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The kinetics and kinematics of the free-weight back squat and loaded jump squat

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ABSTRACT

The study aim was to compare kinetics and kinematics of two, lower-body free-weight exercises, calculated from concentric and propulsion sub-phases, across multiple loads. Sixteen strength trained men performed back squat one-repetition maximum tests (1RM) (visit 1), followed by two incremental back squat and jump squat protocols (visit 2) (loads = 0% and 30-60%, back squat 1RM). Concentric and propulsion phase force-time-displacement characteristics were derived from force-plate-data and compared via analysis of variance and Hedges *g* effect sizes. Intra-session reliability was calculated via intraclass correlation coefficient (ICC) and coefficient of variation (CV). All dependent variables met acceptable reliability (ICC > 0.7; CV < 10%). Statistically significant three-way interactions (load × phase × exercise) and two-way main effects (phase × exercise) were observed for mean force, velocity (30-60% 1RM), power, work, displacement, and duration (0%, 30-50% 1RM) ($p < 0.05$). A significant two-way interaction (load × exercise) was observed for impulse ($p < 0.001$). Jump squat velocity ($g = 0.94$-3.80), impulse ($g = 1.98$-3.21), power ($g = 0.84$-2.93) and work ($g = 1.09$-3.56) were significantly larger across concentric and propulsion phases, as well as mean propulsion force ($g = 0.30$-1.06) performed over all loads ($p < 0.001$). No statistically significant differences were observed for mean concentric force. Statistically longer durations ($g = 0.38$-1.54) and larger displacements ($g = 2.03$-4.40) were evident for all loads and both sub-phases ($p < 0.05$). Ballistic, lower-body exercise produces greater kinetic and kinematic outputs than non-ballistic equivalents, irrespective of phase determination. Practitioners should therefore utilize ballistic methods when prescribing or testing lower-body exercises to maximize athlete's force-time-displacement characteristics.

KEY WORDS

Force plate testing, mechanical output, ballistic exercise, force-time-displacement characteristics, strength and power testing

INTRODUCTION

Effective strength and conditioning (S&C) interventions induce adaptations that underpin specific movement patterns, velocities, forces and energy demands required for competition (3,22). Such physical qualities (e.g., sprinting, jumping and change of direction) are underpinned by Newton's 2nd law of motion (F = ma), which states that acceleration is directly influenced by the net force applied to an object or system over a given time, and is directly proportional to its change in velocity (i.e., impulse-momentum) (41). Despite this, S&C coaches more commonly focus on variables such as peak power when evaluating performance improvements (8), often questionably referring to it as a 'physical characteristic' rather than by its mechanical definition (20,44,45).

Power (work / Δ time) is a product of force and velocity, as work is force multiplied by displacement and velocity describes the rate of displacement with respect to time (41). Nevertheless, peak power often only refers to the work performed over 1 ms (where force is recorded at 1000 Hz), a common problem with most peak metrics (30). Their practical relevance, therefore, is sometimes questionable as the propulsion phase of sprinting and jumping often occurs over 150-250 ms (1). Mean power, on the other hand, might be a more appropriate metric to measure (24), but can still be misleading as a change in force application, displacement travelled and/or phase duration can all impact it (30). Therefore, understanding an individual's movement '*strategy*' and adhering to strict scientific principia when selecting performance variables (e.g., impulse, velocity, work etc.) could help obtain a clearer picture of an athlete's capabilities during specific tasks rather than a single measurement of power (41).

S&C practitioners utilize a variety of methods to develop underpinning mechanical qualities such as power, impulse, force and velocity, however literature comparing these strategies is somewhat limited (7,16,17,19,28,40). Increases in power have been observed from heavy strength training (e.g., > 80% one repetition maximum (1RM)) through physiological adaptations (e.g., increases in motor unit recruitment and intramuscular co-ordination) that influence the force end of the force-velocity curve (5,7,16,37). Nevertheless, these are often more effective with untrained or weaker athletes, or during the initial stages of a periodized programme (8,43). Further power development, therefore, typically requires the inclusion of additional lighter (e.g., 30-60% (1RM), more mechanically specific training methods that optimize movement velocity as dictated by the force-velocity-power relationship (9,10,27). In practice, methods to implement these faster velocity-type adaptations usually include ballistic (e.g., jump squat) or explosive non-ballistic (e.g., 'speed' back squat) exercises, with the main biomechanical difference being the projection of the body, system or object into free space during the ballistic task (14). However, comparisons of the underpinning mechanical demands of both training strategies are limited yet are vital for practitioners to make informed programming decisions.

