Kinetics and Kinematics of the Push Press, Push Jerk, and Split Jerk

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Abstract

Soriano, MA, Jiménez-Ormeño, E, Lake, JP, McMahon, JJ, Gallo-Salazar, C, Mundy, P, and Comfort, P. Kinetics and kinematics of the push press, push jerk, and split jerk. *J Strength Cond Res* 38(8): 1359–1365, 2024—The aim of this study was to explore the kinetics and kinematics across incremental loads with the push press (PP), push jerk (PJ), and split jerk (SJ). Eighteen resistance-trained men performed the 1 repetition maximum (1RM) tests (visit 1) 3–7 days before an incremental loading protocol (60, 75, and 90% 1RM) of the 3 exercises (visit 2). Kinetics and kinematics were derived from force-time data and compared using a repeated-measures analysis of variance with load and exercise as within-subject factors. Dependent variables for the biomechanics assessment were categorized as output (power and impulse), driver (force and work), and strategy (displacement and duration) metrics. The interrepetition reliability was assessed using the intraclass correlation coefficient and coefficient of variation. The PP, PJ, and SJ 1RM performance were 89.7 ± 15.4, 95.6 ± 14.4, and 103.0 ± 16.9 kg, respectively. Driver, strategy, and outcome metrics displayed moderate-to-excellent (intraclass correlation coefficient: 0.58–0.98) reliability with acceptable variability (% coefficient of variation: 2.02–10.00). Increased load resulted in significantly large increases in force, work, displacement, duration, power, and impulse ($p < 0.001$, $\eta_p^2 = 0.534–0.903$). Exercise selection had a significant and large effect on power, impulse, work, and force ($p < 0.016$, $\eta_p^2 = 0.387–0.534$). There was a significant and large effect of load × exercise interaction on work, displacement, and duration ($p < 0.019$, $\eta_p^2 = 0.158–0.220$). Practitioners are encouraged to use heavier loads ($90 > 75 > 60\%$ 1RM) during the SJ exercise to maximize output, driver, and strategy kinetics and kinematics.

Key Words: weightlifting, impulse, force, power development, biomechanics

Introduction

In most sports, athletes are generally required to execute powerful athletics tasks, including jumping, lifting, throwing, sprinting, and changing of direction over a given range of motion and in a time-constrained context (36,37). Mechanical work (force × displacement) must be performed during dynamic athletic tasks to accelerate the athlete's own center of mass (COM), an opponent, object, or implement (i.e., barbell and ball). And power, the rate of mechanical work, is commonly considered as a key performance indicator of dynamic athletic performance (36,37). Consequently, practitioners have been interested not only in developing power but also in evaluating an athlete's performance improvements through the assessment of their maximal capacity to produce power (9,36,37).

Researchers have evaluated and reported the peak power output (work performed over 1 ms when the sampling frequency is 1,000 Hz) during resistance training exercises such as the back squat and hang power clean (1,14). Its relevance may be questionable because the propulsion phase of most dynamic athletic tasks occurs in timeframes over 100–300 milliseconds (23,34,36). Therefore, mean power and impulse (force × time) may be more appropriate when quantifying dynamic performance. When force, displacement, and duration change during a lift, velocity will also change resulting in changes in power output. This means that power also changes. Consequently, practitioners should understand the mechanical underpinnings of dynamic athletic tasks to obtain a clearer picture for guiding the training process (23,35,36).

Researchers recently evaluated the free-weight back squat and loaded jump squat kinetics and kinematics using a novel approach by selecting output, driver, and strategy metrics (35). Output metrics offer real-time feedback pertinent to athletes and coaches, where their selection is based on sport-specific applicability. Driver metrics underpin the mechanics of athletic motion, whereas strategy variables are approaches used by individuals to accomplish sporting tasks. Together, these metrics elucidate and quantify the nuances of athlete performance and the demands of sports-related activities (35). In the study presented by Thompson et al. (35), power, velocity and impulse were the output metrics examined, with force and work being classified as driver metrics, and displacement and duration were used to describe the athlete's

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task strategy. Researchers have concluded that significantly greater kinetics and kinematics occur during the ballistic jump when compared with the nonballistic back squat and recommended their use to maximize athlete mechanical capacity (35). Mundy et al. (23) examined the effects of load on countermovement vertical jump within a very similar approach that included output (peak power, mean power and velocity, and net impulse), driver (mean force, net average force, and work), and strategy metrics (displacement and duration). Researchers have concluded that the interaction between barbell load and underpinning force, time, and displacement components must be considered when prescribing training loads. Therefore, as practitioners seek interventions that optimize mechanical capacity, researchers have recommended that practitioners should use output, driver, and strategy metrics underpinning a given exercise to better inform decisions about any training adaptations (23,35,36).

To increase athlete mechanical capacity, practitioners use a variety of methods and exercises selection throughout a periodized plan (8,9,37). Ballistic and nonballistic resistance exercises are commonly implemented based on their mechanical qualities to increase maximal strength and rapid force production (35,37). Similarly, weightlifting exercises (and derivatives) are used in athlete training programs because they enable athletes to exert large forces at high velocities (3,5,28,30,31). It is well documented that using these weightlifting exercises can enhance athlete maximum force and power development (5,22,32,33).

