8-11-2022

Comparing biomechanical time series data across countermovement shrug loads

David Meechan

Stuart A. McErlain-Naylor

John J. McMahon

Timothy J. Suchomel

Paul Comfort
Edith Cowan University, p.comfort@ecu.edu.au

10.1080/02640414.2022.2091351
Meechan, D., McErlain-Naylor, S. A., McMahon, J. J., Suchomel, T. J., & Comfort, P. (2022). Comparing biomechanical time series data across countermovement shrug loads. Journal of Sports Sciences, 40(15), 1658-1667. https://doi.org/10.1080/02640414.2022.2091351

Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

Comparing biomechanical time series data across countermovement shrug loads

David Meechan, Stuart A McErlain-Naylor, John J McMahon, Timothy J Suchomel & Paul Comfort

To cite this article: David Meechan, Stuart A McErlain-Naylor, John J McMahon, Timothy J Suchomel & Paul Comfort (2022) Comparing biomechanical time series data across countermovement shrug loads, Journal of Sports Sciences, 40:15, 1658-1667, DOI: 10.1080/02640414.2022.2091351

To link to this article: https://doi.org/10.1080/02640414.2022.2091351

JOURNAL OF SPORTS SCIENCES
2022, VOL. 40, NO. 15, 1658–1667
https://doi.org/10.1080/02640414.2022.2091351

SPORTS PERFORMANCE

OPEN ACCESS

Comparing biomechanical time series data across countermovement shrug loads

David Meechan[a,b], Stuart A McErlain-Naylor[c], John J McMahon[a], Timothy J Suchomel[d] and Paul Comfort[a,e,f]

[a]The Salford Institute of Human Movement and Rehabilitation, University of Salford, Salford, UK; [b]Department of Elite Training Science and Technology Division, Hong Kong Sports Institute, Hong Kong, China; [c]School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK; [d]Department of Human Movement Sciences, Carroll University, Waukesha, Wisconsin, US; [e]School of Medical and Health Sciences, Edith Cowan University, Joondalup, Australia; [f]Institute for Sport, Physical Activity and Leisure, Carnegie School of Sport, Leeds Beckett University, Leeds, UK

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 (1RM) 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 normalized 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% 1RM PC maximised propulsion velocity, whilst 140% 1RM maximized force. At higher loads, the braking and propulsive phases commence at an earlier percentage of the time-normalized 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.

ARTICLE HISTORY
Accepted 14 June 2022

KEYWORDS
Weightlifting; performance; resistance training; statistical parametric mapping

Introduction

Numerous researchers have investigated gross kinetic and kinematic differences in weightlifting derivatives. These have included the power clean [PC] (Comfort et al., 2011a, 2011b, 2018), hang power clean (Kipp et al., 2021, 2016; Suchomel et al., 2014), countermovement shrug (CMS; Meechan, Suchomel et al., 2020), mid-thigh pull (Comfort et al., 2015; Meechan, Suchomel et al., 2020), snatch pull (James et al., 2020), hang pull (Meechan, McMahon et al., 2020), hang high pull (Suchomel et al., 2018; Suchomel, Lake et al., 2017), pull from the knee (Comfort et al., 2017; Meechan, McMahon et al., 2020) and jump shrug (Kipp et al., 2021, 2016; Suchomel et al., 2013, 2018; Suchomel, Lake et al., 2017; Suchomel et al., 2014). Researchers have investigated the kinetic and kinematic characteristics of the second pull, commencing from the mid-thigh ("power") position (DeWeese & Scruggs, 2012), and have reported that this phase produces the greatest force and power in experienced weightlifters during the clean, snatch and PC (Enoka, 1979; Souza et al., 2002). 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 (Comfort et al., 2011a, 2011b, 2018) or greater (Comfort et al., 2017; Kipp et al., 2016; Suchomel et al., 2015; Suchomel, Lake et al., 2017; Suchomel & Sole, 2017a, 2017b; Suchomel et al., 2014) training stimulus to catching derivatives, and may be easier to coach and implement (Comfort et al., 2018; Suchomel et al., 2015).

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 (Meechan, Suchomel et al., 2020), 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 (Comfort et al., 2011a, 2018; Suchomel, Comfort et al., 2017). 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 (Suchomel & Sole, 2017a).

CONTACT David Meechan D.Meechan@edu.salford.ac.uk The Salford Institute of Human Movement and Rehabilitation, School of Health and Society, University of Salford, Greater Manchester, UK, M5 4WT
Supplemental data for this article can be accessed online https://doi.org/10.1080/02640414.2022.2091351.

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 (Pataky et al., 2013, 2015, 2016). Researchers have utilized time-normalized curve analysis (sometimes termed waveform or temporal phase analysis) to assess force–, velocity–, power– and displacement–time data during weightlifting derivatives (Kipp et al., 2021; Suchomel & Sole, 2017a, 2017b) and jumps (Cormie et al., 2008, 2009; McMahon, Murphy et al., 2017; McMahon, Rej et al., 2017). 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 (McMahon, Jones et al., 2017). Briefly, SPM uses random-field theory to construct probability distributions based on continuous curve or time-series data (Pataky, 2010), whilst 95% confidence intervals utilize pair-wise comparison across data time points (Kipp et al., 2021).