Performing non-ballistic exercise with maximal intent at loads that optimize the trade-off between force and velocity (e.g., 30-60% 1RM) has been suggested as an appropriate strategy for inducing adaptations that underpin power and rate of force development (RFD) (4,6,42). However, inherent within non-ballistic exercise is a period of negative acceleration, commonly referred to as the *'deceleration sub-phase'* (velocity maxima to displacement maxima). The contribution of this sub-phase (e.g., 10-50% of the full '*concentric phase'* (displacement minima to displacement maxima) in loads of 30-81% 1RM) can result in a reduction in kinetic and kinematic output and muscle activation (11,31,36), potentially reducing adaptive stimuli and limiting dynamic correspondence to key sporting actions such as jumping and sprinting (6,8).

Ballistic exercises typically produce higher mechanical outputs than their non-ballistic counterparts as they exhibit a longer period of positive acceleration (displacement minima to velocity maxima), referred to as the *'propulsion sub-phase'* (8,14,26). As a result, when compared with non-ballistic equivalents, ballistic exercises exhibit higher velocities and larger forces, power and muscle activity, often making them the preferred choice for S&C coaches when designing 'power-type' training blocks (6,11,23,26,31). Despite this, ballistic exercise such as the jump squat must contain a landing phase. Previous researchers have observed significant increases in ankle range of motion (disproportionate to knee and hip), ankle eccentric work contribution (% of total eccentric work) and slight increases in ankle landing joint moments because of longer landing durations caused by increasing loads (13,25). This change in landing strategy, therefore, must be a consideration for S&C coaches, particularly those working with athletes undertaking return to play protocols or during in-season prescription for athletes that participate in sports where a high number of jumps are common (e.g., 60-100 jumps in a competitive game of basketball) (12,33). However, practitioners must be sure that the appropriate neuromuscular adaptations would still occur if opting for alternative methods to traditional ballistic exercise.

The differences in kinetic and kinematic outputs between ballistic and non-ballistic exercise could be due to the influence of the deceleration sub-phase when calculating key mechanical variables (15), potentially underestimating the mechanical output of non-ballistic exercise. Researchers have proposed more analogous demands when considering the propulsion sub-phase alone (15,23). Comparable force, velocity and power outputs have been reported between the bench press and bench throw exercises when removing this period of negative acceleration(15). Similarly, Lake et al. (23) found no significant differences in mean force and power when comparing the jump squat and back squat over the propulsion sub-phase only, however, this was limited to a single load (45% 1RM). Despite this, no study to date has compared the mechanical demands of lower-body ballistic and non-ballistic exercise across multiple loads that reflect typical ‘power’ or ‘optimal’ training prescriptions. Providing this comparison will help to clarify the theoretical and mechanical underpinnings of these two training strategies currently used in practice, whilst using applied data.

Optimal loading has been observed in 0% 1RM (body weight) and 30-60% 1RM for the jump squat and back squat, respectively (6,8). Similarly, research has observed maximal propulsion and concentric impulse to occur at 50-75% body mass during the loaded jump squat (25,30), equating to 50% 1RM of an individual with a relative strength level of 1.5 kg x body mass. Therefore, comparing the mechanical demands of training strategies within this range of loads designed to increase key physical qualities such as power and impulse is vital for practitioners to make appropriate programming decisions.

Similarly, to provide a comprehensive evaluation of the kinetic and kinematic variables that underpin ballistic and non-ballistic exercise across different phases of movement in comparable loads will enable coaches to better understand the appropriateness of ballistic and non-ballistic exercise. Therefore, the aim of this study was to compare the kinetics and kinematics of the ballistic jump squat and non-ballistic back squat across incremental loads (0, 30-60% 1RM) that were calculated over both the full concentric phase (inclusive of the period of negative acceleration) and the propulsion sub-phase only.

METHODS

Experimental approach to the problem

A within-participant, repeated measures design was adopted to compare the kinetic and kinematic differences between ballistic (jump squat) and non-ballistic (back squat) lower body exercise when measured within two different movement phases (concentric vs. propulsion) across five incremental loads (0, 30-60% 1RM) that reflect typical 'power-type' training prescriptions. Importantly, to provide a true comparison, loads were required to be comparable. Subjects attended the laboratory on two separate occasions, separated by a minimum of 72 hours. The first visit determined back squat 1RM, and incremental protocols in both exercises were performed in the second visit. Vertical force-plate-data was used to derive ground reaction force within which all dependent variables were calculated. Only mean metrics were considered and included force, velocity, power, impulse, work, duration and displacement. These metrics were used to consider the impact phase of determination (inclusion or exclusion of the negative period of acceleration) had on the two exercises when performed over incremental loads (0%, 30-60% 1RM).