It is commonly accepted that load and the type of weightlifting exercise affect exercise kinetics and kinematics (6,7,16,29). Comfort et al. (6,7) reported that when performing the mid-thigh clean pull with 40, 60, 80, 100, 120, and 140% of 1 repetition maximum (1RM) power clean, lighter loads (40–60% 1RM) maximized power, whereas heavier loads (120–140% 1RM) maximized force production (peak force, rate of force development, and impulse). Suchomel et al. (29) reported significant load effects on hang power clean kinetics and kinematics with 30, 45, 65, and 80% 1RM. Force-time characteristics were recently used to explain load and exercise-based changes in output, driver, and strategy metrics during the countermovement shrug, mid-thigh pull, pull from the knee, and hang pull (18–21). To the authors' knowledge, there is minimal research exploring the impact of load on the kinetics and kinematics of the push press (PP), push jerk (PJ), and split jerk (SJ). For example, Lake et al. (16) investigated the load that maximized system power and impulse during the PP across incremental loads (10–90% 1RM), whereas Soriano et al. (27) investigated the differences in kinetics (force, power, and impulse) and kinematics (displacement and duration) between the PP, PJ, and SJ performed at a fixed load. However, researchers have not compared the effect of incremental loads and exercise (PP, PJ, and SJ) on kinetics and kinematics, providing a framework to gain a better understanding of the mechanics of each exercise and load selection.

Therefore, the primary aim of this study was to explore load (60, 75, and 90% 1RM) and exercise (PP, PJ, and SJ) effects on kinetics and kinematics using a framework that categorized metrics as output (power and impulse), driver (force and work), and strategy (displacement and duration) (23,35). We hypothesized that PP, PJ, and SJ kinetics and kinematics would increase with load as shown in previous studies (7,19,21,23,35). For example, when lifting heavier loads, athletes may need to increase their force production to successfully complete the lift, which may drive to an increase in power and impulse (7,35). To achieve their lifting goals, an athlete can choose from various strategies. One such strategy is applying a specific amount of force over a longer distance and time, which results in an increase in both work and impulse (16,19,21,23,35). Another strategy is to apply higher forces over a shorter duration or distance, which results in an increase in power (16,19,21,23,35). It was also hypothesized that exercise and load × exercise interaction would not affect exercise kinetics and kinematics because of similarities in the propulsion phase kinematics (27).

Methods

Experimental Approach to the Problem

A cross-sectional study, including a within-subject repeated-measures research design was used to compare the effects of load, exercise, and load × exercise interaction on kinetics and kinematics. Subjects attended the laboratory on 2 occasions. On the first occasion, the 1RM for the 3 exercises and participant information (e.g., age, height, body mass, and weightlifting training experience) were recorded. On the second occasion, vertical force data were recorded during PP, PJ, and SJ with 60, 75, and 90% 1RM of the previously recorded 1RM. Subjects performed the 1RM assessment 3–7 days before exploring the biomechanics of PP, PJ, and SJ. Mean force and power, work, displacement, duration, and impulse metrics from the propulsion phase were considered for the biomechanical analysis.

Subjects

An a priori sample size estimation for analysis of variance (ANOVA) using G Power software (version 3.1; Heinrich Heine University, Düsseldorf, Germany) showed that a sample size of 18 would be sufficient when considering a η_p^2 medium effect size of 0.06 (F effect size = 0.25), an alpha of 0.05, a statistical power of 0.8, 3 groups, 3 measurements, and hypothesized moderate-to-high correlations among repeated measures (r = 0.8), with an observed statistical power of 0.88. Eighteen resistance-trained men (age: 26.1 ± 6.9 years; height: 1.8 ± 0.1 m; body mass: 86.5 ± 10.6 kg; experience performing weightlifting exercises: 2.5 ± 1.6 years; PP 1RM: 89.7 ± 15.4 kg; PJ 1RM: 95.6 ± 14.4 kg; SJ 1RM: 103.0 ± 16.9 kg; relative PP 1RM = 1.04 ± 0.13 kg/kg, PJ 1RM = 1.12 ± 0.17 kg/kg, and SJ 1RM = 1.22 ± 0.20 kg/kg) took part in this study. Subjects were competitors in CrossFit, rugby, volleyball, swimming, track and field, soccer, and weightlifting (regional and national championships) and had ≥6 months of weightlifting experience as a minimum criterion. There were no highly skilled weightlifters in this study, but a general sporting population that uses weightlifting exercises and their derivatives as part of their training program along with some amateur weightlifters, with the PP, PJ, and SJ regularly performed (≥3 × a week). Institutional review board approval was gained from the University of Salford, Manchester (HSR1819-060), and all subjects provided written informed consent before participation. This study conformed to the principles of the World Medical Association's Declaration of Helsinki 2013.

Procedures

Subjects performed the combined 1RM assessment method 3–7 days before biomechanical PP, PJ, and SJ performance was recorded. This method is a valid, reliable, and less time-consuming way to record maximum exercise PP, PJ, and SJ performance (24,25). Each exercise saw the barbell lifted from squat stands before starting each attempt to minimize fatigue (of performance of the clean) (24). The technical aspects of these exercises are well defined in previous research, and the guidelines provided were strictly followed to determine either a successful or an unsuccessful lift (24,28).

