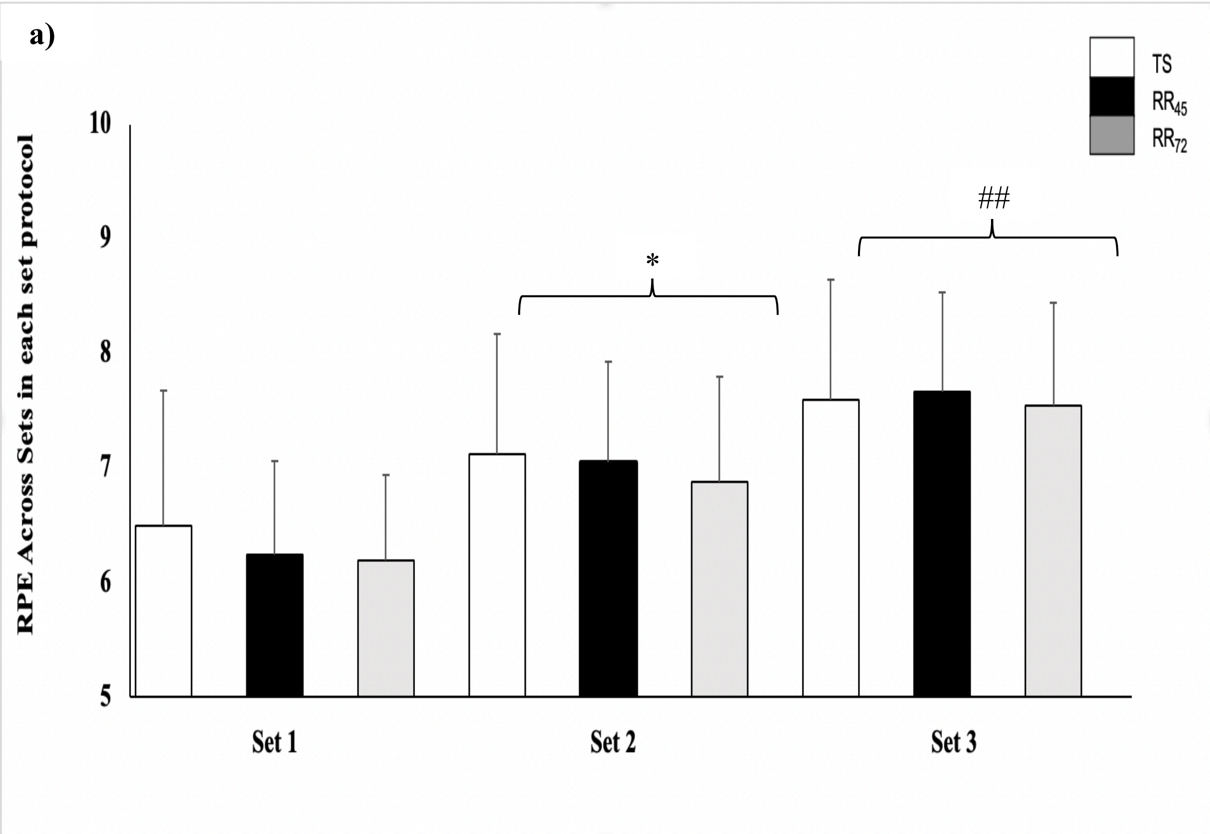


Peak velocity percentage decline for all 3 sets of 6 repetitions. No significant ($p > 0.05$) differences



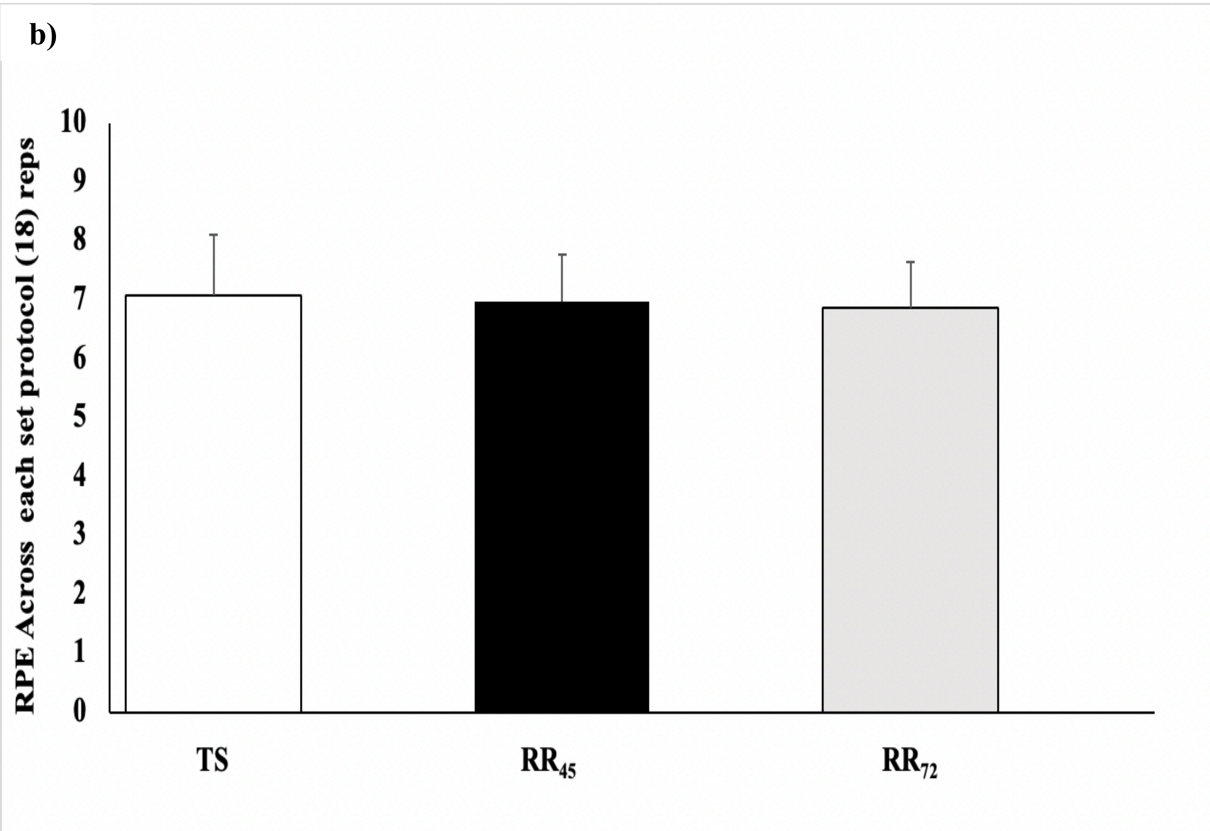
Percentage decline for peak velocity for entire protocols. No significant ($p > 0.05$) differences

10.8.4. RPE Scores



RPE for all collapsed 3 sets of 6 repetitions
* Significantly greater ($p \leq 0.001$) than Set 1

Significantly greater ($p \leq 0.015$) than Set 1 & 2



RPE for each set protocol across all repetitions. No significant ($p > 0.05$) differences