Kipp et al. (2021) 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 (1RM). Curve analysis indicated that the jump shrug exhibited greater ground reaction force from ~46% to 50% of the movement and lower vertical velocities and power from ~72% to 76% and ~70% to 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 (Pataky et al., 2016). Statistical parametric mapping has been previously used to compare performances in jumping (Hughes et al., 2021) and weightlifting derivatives (Kipp et al., 2021), and may be a more appropriate analysis of time-series data compared to a temporal phase analysis (Kipp et al., 2021). 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 (Pataky et al., 2013).

Suchomel and Sole (2017a) investigated differences in time-normalized force characteristics between the jump shrug, hang high pull and hang power clean at relative loads of 30%, 45%, 65% and 80% of 1RM 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 participant 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 (Kipp et al., 2021; Suchomel & Sole, 2017a, 2017b), 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 (Meechan, McMahon et al., 2020; Meechan, Suchomel et al., 2020). Additionally, training at the loads that elicit the maximal power does not appear to be more beneficial than heavy load training for developing power (Haff & Nimphius, 2012; Harris et al., 2007). 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% 1RM PC. It was hypothesized that an increase in load would result in greater values in the time-normalized force and lower time-normalized 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 hypothesized that the total CMS absolute durations would increase with an increase in load.

Materials and methods

Experimental approach

A within-participant 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 participants performing all lifts on a force platform using progressively increasing relative loads of 40, 60, 80, 100, 120, 140% 1RM 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, participants visited the strength and conditioning facility on two occasions, at the same time of day (5–7 days apart), to establish 1RM PC reliability, following the protocol previously used in similar research (Comfort et al., 2015; Meechan, Suchomel et al., 2020), 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. Participants 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 ($p = 0.684$). To ensure adequate power to detect effects typically considered "small" or greater (Cohen, 1988) a within factors repeated- measures analysis of variance (ANOVA) 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 participants was determined GPower 3.1 software (Faul et al., 2009).

Participants

Twenty-nine male participants (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 1RM PC 1.02 BW) from various national-level sports such as rugby, swimming, 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. Participants 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.

Procedures

1RM power clean testing

Participants performed a dynamic warm-up consisting of body weight squats, lunges, and dynamic stretching and 5 minutes of low-intensity cycling. The 1RM testing protocol followed procedures previously described (Meechan, Suchomel et al., 2020). Three sub-maximal PC efforts were performed with decreasing volume (6–2 repetitions) and increasing loads of approximate 50–90% 1RM before commencing their first 1RM attempt. The 1RM for each participant was then determined within five attempts (interspersed by 3–4 minutes of rest) by gradually increasing the load (2.5–5.0 kg increments) until a failed 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); International Weightlifting Federation approved weightlifting barbell, and bumper plates (Eleiko, Halmstad, Sweden). The greatest load achieved across the two 1RM testing sessions was used to calculate the loads subsequently used during the CMS. An accredited strength and conditioning coach supervised all sessions.

Countermovement shrug testing

Participants completed the same standardized warm-up as during the PC testing session, followed by one set of three repetitions of the CMS at 40% 1RM PC. Participants then completed one CMS set at intensities of 40%, 60%, 80%, 100%, 120%, and 140% of their pre-determined 1RM PC in a progressive order (40–140%) to replicate the progression of loads that occur during 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 minimize fatigue (Comfort et al., 2015, 2012; Meechan, Suchomel et al., 2020). The barbell was placed on the safety bars of the power cage between all repetitions to prevent fatigue. Once the body was stabilized (verified by observing the participant and live force–time data), the lift was initiated with the countdown "3, 2, 1, go", and all participants were instructed to exert maximal intent during each repetition. All lifts were performed in a power cage on the Fitness Technology ballistic measurement

Figure 1. Sequence of countermovement shrug.