For the biomechanical assessment, subjects performed a standardized warm-up protocol described in previous research (16,27), before performing 3 PP, PJ, and SJ (randomized) repetitions in a progressive configuration with 60, 75, and 90% 1RM of each exercise. After each repetition, subjects returned the barbell back to the squat stands, resting between repetitions for 60, 90, and 120 seconds, respectively. Subjects rested for 3 minutes between exercises. Additional repetitions were performed after appropriate rest when technical standards were not met, following previous guidelines (27). In the PP, the athlete executes an upward barbell press with shoulder flexion and elbow extension, concurrent with full hip, knee, and ankle extension, maintaining ground contact with the feet. The PJ involves complete extension of the hip, knee, and ankle, propelling the barbell upwards, followed by a rapid descent into a quarter squat to secure the barbell overhead, with full elbow and shoulder extension. In the SJ, identical to the PJ's initial phase, the athlete concludes with a split stance, with 1 foot forward and the other back, differing from the PP by the feet leaving the ground in both the PJ and SJ (24,27).

Measurement Equipment and Data Analysis. All tests were performed using standardized barbells and weight plates (Werksan weights and barbells; Werksan, Moorestown, NJ), lifting platforms, and squat stands (Powerlift, IA). During the biomechanics assessment, all lifts were performed with subjects standing on an in-ground force platform (AMTI; Advanced Medical Technologies Inc., Newton, MA). The force platform was zeroed between trials with nothing on it. Data were collected in Qualisys Track Manager software at 1,000 Hz and gross vertical force data were exported for later analysis in a custom-built Microsoft Excel spreadsheet (Microsoft, Redmond, WA).

Following the guidelines and methods previously described (35), dependent variables were selected based on 3 categories: output, driver, and strategy metrics (Table 1). All variables (output, driver, and strategy) were derived from the vertical force-time data using methods previously described during weightlifting exercises (16,26). The first step was to identify the PP, PJ, and SJ dip and thrust phases. To determine these phases, the velocity of the system (i.e., barbell plus body mass) COM was obtained by subtracting system weight (system weight: force averaged over 0.5 seconds period of pre-exercise standing still [collected on a trial-by-trial basis]) from vertical force before dividing it by system mass (system weight/acceleration of gravity) and then integrating this using the trapezoid rule (16,27). Then, the thrust (i.e., propulsion) system COM displacement and duration was identified. The propulsion phase started as the lowest system COM displacement, ending at peak velocity, which provided a landmark common to the 3 exercises (27). Thrust displacement (calculated by integrating velocity-time data) and duration were calculated as the change in position during and duration of this phase and were saved for further analysis (27). Only the thrust phase was considered because researchers have reported the greatest force and power outputs during the PP, PJ, and SJ in the scientific literature (28). The averages of the 3 repetitions for force, work, power, impulse, displacement, and duration during the PP, PJ, and SJ, for each loading condition (60, 75, and 90% 1RM), were selected for further analysis using Microsoft Excel (Microsoft).

Statistical Analysis

All data are presented as mean ± *SD* where appropriate. The interrepetition reliability of all dependent variables for each exercise variation (PP, PJ, and SJ) was determined using the coefficient of variation (CV), intraclass correlation coefficient (ICC; model 3.1), and their 95% confidence intervals. The ICC threshold was set based on the lower bound 95% CI as poor (<0.50), moderate (0.5–0.74), good (0.75–0.90), and excellent (>0.90) reliability (15). A CV <10% was used as a criterion for the minimum acceptable reliability (2). The reliability analysis was performed using a custom spreadsheet (12).

Normal distribution was verified using the Shapiro–Wilk's test. Either Greenhouse-Geisser or Huynh-Feldt corrections were used when the assumption of sphericity was violated. A 2-way ANOVA for repeated measures, followed by Bonferroni post hoc analysis, was conducted to examine the main effects of load (60, 75, and 90%), exercise (PP, PJ, and SJ), and their interaction (load × exercise) on each dependent variable (Table 1). The statistical significance was set at $p \leq 0.05$. Eta partial squared (η_p^2) was used to determine the magnitude of the effect independently of the sample size, as recommended for ANOVA designs (17) and interpreted as follows (4): small <0.06, medium 0.06–0.14, and large >0.14. If a significant effect was detected, Hedge's *g* effect size for pairwise comparison were applied and interpreted based on a study (13): trivial <0.2, small ≥0.2 to <0.6, moderate ≥0.6 to <1.2, large ≥1.2 to <2.0, and very large ≥2.0. All statistical tests were performed using JASP (JASP Team, version 0.17.3 [Computer Software], Amsterdam, The Netherlands).

Results

The 1RM performance during the PP, PJ, and SJ were 89.7 ± 15.4 kg, 95.6 ± 14.4 kg, and 103.0 ± 16.9 kg, respectively. For the PP, the mean ± *SD* of the 60, 75, and 90% loads were 53.8 ± 9.2, 67.3 ± 11.5, and 80.8 ± 13.8 kg, respectively. For the PJ and SJ, the incremental loads were 57.3 ± 8.7, 71.7 ± 10.8, and 86.1 ± 13.0 kg,

Table 1

Definitions, Système Internationale (SI) units, and calculation methods for all dependent variables.