Subjects

Sixteen healthy, strength-trained males (age: 26.2 ± 4.1 years; body mass: 83.2 ± 9.3 kg; stature: 174.7 ± 4.3 cm) volunteered for this study after providing informed consent and completing a medical pre-screening questionnaire. A sample size of sixteen subjects was calculated *a priori* (G*Power, version 3.1.9.7, Dusseldorf, Germany) using an alpha level of 0.05, statistical power of 0.95 and an effect size of 0.48 (Cohen's *f*) for a repeated measures design. Cohen's *f* was determined from Rossetti et al. (35) by taking the smallest Cohen's *d* values from the dependent variables that were collected in the present study and then divided by two. This approach to calculating effect size was based on parity between exercise modes and outcomes between Rossetti et al. (35) and the present study. Ethical approval was granted via the institution's ethics board (*ER13605026*) in accordance with the seventh revision (2013) of the declaration of Helsinki. Subjects were required to have a maximal back squat of

> 1.5 x body mass, be resistance trained for a minimum of 12 months, be technically competent in the free-weight back squat and jump squat exercises and be injury free.

Procedures

Subjects were instructed to attend fully rested and hydrated, having abstained from caffeine and following a similar nutritional intake up to all testing sessions. Each subject confirmed zero alcohol consumption 24 hours before testing and zero lower-body exercise 48 hours before and during the testing period.

The back squat and jump squat exercise techniques were standardized across all subjects, using an International Weightlifting Federation approved, calibrated 20 kg barbell and competition bumper plates (Werksan, Turkey). A '*high-bar'* position was performed, with the barbell sitting directly on the upper trapezius muscles. A lift was deemed successful when the greater trochanter was positioned lower than the lateral epicondyle of the knee at the lowest descent displacement and the subject could fully extend the hips, knees, and ankles during the ascent. The jump squat was standardized identically to the back squat during the descent phase, but subjects were required to take-off following ascent. The standardized technique was verified retrospectively using 2d video by the principal investigator.

Loads were selected based on previous literature reporting the optimal loading from a power and impulse perspective (6,8,25,30). Similarly, loads were equated across exercises to provide a clear comparison of mechanical demands. Finally, from a practical perspective, to ensure competency and safety, 60% was deemed the heaviest load appropriate for subjects to lift based on an inclusion criteria of > 1.5 x body mass.

1RM Testing (Visit 1)

Informed consent,pre-screening questionnaire, body mass (kg) (from the force plate) and stature (cm) (Seca, Leicester, Hamburg, Germany) were recorded. An individualized, standardized warm-up was performed using a combination of static stretching, dynamic mobility, activation exercises, light barbell exercises and unloaded squats and jumps. Habituation of 1 s of quiet standing before initiating movement and performing all concentric phases with '*maximal intent and velocity'* also occurred.

Subjects were guided through an incremental, 1RM protocol in the free-weight back squat that consisted of performing loads with 50% (5 repetitions), 70% (3 repetitions), 80% (2 repetitions), 85%, 90% and 95% (1 repetition) of an estimated 1RM, followed by up to 5 attempts at finding a true 1RM. Five minutes rest was prescribed between loads (38,39).

Force Plate Testing (Visit 2)

Subjects performed incremental protocols in the back squat and jump squat, with loads lifted in sequential order. All loads were determined for both exercisesas percentages of back squat 1RM. All repetitions were performed on a Kistler portable force plate (Kistler, 9286A, Winterthur, Switzerland) sampling at 1000 Hz. Ground reaction force data were collected and exported using Bioware (Kistler, Winterthur, Switzerland) software.

Before the experimental trials, subjects completed the standardized warm-up from visit one. Subjects also completed two bodyweight warm-up (using a wooden dowel with a mass of approximately 0.7 kg) sets of both exercises. The following incremental loads [repetition ranges] were then performed simultaneously in both exercises, with the order of each exercise counterbalanced across participants: 0% [5], 30% [3], 40% [3], 50% [2], 60% [2]. Five minutes and three minutes rest was provided between loads and exercises (sets) at each load, respectively. Subjects were instructed to perform all repetitions with '*maximal intent and velocity'*.