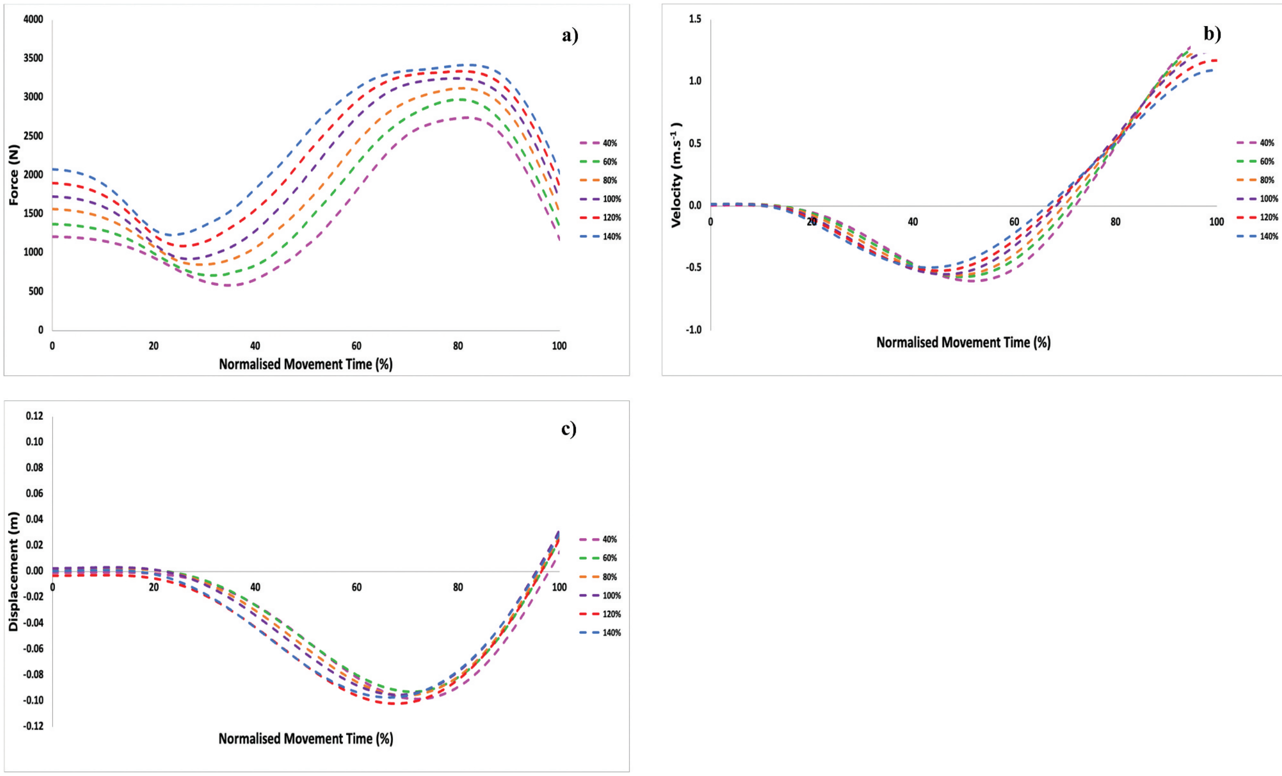

Figure 2. Comparison of the average force–time (a), velocity–time (b), and displacement–time (c) curves during the countermovement shrug with loads of 40%, 60%, 80%, 100%, 120% and 140% 1RM power clean. The differences between loads are described in results section.

system with integrated force platform (400 Series, Fitness Technology, Adelaide, Australia) sampling at 600 Hz. Standardized verbal encouragement was provided throughout testing. During all repetitions, participants were required to use lifting straps for standardization and to reduce technique breakdown due to loss of grip, especially at higher loads (Hori et al., 2010).

Prior to the CMS (Figure 1), participants stood completely vertical with knees and hips extended for 2 s and then transitioned to the mid-thigh 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 one continuous movement (Meechan, Suchomel et al., 2020).

Data analysis

Prior to the onset of the pull, participants were instructed to remain stationary on the force platform for 1 s to allow for subsequent determination of the system weight (body weight + barbell weight; average of this second; Owen et al., 2014). The onset of movement was deemed to have occurred 30 ms before the system weight VGRF was exceeded or reduced by 5 multiples of the first second VGRF standard deviation (Owen et al., 2014). Vertical velocity and displacement of the system (barbell + body) centre of mass were calculated from VGRF force–time data using integration via the trapezoid rule (Kipp et al., 2021; Owen et al., 2014). The propulsion phase was deemed to have started when velocity exceeded 0.01 $m{\cdot}s^{-1}$ and ended at peak positive velocity (McMahon, Suchomel et al., 2018). Time-series data were time-normalized to 101 data points in line with previous research (Kipp et al., 2021) 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).

Statistical analyses

Reliability of the 1RM 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 (Koo & Li, 2016), and the %CV considered acceptable if < 10% (Cormack et al., 2008).

The primary analyses performed were 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)

Table 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.

code (http://www.spm1d.org). Where significant effects (α = 0.05) were reported, the SPM paired sample t-test was used to compare between loads. A Bonferroni correction resulted in a critical threshold for a 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, was determined via repeated measures 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). Standardized differences were calculated using Hedges' *g* effect sizes as previously described (Hedges & Olkin, 1985) 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; Hopkins et al., 2009). An *a priori* alpha level was set at $p \leq 0.05$.

Results

The 1RM 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-normalized 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 2, Table 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 the supplementary digital content). The results for the effect of load on absolute phase durations and percentage of movement time are shown in Table 1.