SI-dependent variable (unit)	Calculation	Type of variable
Force (N)	Average of gross vertical ground reaction force data	Driver
Work (J)	Force × displacement	Driver
Duration (s)	Time point at phase end–time point at phase start	Strategy
Displacement (m)	Change in position (end position–start position)	Strategy
Power (W)	Work/time	Outcome
Impulse (N·s)	Mean net force: Average of force less system weight Integrated mean net force about time	Outcome

Table 2

Kinetics and kinematics during the push press, push jerk, and split jerk across 60, 75, and 90% loading conditions.*†

	Push press			Push jerk			Split jerk		
Metrics	**60% 1RM**	**75% 1RM**	**90% 1RM**	**60% 1RM**	**75% 1RM**	**90% 1RM**	**60% 1RM**	**75% 1RM**	**90% 1RM**
Force (N)	2,478 ± 292‡§	2,592 ± 341‡	2,737 ± 332	2,548 ± 347‡§	2,666 ± 350‡	2,770 ± 347	2,648 ± 342‡§	2,752 ± 365‡	2,855 ± 365
Work (J)	386 ± 111‡§	441 ± 128	471 ± 129	408 ± 109‡§	467 ± 133	474 ± 111	399 ± 96.7‡§	474 ± 111‡	532 ± 111
Displacement (m)	0.16 ± 0.04	0.18 ± 0.04	0.18 ± 0.04	0.17 ± 0.04‡	0.18 ± 0.05	0.19 ± 0.03	0.16 ± 0.04‡§	0.18 ± 0.04	0.19 ± 0.03
Duration (s)	0.20 ± 0.04‡§	0.22 ± 0.05	0.23 ± 0.04	0.20 ± 0.04‡§	0.22 ± 0.5‡	0.24 ± 0.05	0.19 ± 0.04‡§	0.22 ± 0.04‡	0.25 ± 0.04
Power (W)	1,959 ± 310	2,023 ± 355	2,041 ± 360	2,045 ± 346	2,107 ± 373	2,099 ± 366	2,058 ± 306	2,134 ± 314	2,147 ± 310
Impulse (N·s)	228 ± 36.7‡§	246 ± 42‡	258 ± 45.5	237 ± 36.5‡§	256 ± 42.2‡	268 ± 40.3	239 ± 35.1‡§	262 ± 37.6‡	279 ± 39.1

*1RM = 1 repetition maximum.

†Data as mean and *SD*.

‡Significantly lower than 90% 1RM ($p \leq 0.05$).

§Significantly lower than 75% 1RM ($p \leq 0.05$). Only the effect of load, for each exercise, is shown to avoid or reduce data overload.

and 62.0 ± 10.1, 71.7 ± 10.8, and 93.0 ± 15.2 kg, respectively. Driver metrics (force and work), strategy metrics (displacement and duration), and outcome metrics (power and impulse) displayed good-to-excellent (ICC 95% lower-CI range: 0.87–0.98), moderate-to-good (ICC 95% lower-CI range: 0.58–0.88), and good-to-excellent (ICC 95% lower-CI range: 0.85–0.97) interrepetition reliability for each exercise variation (PP, PJ, and SJ), respectively. All metrics demonstrated acceptable variability (%CV range: 2.02–10.00) (see Supplemental Digital Content 1 and 2, http://links.lww.com/JSCR/A490).

Driver Metrics

Increased load resulted in significantly large increases in force and work (90% > 75% > 60% 1RM; $p < 0.001$, η_p^2 =0.534–0.903) (see Supplemental Digital Content 3, http://links.lww.com/JSCR/A490). Force and work were significantly lower at 60% compared with 75 and 90% load ($p < 0.001$, g = 0.323–0.961). Moreover, both metrics (i.e., force and work) were also significantly lower at 75% compared with 90% load ($p < 0.001$, g = 0.323–0.344) (Table 2).

There were significant and large differences in exercise selection on force and work (SJ > PJ > PP; $p < 0.001$, η_p^2 =0.387–0.534) (see Supplemental Digital Content 3, http://links.lww.com/JSCR/A490). Force and work were significantly lower during the PP compared with PJ and SJ ($p \leq 0.04$, g = 0.191–0.455). Force during the PJ was also significantly lower compared with SJ (p = 0.003, g = 0.263), whereas work was not significantly different between exercises ($p > 0.05$, g = 0.089) (Table 2).

The interaction of exercise and load for force and work can be seen in Supplemental Digital Content 3, http://links.lww.com/JSCR/A490 and Figure 1A,B. Work at 90% was significantly higher during the SJ compared with PP ($p \leq 0.04$; g = 0.528; see Figure 1B), whereas force did not present any significant effect between load and exercise (p = 0.08, η_p^2 = 0.024; see Supplemental Digital Content 3, http://links.lww.com/JSCR/A490).

Strategy Metrics

Increased load resulted in significant and large increases in displacement and duration (90 > 75 > 60% 1RM; $p < 0.001$, η_p^2 =0.528–0.828; see Supplemental Digital Content 3, http://links.lww.com/JSCR/A490). Displacement and duration were significantly lower at 60% compared with 75 and 90% load ($p < 0.001$, g = 0.399–0.975). Duration was also significantly lower at 75% compared with 90% load ($p < 0.001$, g = 0.405), whereas displacement remained similar for both loads ($p > 0.05$, g = 0.171; Table 2).

Neither displacement nor duration presented significant or meaningful differences between exercises (SJ ~ PJ ~ PP, $p > 0.05$, η_p^2 =0.079–0.088; see Supplemental Digital Content 3, http://links.lww.com/JSCR/A490).