Data Analysis

Raw force data were analyzed using a custom-built Microsoft Excel script (Microsoft Excel, Microsoft, Albuquerque, NM, USA). The trial(s) with the highest system (center of mass) peak velocity were selected for analysis given their direct relationship with jump height and impulse-momentum. The dependent variables and respective calculations are presented in Table 1. All metrics were calculated as the average recorded across the course of the predetermined phases. In addition, the proportion of time and displacement spent in the propulsion phase relative to the concentric and descent phases were calculated and expressed as percentages.

** Insert Table 1 **

Dependent variables were selected based on three categories: output, driver and strategy variables. Output variables (power, velocity and impulse) refer to instantaneous feedback that might be presented and useful to an athlete or a coach; driver variables (force and work) refer to the underpinning mechanics that help to determine athletic movement; and strategy variables (duration and displacement) refer to a specific approach an individual may undertake to complete a task. The combination of these variables helps provide a clear picture of the demands of both exercises.

The repetition start for both exercises was calculated from an initial 1 s of pre-movement quiet standing. The mean force from this 1 s was used to calculate body weight (system weight for loaded trials), and force standard deviation (SD) was also calculated from this period and the mean ± 5 SD was used as the start threshold on a trial-by-trial basis (32). A graphical representation of the propulsion, concentric and '*descent*' phase (start point to displacement minima) is explained in figure 1.

** Insert Figure 1 **

Statistical Analyses

Data were checked for normality via the assessment of skewness, kurtosis, and univariate outliers. Mean and standard deviations were calculated for all dependent variables. Three-way repeated measures analysis of variance (ANOVA) was utilized to assess the load × phase × exercise interactions for force, velocity, power, work, displacement and duration, simple two-way interactions were then calculated, followed by simple main effects using the Bonferroni post-hoc correction. Impulse was analyzed via a two-way repeated measures ANOVA (load × exercise), with simple main effects assessed also using Bonferroni corrections. Mean differences and 95% confidence intervals were calculated between the two exercises for each load. Meaningful between-exercise differences were assessed using Hedges *g*, with magnitudes interpreted as: trivial (< 0.2); small (0.2-0.59); moderate (0.6-1.19); large (1.2-2.0); very large (> 2.0) (18). The proportion of time and displacement (as a percentage ratio) spent in the propulsion phase compared to the concentric and descent phase were also calculated. Intra-session reliability was assessed on the two best repetitions (those with the highest peak velocity in each session) via intraclass-correlation (ICC) and coefficient of variation (CV), with 95% confidence intervals also calculated. ICC thresholds were set as poor (< 0.5), moderate (0.5-0.74), good (0.75-0.9) and excellent (> 0.9), with CV thresholds set as poor (> 10%), moderate (5-10%) and good (< 5%) (2,21).

RESULTS

All data were normally distributed and met assumptions for parametric analysis. Mean back squat 1RM was 158.8 ± 19.2 kg (1.92 ± 0.3 kg.bm^{-1}). The ICC and CV reliability data is presented in the supplementary files. The mean (SD), differences (95% confidence intervals) and statistical significance for all dependent variables are presented in Figure 2.

** Insert Figure 2 **

Three-way repeated measures ANOVA revealed statistically significant load × phase × exercise interactions for force ($F_{(1.37,\ 20.48)} = 17.02$, $P < 0.001$), velocity ($F_{(2.27,\ 34.02)} = 6.65$, $P = 0.003$), power ($F_{(1.24,\ 18.64)} = 82.13$, $P < 0.001$), work ($F_{(1.81,\ 27.19)} = 7.74$, $P = 0.003$), duration ($F_{(4,\ 60)} = 48.60$, $P < 0.001$) and displacement ($F_{(1.98,\ 29.71)} = 136.40$, $P < 0.001$). Statistically significant simple two-way interactions (phase × exercise) were observed for force ($F_{(1,\ 15)} = 31.74\text{-}88.53$, $P < 0.001$), power ($F_{(1,\ 15)} = 53.09\text{-}115.67$, $P < 0.001$), displacement ($F_{(1,\ 15)} = 31.91\text{-}216.87$, $P < 0.001$), and work ($F_{(1,\ 15)} = 10.45\text{-}136.32$, $P = 0.006$ - < 0.001) across all five loads. Whereas significant simple two-way interactions were only observed for velocity across loads of 30-60% 1RM ($F_{(1,\ 15)} = 19.27\text{-}36.13$, $P = 0.001$ - < 0.001) and duration across loads of 0% and 30-50% 1RM ($F_{(1,\ 15)} = 10.91\text{-}176.33$, $P = 0.005$ - < 0.001).