Force–time

The SPM repeated-measures ANOVA indicated a significant effect of load on force ($p < 0.001$, F* = 3.559, Figure 3a) throughout the entire time-normalized movement. Force was generally greater at greater relative loads (Figure 2a). For example, force at 40% 1RM PC was less than at 60%, 80%, 100%, 120%, and 140% 1RM PC during 67%, 91%, 94%, 100% and 100% of the movement, respectively (Figure 4a). All pairwise comparisons revealed significantly greater force during higher loads for early (0–14%), mid (36–54%), and late (90–100%) time-normalized movement. Peak force was 24.9% greater at 140% compared to 40% 1RM and occurred between 79% and 82% of time-normalized movement in all loads (Figure 2a). All differences between loads are illustrated in Figure 4a.

Velocity–time

Load had a significant effect on velocity between 12–38%, 47–79% and 84–100% of time-normalized movement. ($p \leq 0.001$, F* = 3.713, Figure 3b). The effect of load on velocity followed these three distinct phases (Figures 2(b), 4 (b) and Figure 5(b)). 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 1RM (Figure 4b). All other comparisons are displayed in Figure 4b. An example of the SPM output and 95% CI is shown in Figure 5.

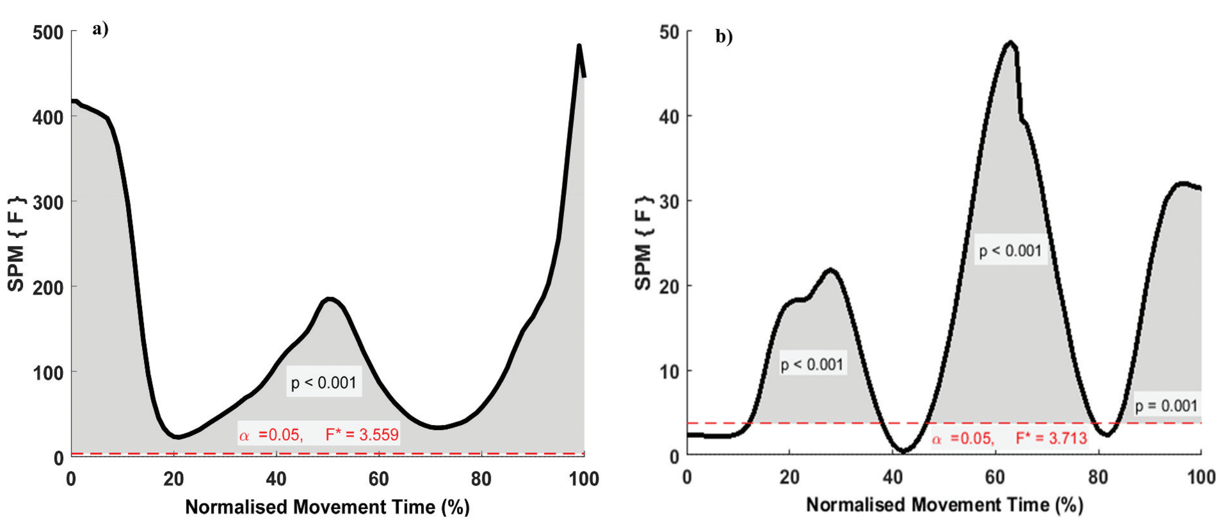

Figure 3. SPM repeated measures ANOVA (SPM{F} statistic) during the countermovement shrug at 40–140% 1RM comparing a) force–time and b) velocity–time series. The dashed horizontal line designates the critical threshold for the SPM{F}statistics. The grey shaded area represents supra-threshold clusters, indicating statistically significant differences at those timepoints.