The interaction of exercise and load for displacement and duration can be observed in Supplemental Digital Content 3, http://links.lww.com/JSCR/A490 and Figure 1C,D. Duration at 90% was significantly higher during the SJ compared with PP (p = 0.044; g = 0.396; see Figure 1D). However, even though displacement did present significant interaction effect between load and exercise (p = 0.019, η_p^2 = 0.158), none of the exercises differed significantly at the same loads after Bonferroni adjustments (Figure 1C).

Output Metrics

Increased load resulted in significant and large increases in power and impulse (90 > 75 > 60% 1RM; $p \leq 0.002$, η_p^2 =0.298–0.851; see Supplemental Digital Content 3, http://links.lww.com/JSCR/A490). Power and impulse were significantly lower at 60% compared with 75 and 90% load ($p < 0.012$, g = 0.200–0.840). Impulse was also significantly lower at 75% compared with 90% load ($p < 0.001$, g = 0.342), whereas power was not significantly or meaningfully different between both loads ($p > 0.05$; g = 0.023; Table 2).

There were significant and meaningful differences in exercise selection on power and impulse with small effect sizes ($p < 0.016$, η_p^2 =0.217–0.507; see Supplemental Digital Content 3, http://links.lww.com/JSCR/A490). Power and impulse were significantly lower during the PP compared with the SJ with small effect sizes ($p < 0.016$, g = 0.312–414). Impulse was significantly lower during the PP compared with the PJ (p = 0.003, g = 0.256), whereas power was not significantly or meaningfully different between these exercises (p = 0.118; g = 0.225). Power and impulse were not significant between PJ and SJ ($p > 0.096$; g = 0.087–0.158; Table 2).

Neither power (p = 0.891, η_p^2 = 0.009) nor impulse (p = 0.158, η_p^2 = 0.099) presented significant or meaningful differences for the interaction of exercise and load as it can be observed in Supplemental Digital Content 3, http://links.lww.com/JSCR/A490 and Figure 1E,F.

Discussion

This study examined the kinetics and kinematics of the PP, PJ, and SJ performed across incremental loads using a theoretical framework that categorized metrics as output (power and impulse), drivers (force and work), and strategy (displacement and