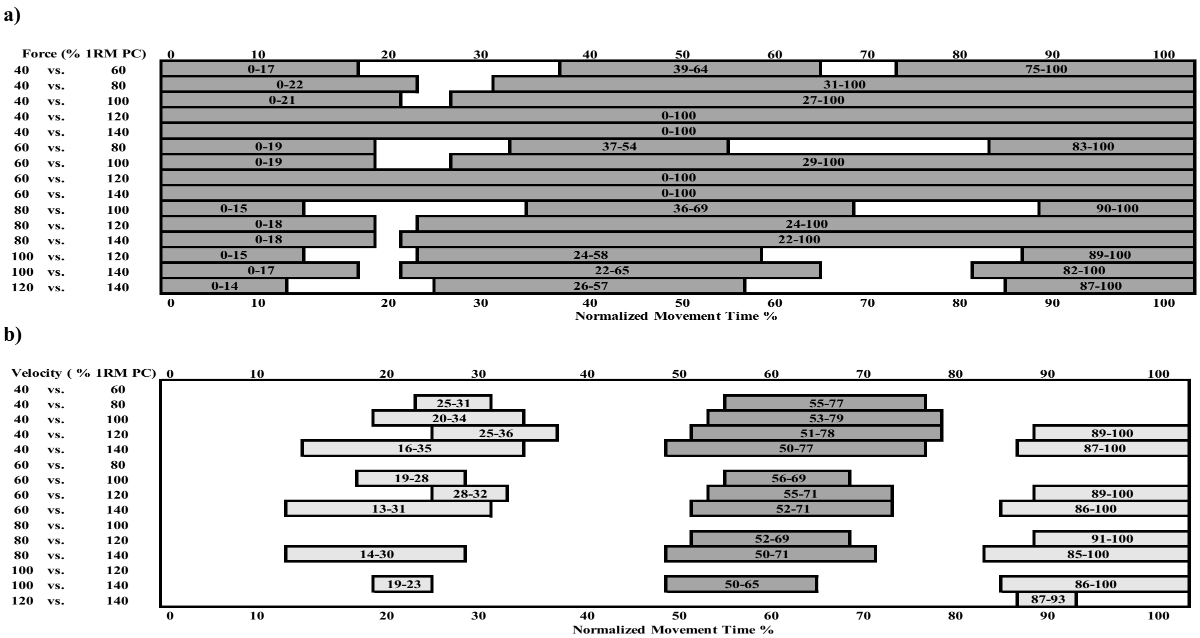

Figure 4. Summary of differences between countermovement shrug intensity of loads of 40%, 60%, 80%, 100%, 120% and 140% 1RM power clean (1RM PC) from SPM analysis for a) normalized force–time series, b) normalized velocity–time series. Shaded area illustrates significant differences between time points and intensity of load. Higher load greater Lower load greater No differences

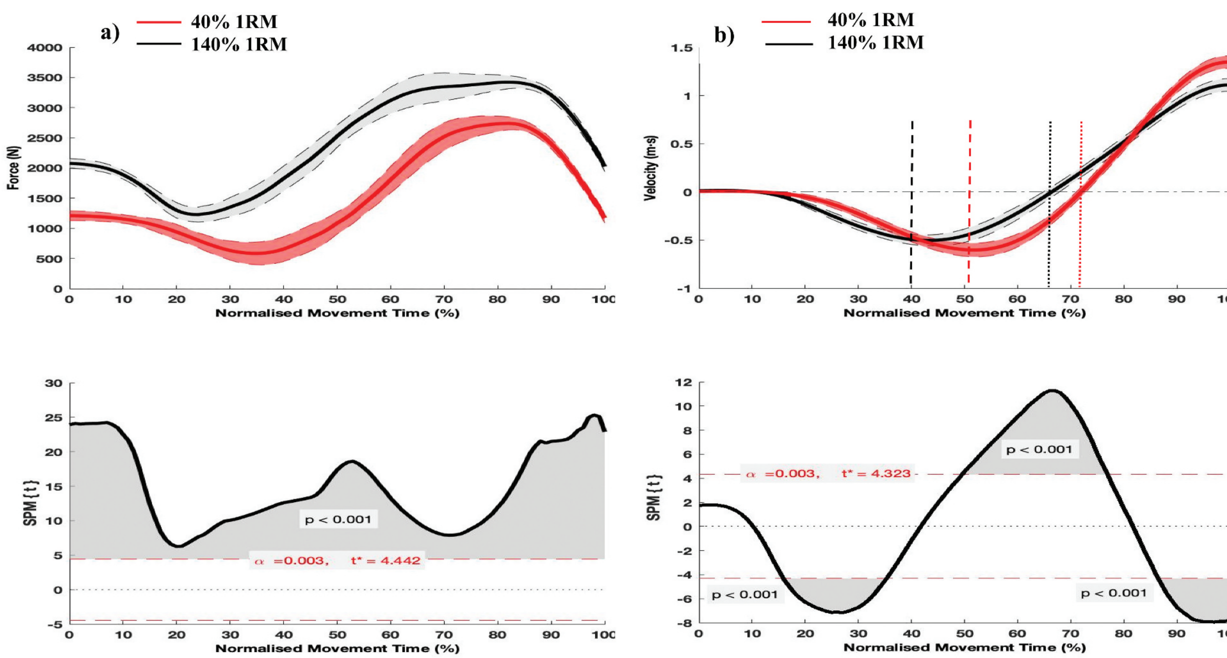

Figure 5. Top – mean and 95% confidence intervals for 40 vs.140% 1RM a) time-normalized force, and b) time-normalized velocity. Bottom – Statistical parametric mapping (SPM) paired t-test for 40 vs.140% 1RM – inference curve as a function of time, with suprathreshold clusters (shaded) and critical threshold 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% 1RM; red dashed line = onset of braking 40% 1RM; black dotted line = onset of propulsion 140% 1RM; red dotted line = onset of propulsion 40% 1RM.

Absolute phase durations

There were no significant or meaningful differences ($p > 0.05$, $g = 0.00–0.39$) in the total duration of the unweighting phase between loads (Table 1). The duration of the braking phase increased with load and was greatest at 140% 1RM, which was significantly greater ($p \leq 0.03$, $g = 0.43–1.12$) than all other loads, with small to moderate effect sizes (Table 1). The duration of the propulsion phase increased with an increase in load and was greatest at 140% 1RM, which was significantly greater than all other loads ($p \leq 0.003$, $g = 0.43–2.32$), with a small to very large effect size. The total movement duration progressively increased with load. The greatest duration occurred at 140% 1RM, which demonstrated a significantly greater duration ($p < 0.001$, $g = 0.97–1.42$, moderate to large) than 40–100% 1RM, but not significantly different to 120% 1RM ($p > 0.05$, $g = 0.31$). All other total movement results are shown in Table 1). All other results are shown in Table 1.

Percentage of absolute movement time

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

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 strength and conditioning practitioners who prescribe weightlifting pulling derivatives. As expected, a greater force was produced as load increased from 40% to 140% 1RM. The greatest force was observed at 140% 1RM, in line with previous research (Meechan, Suchomel et al., 2020). 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 maximized at 40% 1RM (Figures 2–4b). Force increased with an increase in load, with 140% 1RM resulting in 24.9% greater peak force than 40% 1RM (Figures 2–4a) As load increased, there were differences throughout the time-normalized movement. This provides a greater mechanistic understanding to strength and conditioning 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 (Meechan, Suchomel et al., 2020). 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 (Kipp et al., 2021; Suchomel & Sole, 2017a, 2017b), loaded jumps (Cormie et al., 2008) and unloaded jumps (McMahon, Jones et al., 2017, 2018). 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-normalized velocity curves between loads. The increase of load also alters the shape of the average velocity–time curves, with peak negative velocity in 140% 1RM occurring 9% earlier in the time-normalized total movement than 40% 1RM, thus affecting the phases of the time-normalized movement (Figure 2b). The greater the load, the greater the duration of significant differences in velocity compared to 40% 1RM. Indeed, 140% showed significant differences across 59% of total movement time when compared to 40% 1RM, highlighting key differences that occur outside peak variables (Figure 4b). 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% 1RM compared to all relative loads of <100% 1RM (Figure 4b), illustrative of the load–velocity relationship. Participants likely managed to accelerate through the full triple extension more at loads of >100% 1RM. 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 participants were encouraged not to jump off the platform as in a jump shrug (Suchomel et al., 2013, 2015); 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 a 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-normalized velocity curves in the present study shows that load affects when the braking and propulsion phase commences (Figures 2b, 5b). At 140% compared to 40% 1RM, 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% 1RM 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 (Suchomel, Suchomel, Comfort et al., 2017). 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 (Haff & Nimphius, 2012). 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 (Haff & Nimphius, 2012). This allows for power output during the CMS to be maximized at loads of 80–140% 1RM PC, as previously shown (Meechan, Suchomel et al., 2020).

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 1RM, and therefore greater loads during testing sessions. The authors acknowledge that it may be impractical to perform 1RM 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 participants 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 (Nimphius et al., 2019), and no differences in the effect of load between the sexes on kinetics or kinematics during the mid-thigh pull (Comfort et al., 2015; Nimphius et al., 2019). It is acknowledged that a greater sample size may be required for 1D data analysis (Robinson et al., 2021). 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, the 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.

Conclusion

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-normalized movement, and practitioners may be able to prescribe specific loads to target specific phases of the movement, with relative loads of 40% power clean 1RM most appropriate to maximize velocity during the CMS, and relative loads of 140% to maximize force. Practitioners are encouraged to use a combination of heavy and light loads when prescribing weightlifting pulling derivatives, to emphasize force and velocity or to maximize 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 1RM. The results also show that the braking and propulsion phases commence at an earlier percentage of time-normalized movement at higher loads, whilst absolute durations are also greatest at higher loads. Future research should assess the effect of load on individual time-normalized phases to determine if differences between loads exist within each time-normalized phase.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported that there is no funding associated with the work featured in this article.

References

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). L. Erlbaum Associates.

Comfort, P., Allen, M., & Graham-Smith, P. (2011a). Comparisons of peak ground reaction force and rate of force development during variations of the power clean. *Journal of Strength and Conditioning Research*, *25*(5), 1235–1239. https://doi.org/10.1519/JSC.0b013e3181d6dc0d

Comfort, P., Allen, M., & Graham-Smith, P. (2011b). Kinetic comparisons during variations of the power clean. *Journal of Strength and Conditioning Research*, *25*(12), 3269–3273. https://doi.org/10.1519/JSC.0b013e3182184dea

Comfort, P., Udall, R., & Jones, P. A. (2012). The effect of loading on kinematic and kinetic variables during the midthigh clean pull. *Journal of Strength and Conditioning Research*, *26*(5), 1208–1214. https://doi.org/10.1519/JSC.0b013e3182510827n

Comfort, P., Jones, P. A., & Udall, R. (2015). The effect of load and sex on kinematic and kinetic variables during the mid-thigh clean pull. *Sports Biomechanics*, *14*(2), 139–156 https://www.ncbi.nlm.nih.gov/pubmed/25896197