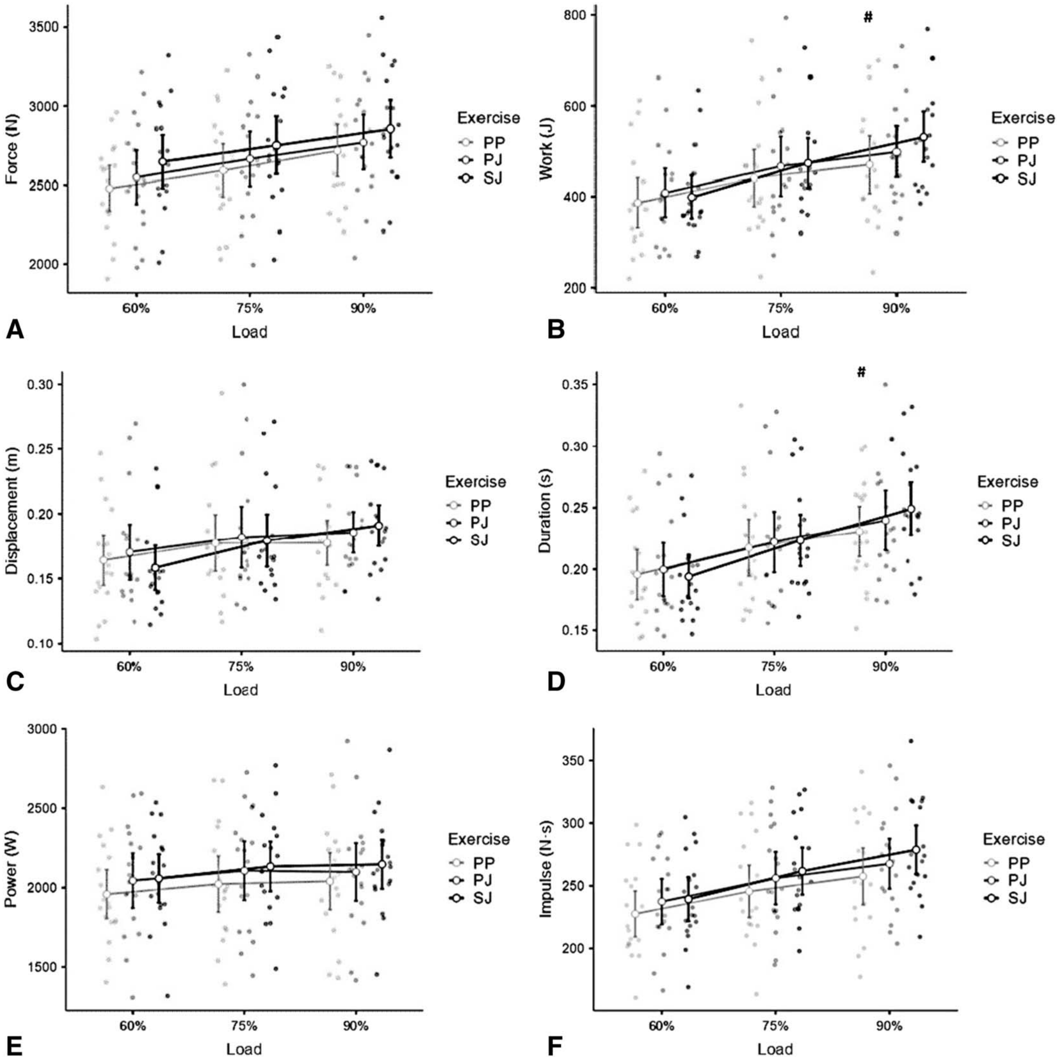

Figure 1. Distribution of the individual values and the interaction between load (60, 75, and 90% 1RM) and exercise (push press [PP], push jerk [PJ], and split jerk [SJ]) for all the variables studied (driver metrics: force [A], work [B]; strategy metrics: displacement [C], duration [D]; output metrics: power [E], impulse [F]). Values are presented as mean ± 95% CI. #, Significantly lower than SJ at 90% ($p < 0.05$). Only the interaction effects between exercises at the same load were included in the analyses to avoid or reduce data overload.

duration). The main findings of this research were that load significantly increased the kinetics and kinematics, irrespective of the PP, PJ, and SJ exercises, as hypothesized. Exercise selection significantly affected the output and diver metrics, where the SJ maximized the kinetics (i.e., force, work, power, and impulse) over the PJ and PP, but there were no differences in strategy kinematics (i.e., displacement and duration) between exercises, which partially agrees with the initial hypothesis. Contrary to our initial hypothesis, exercise × load interaction affected work, displacement, and duration metrics. This study should aid strength and conditioning coaches in selecting loads and exercises for a periodized training program.

Power and impulse increased with heavier loads (90 > 75 > 60% 1RM) during the PP, PJ, and SJ, although it was not significant between 75 and 90% 1RM loads ($p > 0.05$; Table 2). Lake et al. (16) previously found that increasing or decreasing load by 10 and 20% 1RM, from the load that maximized mean power, resulted in significant reductions in power outputs (7–15%, $p \leq 0.012$). This is in agreement with our results because lower power outputs were registered at 60% 1RM compared with 75 and 90% 1RM, where mean power was maximized during the PP, PJ, and SJ. It is difficult to understand the rationale behind the results of Lake et al. (16) because authors did not report the changes in strategy (displacement and duration) and driver metrics (force and work) underpinning the resulting reductions in the mean power outputs (16). By contrast, our results can be explained using a theoretical framework to elucidate the reason behind the change in power outputs. As such, because power is the rate of mechanical work, increments in both sides of the equation (e.g., increases in work accompanied with a longer phase duration of 75 and 90% 1RM loads) may not necessarily result in a change in the resultant power outputs (23,36). Impulse was significantly ($p < 0.001$) increased by load because greater forces were applied over longer phase durations as load increased. To our knowledge, impulse has not been investigated during the PP, PJ, and SJ exercise across loading conditions. Researchers have previously suggested that practitioners should focus on examining impulse for programming because selecting loads based on impulse or its subsequent product momentum (mass × velocity) could help athletes to focus on their ability to accelerate through prolonged contact or when loaded by an opponent during sport-specific tasks (e.g., mauling, lifting, and tackling) (11,23,36,37). In summary, power and impulse are, as previously mentioned, output metrics that can be effective feedback for athletes and practitioners; however, these variables do not explain the mechanical demands of a given sporting task and should be reported together with driver and strategy metrics (11,23,36,37). For example, for a given impulse, one athlete may produce a given force during a longer time in the SJ exercise (← force × ↑ time), whereas the other athlete may produce higher forces if he or she opt for a shorter duration during his or her SJ propulsion phase (↑ force × ↓ time).

Force and work significantly ($p < 0.001$) increased with increased load (90 > 75 > 60% 1RM) during the PP, PJ, and SJ (Table 2). Häkkinen et al. (10) investigated the peak relative ground reaction forces with elite and district Finnish weightlifters who performed the clean and jerk on a force plate with 70, 80, 90, and 100% 1RM, reporting that peak relative ground reaction forces during the SJ propulsion phase significantly decreased (5–27%, $p < 0.05$) as the load increased in both groups. A possible explanation for the conflicting results is that Häkkinen et al. (10) selected peak force (relative to the body weight) instead of mean force and work. According to our results, load increased mean force and displacement, leading to an increase in work (force × displacement). Therefore, the reductions in peak force as load increased, as reported by Häkkinen et al. (10), may be a consequence of changes in driver and strategy metrics. The interaction between mean force (not peak force), together with displacement and duration, provides insights into the force-time-displacement demands of each exercise and explains prerequisites for outcome metrics and dynamic performance (23,35,36).

Displacement and duration increased significantly ($p \leq 0.001$) as load increased (90 > 75 > 60% 1RM) (Table 2). To better understand the changes in the strategy metrics during the PP, PJ, and SJ, it is appropriate to put these exercises into context. The PP, PJ, and SJ lifting technique involve the dip (i.e., unweighing and braking phase) and thrust (i.e., propulsion) phases (16,28). A greater thrust displacement and duration with increasing load may subsequently increase work and impulse, assuming an adequate force application to accelerate and overcome heavier loads. Similar results have been reported during loaded countermovement jumps, where the authors reported longer phase duration, work, and impulse as the load increased (23). Therefore, increasing loads can be a useful training tool for practitioners to modify the strategy metrics (i.e., thrust displacement and duration) of their athletes, subsequently altering the driver (i.e., force and work) and output metrics (i.e., power and impulse) when performing the PP, PJ, and SJ.