Comfort, P., Williams, R., Suchomel, T. J., & Lake, J. P. (2017). A comparison of catch phase force-time characteristics during clean derivatives from the knee. *Journal of Strength and Conditioning Research*, *31*(7), 1911–1918. https://doi.org/10.1519/JSC.0000000000001660

Comfort, P., Dos'Santos, T., Thomas, C., McMahon, J. J., & Suchomel, T. J. (2018). An investigation into the effects of excluding the catch phase of the power clean on force-time characteristics during isometric and dynamic tasks: An intervention study. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *32*(8), 2116–2129. https://doi.org/10.1519/jsc.0000000000002656

Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*, *3*(2), 131–144. https://doi.org/10.1123/ijspp.3.2.131

Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: Impact of load. *Journal of Applied Biomechanics*, *24*(2), 112–120. https://doi.org/10.1123/jab.24.2.112

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: Impact of training. *Journal of Strength and Conditioning Research*, *23*(1), 177–186. https://doi.org/10.1519/JSC.0b013e3181889324

DeWeese, B. H., & Scruggs, S. K. (2012). The countermovement shrug. *Strength and Conditioning Journal*, *34*(5), 20–23. https://doi.org/10.1519/SSC.0b013e318262f7d5

Enoka, R. M. (1979). The Pull in Olympic weightlifting. *Medicine and Science in Sports*, *11*(2), 131–137. https://journals.lww.com/acsm-msse/Abstract/1979/01120/The_pull_in_Olympic_weightlifting.2.aspx

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/brm.41.4.1149

Haff, G. G., & Nimphius, S. (2012). Training principles for power. *Strength and Conditioning Journal*, *34*(6), 2–12. https://doi.org/10.1519/SSC.0b013e31826db467

Harris, N. K., Cronin, J. B., & Hopkins, W. G. (2007). Power outputs of a machine squat-jump across a spectrum of loads. *Journal of Strength and Conditioning Research*, *21*(4), 1260–1264. https://doi.org/10.1519/R-21316.1

Hedges, L., & Olkin, I. (1985). *Statistical methods for meta-analysis*. Academic Press, Inc.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports*, *41*(1), 3–12. doi:10.1249/mss.0b013e31818cb278

Hori, N., Appleby, B. B., Andrews, W. A., & Nosaka, K. (2010). The effect of lifting straps on peak velocity, force, and power during clean pull. *Journal of Australian Strength and Conditioning*, *18*(2), 4–9. https://www.strengthandconditioning.org/jasc-18-2/1418-peer-review-the-effect-of-lifting-straps-on-peak-velocity-force-and-power-during-clean-pull

Hughes, S., Warmenhoven, J., Haff, G. G., Chapman, D. W., & Nimphius, S. (2021). Countermovement jump and squat jump force-time curve analysis in control and fatigue conditions. *Journal of Strength and Conditioning Research*, *00*, 1–10. doi: 10.1519/JSC.0000000000003955

James, L. P., Suchomel, T. J., McMahon, J. J., Chavda, S., & Comfort, P. (2020). Effect of onset threshold on kinetic and kinematic variables of a weightlifting derivative containing a first and second pull. *Journal of Strength and Conditioning Research*, *34*(2), 298–307. https://doi.org/10.1519/jsc.0000000000003316

Kipp, K., Malloy, P. J., Smith, J., Giordanelli, M. D., Kiely, M. T., Geiser, C. F., & Suchomel, T. J. (2016). Mechanical demands of the hang power clean and jump shrug: A joint-level perspective. *Journal of Strength and Conditioning Research S*, *32*(2), 466–474. https://www.ncbi.nlm.nih.gov/pubmed/27669182

Kipp, K., Comfort, P., & Suchomel, T. J. (2021). Comparing biomechanical time series data during the hang-power clean and jump shrug. *Journal of Strength and Conditioning Research S*, *35*(9), 2389–2396. https://doi.org/10.1519/jsc.0000000000003154

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

McMahon, J. J., Murphy, S., Rej, S. J. E., & Comfort, P. (2017). Countermovement jump-phase characteristics of senior and academy rugby league players. *International Journal of Sports Physiology and Performance*, *12*(6), 803–811. https://doi.org/10.1123/ijspp.2016-0467

McMahon, J. J., Jones, P. A., Dos' Santos, T., & Comfort, P. (2017). Influence of dynamic strength index on countermovement jump force-, power-, velocity-, and displacement-time curves. *Sports*, *5*(72), 1–11. https://doi.org/10.3390/sports5040072

McMahon, J. J., Rej, S. J. E., & Comfort, P. (2017). Sex differences in countermovement jump phase characteristics. *Sports (Basel)*, *5*(1), 1–11 doi:10.3390/sports5010008.