In this study, as hypothesized, strategy metrics were not significantly ($p > 0.05$) affected by exercise selection. These results are in line with those reported by Soriano et al. (27), who demonstrated no differences in resistance-trained individuals for kinetics and kinematics between the PP, PJ, and SJ when performed at the same absolute load (80% 1RM PP). It was found that exercise selection had a significant impact on output and driver metrics, which was contrary to our hypothesis. Power, impulse, and work were significantly ($p < 0.016$) higher during the SJ and PJ exercises compared with the PP exercise, although no differences were found between the SJ and PJ. Considering that there were no differences in strategy metrics (as indicated by consistent displacement and duration kinematics), our theoretical framework can be instrumental in delineating the causes of these observed differences between exercises. The significantly ($p < 0.04$) higher forces applied during the SJ, compared with the PJ, and both exercises compared with the PP exercise, can explain the changes in power, impulse, and work. These higher forces can be attributed to lifting higher absolute loads for each loading condition (i.e., 60, 75, and 90% 1RM), during the SJ, compared with the PJ (~8%), and both exercises compared with the PP exercise (~13.5% and ~6.2%, respectively) because loads were selected based on each exercise 1RM. Contrary to our initial hypothesis, exercise × load interaction significantly ($p < 0.019$) affected work, displacement, and duration metrics. However, on further analysis, we discovered that the interaction effect was only present when the load was at 90% 1RM. This resulted in higher work during the SJ exercise compared with PJ and PP exercises and a longer propulsion duration in SJ compared with PP. These findings show that the SJ exercise may be a superior training tool to optimize the force- and power-generating capacity of athletes. However, it may be hypothesized that implementing equal loading conditions, the PP, PJ, and SJ could have a similar impact to optimize the strength and power development (27).

In conclusion, it was demonstrated that additional barbell loads significantly increased the kinetics and kinematics of the PP, PJ, and SJ, irrespective of exercise. Although our study provides an in-depth comparison of the PP, PJ, and SJ across loads, there are several limitations to be highlighted. First, this study can only be extrapolated to general sporting populations that use weightlifting exercises as part of their strength and conditioning programs. Therefore, researchers should cover the highly skilled weightlifting population, which may differ from our results as previously reported in this article (10). Second, the narrow range of loading conditions (60, 75, and 90% 1RM) may limit the application and interpretation of our data across the full-load spectrum (16). However, using these weightlifting overhead pressing derivatives with lighter loads (e.g., <60% 1RM) may lack effectiveness in practical settings (5). Nonetheless, the results of this study provide the strength and conditioning coach a clear picture of the force-time-displacement demands of the PP, PJ, and SJ exercises across loads (60, 75, and 90%) for their effective implementation in periodized training programs.

Practical Applications

Weightlifting exercises and their derivatives are implemented in strength and conditioning programmes as training tools to develop rapid force and power production. Strength coaches may select a spectrum of weightlifting derivatives, together with loads, for targeting specific zones of the force-velocity relationship. According to the results of this study, additional barbell loads significantly increased the kinetics and kinematics of the PP, PJ, and SJ, irrespective of exercise. Practitioners are encouraged to use heavier loads (60% < 75% < 90% 1RM) during the PP, PJ, and SJ to maximize output (power and impulse) because of changes in driver (force and work) and strategy (displacement and duration) metrics. Furthermore, the SJ exercise is a superior training tool when compared with the PJ and PP exercises (SJ > PJ > PP), with SJ exercise being the most effective for optimizing the force- and power-generating capacity of athletes. This is because of the higher output and drive metrics registered during SJ exercises. By using a theoretical framework that incorporates output, driver, and strategy metrics, practitioners can gain a better understanding of the mechanics and demands of each exercise and load selection. This will enable them to detect changes in dynamic performance and program loads and exercises more accurately.

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References

1. Alcaraz PE, Romero-Arenas S, Vila H, Ferragut C. Power-load curve in trained sprinters. *J Strength Cond Res* 25: 3045–3050, 2011.
2. Baumgartner TA, Chung H. Confidence limits for intraclass reliability coefficients. *Meas Phys Educ Exerc Sci* 5: 179–188, 2001.
3. Chiu LZF, Schilling BK. A primer on weightlifting: From sport to sports training. *Strength Cond J* 27: 42–48, 2005.
4. Cohen J. The analysis of variance and covariance. *Statistical Power Analysis for the Behavioural Science*. (2nd ed.). Mahwah, NJ: Erlbaum, 1988. pp. 274–288.
5. Comfort P, Haff GG, Suchomel TJ, et al. National Strength and Conditioning Association position statement on weightlifting for sports performance. *J Strength Cond Res* 37: 1163–1190, 2023.
6. Comfort P, Jones PA, Udall R. The effect of load and sex on kinematic and kinetic variables during the mid-thigh clean pull. *Sports Biomech* 14: 139–156, 2015.
7. Comfort P, Udall R, Jones PA. The effect of loading on kinematic and kinetic variables during the midthigh clean pull. *J Strength Cond Res* 26: 1208–1214, 2012.
8. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: Part 2—Training considerations for improving maximal power production. *Sports Med* 41: 125–146, 2011.
9. Cormier P, Freitas TT, Seaman K. A systematic review of resistance training methodologies for the development of lower body concentric mean power, peak power, and mean propulsive power in team-sport athletes. *Sports Biomech* 4: 1–34, 2021.
10. Häkkinen K, Kauhanen H, Komi P. Biomechanical changes in the Olympic weightlifting technique of the snatch and clean and jerk from submaximal to maximal loads. *Scand J Sports Sci* 6: 57–66, 1984.
11. Harry JR, Krzyszkowski J, Harris K, et al. Momentum-based load prescriptions: Applications to jump squat training. *J Strength Cond Res* 36: 2657–2662, 2022.
12. Hopkins WG. A new view of statistics: A scale of magnitudes for effect statistics. *Sportsci* 2002.
13. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–13, 2009.
14. Kilduff LP, Bevan H, Owen N, et al. Optimal loading for peak power output during the hang power clean in professional rugby players. *Int J Sports Physiol Perform* 2: 260–269, 2007.
15. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med* 15: 155–163, 2016.
16. Lake JP, Mundy PD, Comfort P. Power and impulse applied during push press exercise. *J Strength Cond Res* 28: 2552–2559, 2014.
17. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for *t*-tests and ANOVAs. *Front Psychol* 4: 863–868, 2013.
18. Meechan D, McErlain-Naylor SA, McMahon JJ, Suchomel TJ, Comfort P. Comparing biomechanical time series data across countermovement shrug loads. *J Sports Sci* 40: 1658–1667, 2022.
19. Meechan D, McMahon JJ, Suchomel TJ, 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: 1819–1829, 2020.
20. Meechan D, McMahon JJ, Suchomel TJ, Comfort P. The effect of rest redistribution on kinetic and kinematic variables during the countermovement shrug. *J Strength Cond Res* 37: 1358–1366, 2023.
21. Meechan D, Suchomel TJ, McMahon JJ, Comfort P. A comparison of kinetic and kinematic variables during the midthigh pull and countermovement shrug, across loads. *J Strength Cond Res* 34: 1830–1841, 2020.
22. Morris SJ, Oliver JL, Pedley JS, Haff GG, Lloyd RS. Comparison of weightlifting, traditional resistance training and plyometrics on strength, power and speed: A systematic review with meta-analysis. *Sports Med* 52: 1533–1554, 2022.
23. Mundy PD, Smith NA, Lauder MA, Lake JP. The effects of barbell load on countermovement vertical jump power and net impulse. *J Sports Sci* 35: 1781–1787, 2017.
24. Soriano MA, García-Ramos A, Torres-González A, et al. Validity and reliability of a standardized protocol for assessing the one repetition maximum performance during overhead pressing exercises. *J Strength Cond Res* 35: 2988–2992, 2021.
25. Soriano MA, García-Ramos A, Torres-González A, et al. Comparison of 1-repetition-maximum performance across 3 weightlifting overhead pressing exercises and sport groups. *Int J Sports Physiol Perform* 15: 862–867, 2020.
26. Soriano MA, Kipp K, Lake JP, et al. Mechanical power production assessment during weightlifting exercises. A systematic review. *Sports Biomech* 22: 633–659, 2023.
27. Soriano MA, Lake J, Comfort P, et al. No differences in weightlifting overhead pressing exercises kinetics. *Sports Biomech* 27: 1–13, 2021.
28. Soriano MA, Suchomel TJ, Comfort P. Weightlifting overhead pressing derivatives: A review of the literature. *Sports Med* 49: 867–885, 2019.
29. Suchomel TJ, Beckham GK, Wright GA. The impact of load on lower body performance variables during the hang power clean. *Sports BioMech* 13: 87–95, 2014.
30. Suchomel TJ, Comfort P, Lake JP. Enhancing the force-velocity profile of athletes using weightlifting derivatives. *Strength Cond J* 39: 10–20, 2017.
31. Suchomel TJ, Comfort P, Stone MH. Weightlifting pulling derivatives: Rationale for implementation and application. *Sports Med* 45: 823–839, 2015.
32. Suchomel TJ, McKeever SM, Comfort P. Training with weightlifting derivatives: The effects of force and velocity overload stimuli. *J Strength Cond Res* 34: 1808–1818, 2020.
33. Suchomel TJ, McKeever SM, McMahon JJ, Comfort P. The effect of training with weightlifting catching or pulling derivatives on squat jump and countermovement jump force-time adaptations. *J Funct Morphol Kinesiol* 5: 28–33, 2020.
34. Taber C, Bellon C, Abbott H, Bingham GE. Roles of maximal strength and rate of force development in maximizing muscular power. *Strength Cond J* 38: 71–78, 2016.
35. Thompson SW, Lake JP, Rogerson D, Ruddock A, Barnes A. Kinetics and kinematics of the free-weight back squat and loaded jump squat. *J Strength Cond Res* 37: 1–8, 2023.
36. Turner AN, Comfort P, McMahon JJ, et al. Developing powerful athletes, Part 1: mechanical underpinnings. *Strength Cond J* 42: 30–39, 2020.
37. Turner AN, Comfort P, McMahon J, et al. Developing powerful athletes Part 2: practical applications. *Strength Cond J* 43: 23–31, 2021.