McMahon, J. J., Jones, P. A., Suchomel, T. J., Lake, J., & Comfort, P. (2018). Influence of the reactive strength index modified on force- and power-time curves. *International Journal of Sports Physiology and Performance*, *13*(2), 220–227. https://doi.org/10.1123/ijspp.2017-0056

McMahon, J. J., Suchomel, T. J., Lake, J., & Comfort, P. (2018). Understanding the key phases of the countermovement jump force-time curve. *Strength and Conditioning Journal*, *40*(4), 96–106. https://doi.org/10.1519/SSC.0000000000000375

Meechan, D., Suchomel, T. J., McMahon, J. J., & Comfort, P. (2020). A comparison of kinetic and kinematic variables during the mid-thigh pull and countermovement shrug, across loads. *Journal of Strength and Conditioning Research*, *34*(7), 1830–1841. https://doi.org/10.1519/JSC.0000000000003288

Meechan, D., McMahon, J. J., Suchomel, T. J., & Comfort, P. (2020). A comparison of kinetic and kinematic variables during the pull from the knee and hang pull, across loads. *Journal of Strength and Conditioning Research*, *34*(7), 1819–1829. https://doi.org/10.1519/JSC.0000000000003593

Nimphius, S., McBride, J. M., Rice, P. E., Goodman-Capps, C. L., & Capps, C. R. (2019). Comparison of quadriceps and hamstring muscle activity during an isometric squat between strength-matched men and women. *Journal of Sports Science & Medicine*, *18*(1), 101–108. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6370970/

Owen, N., Watkins, J., Kilduff, L., Bevan, H., & Bennett, M. (2014). Development of a criterion method to determine peak mechanical power output in a countermovement jump. *Journal of Strength and Conditioning Research S*, *28*(6), 1152–1158. doi:10.1519/JSC.0000000000000311

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics*, *43*(10), 1976–1982. https://doi.org/10.1016/j.jbiomech.2010.03.008

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, *46*(14), 2394–2401. https://doi.org/10.1016/j.jbiomech.2013.07.031

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics*, *48*(7), 1277–1285. https://doi.org/10.1016/j.jbiomech.2015.02.051

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2016). The probability of false positives in zero-dimensional analyses of one-dimensional kinematic, force and EMG trajectories. *Journal of Biomechanics*, *49*(9), 1468–1476. https://doi.org/10.1016/j.jbiomech.2016.03.032

Robinson, M. A., Vanrenterghem, J., & Pataky, T. C. (2021). Sample size estimation for biomechanical waveforms: Current practice, recommendations and a comparison to discrete power analysis. *Journal of Biomechanics*, *122*, 110451. https://doi.org/10.1016/j.jbiomech.2021.110451

Souza, A. L., Shimada, S. D., Koontz, A., Comfort, P., Dos'Santos, T., Thomas, C., McMahon, J. J., & Suchomel, T. J. (2002). Ground reaction forces during the power clean. *Journal of Strength and Conditioning Research*, *16* (3), 423–427. https://www.ncbi.nlm.nih.gov/pubmed/12173957

Suchomel, T. J., Beckham, G. K., & Wright, G. A. (2013). Lower body kinetics during the jump shrug: Impact of load. *Journal of Trainology*, *2*(2), 19–22. https://doi.org/10.17338/trainology.2.2_19

Suchomel, T. J., Wright, G. A., Kernozek, T. W., & Kline, D. E. (2014). Kinetic comparison of the power development between power clean variations. *Journal of Strength and Conditioning Research*, *28*(2), 350–360. https://doi.org/10.1519/JSC.0b013e31829a36a3

Suchomel, T. J., Comfort, P., & Stone, M. H. (2015). Weightlifting pulling derivatives: Rationale for implementation and application. *Sports Medicine*, *45*(6), 823–839. https://doi.org/10.1007/s40279-015-0314-y

Suchomel, T. J., Comfort, P., & Lake, J. P. (2017). Enhancing the force-velocity profile of athletes using weightlifting derivatives. *Strength & Conditioning Journal*, *39*(1), 10–20. https://doi.org/10.1519/SSC.0000000000000275

Suchomel, T. J., Lake, J. P., & Comfort, P. (2017). Load absorption force-time characteristics following the second pull of weightlifting derivatives. *Journal of Strength and Conditioning Research*, *31*(6), 1644–1652. https://www.ncbi.nlm.nih.gov/pubmed/27669195

Suchomel, T. J., & Sole, C. J. (2017a). Force-time–curve comparison between weight-lifting derivatives. *International Journal of Sports Physiology and Performance*, *12*(4), 431–439. https://www.ncbi.nlm.nih.gov/pubmed/27400372

Suchomel, T. J., & Sole, C. J. (2017b). Power-time curve comparison between weightlifting derivatives. *Journal of Sports Science & Medicine*, *16*(3) , 407–413. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5592293/

Suchomel, T. J., Giordanelli, M. D., Geiser, C. F., & Kipp, K. (2018). Comparison of joint work during load absorption between weightlifting derivatives. *Journal of Strength and Conditioning Research*, *35*(2S), S127–S135. https://doi.org/10.1519/JSC.0000000000002927