Simple main effects revealed significantly higher velocities ($F_{(1,\ 15)} = 34.05\text{-}213.24$, $P < 0.001$, $g = 1.43\text{-}3.80$), larger power ($F_{(1,\ 15)} = 34.81\text{-}194.42$, $P < 0.001$, $g = 0.84\text{-}2.54$), more work ($F_{(1,\ 15)} = 64.99\text{-}282.09$, $P < 0.001$, $g = 1.09\text{-}3.02$), larger displacements ($F_{(1,\ 15)} = 71.70\text{-}298.51$, $P < 0.001$, $g = 2.54\text{-}4.40$) and longer durations ($F_{(1,\ 15)} = 9.03\text{-}125.56$, $P = 0.009$ - < 0.001, $g = 0.45\text{-}2.21$) in the jump squat compared to the back squat across all five loads, but no differences for mean force ($F_{(1,\ 15)} = 0.02\text{-}3.55$, $P = 0.08\text{-}0.90$, $g = -0.01\text{-}0.00$) when calculated over the concentric phase. Similarly, significantly larger force ($F_{(1,\ 15)} = 30.48\text{-}91.13$, $P < 0.001$, $g = 0.30\text{-}1.06$), higher velocities ($F_{(1,\ 15)} = 21.28\text{-}70.04$, $P < 0.001$, $g = 0.94\text{-}3.10$), larger power ($F_{(1,\ 15)} = 42.48\text{-}144.40$, $P < 0.001$, $g = 0.98\text{-}2.93$), more work ($F_{(1,\ 15)} = 86.76\text{-}282.09$, $P < 0.001$, $g = 1.30\text{-}3.56$), larger displacements ($F_{(1,\ 15)} = 72.42\text{-}197.49$, $P < 0.001$, $g = 2.03\text{-}3.40$) and longer durations ($F_{(1,\ 15)} = 6.58\text{-}7302.09$, $P = 0.022$ - < 0.001, $g = 0.38\text{-}1.05$) were observed in the jump squat compared to back squat across all five loads when calculated over the propulsion subphase (Figure 2).

Two-way repeated measures ANOVA revealed a statistically significant load × exercise interaction between the two exercises for impulse ($F_{(2.20,\ 32.93)} = 21.20$, $P < 0.001$), with simple main effects indicating larger impulse in the jump squat compared with the back squat across all five loads ($F_{(1,\ 15)} = 102.26\text{-}293.42$, $P = < 0.001$, $g = 1.88\text{-}3.21$) (Figure 2).

The proportion of duration and displacement spent in propulsion subphase in comparison to concentric and descent phases are presented in Table 2. An equal proportion of time and displacement was spent in positive acceleration compared to the concentric phase for both exercises, however, the system center of mass was accelerating over a larger displacement during the jump squat when calculated in relation to total descent.

** Insert Table 2 **

DISCUSSION

This is the first study to examine the kinetics and kinematics of lower-body ballistic (jump squat) and non-ballistic (back squat) exercises performed across incremental loads (0, 30-60% 1RM) and calculated over different movement phases (concentric vs. propulsion). The main findings of this research were that the jump squat exhibited significantly larger mechanical demands than the back squat, irrespective of the phase of interest; and that the proportion of time and displacement spent in the propulsion sub-phase with respect to the concentric phase were comparable across the two exercises, but that a larger propulsion displacement was performed in the jump squat when compared to descent displacement, meaning the propulsion phase in the jump squat occurred over a larger range of motion.

Significantly larger force, impulse, power, work, displacement, higher velocities and longer durations were observed in the jump squat compared to the back squat across all five loads (Figure 2), regardless of the phase of interest (propulsion vs. concentric). Our data, in part, agrees with the limited available data comparing ballistic and non-ballistic squat-based exercise (6,23,35). Significantly more power (6,35), higher velocities (6,23,35), larger forces (35) and displacements (35) have previously been reported across multiple loads (0-85% 1RM) in the free-weight jump squat compared to the back squat when calculated over the full concentric phase (8). As ballistic exercise is accelerative, of high velocity and culminates in the projection of the body, system or projectile into free space, there is a reduced requirement to perform negative acceleration at the end of the concentric phase in comparison to non-ballistic exercise (14). Further, this period of negative acceleration has been reported to contribute from 21.9-47.7% of the concentric phase when performed across incremental loads (15-90% 1RM) in the free-weight bench press (15,23). This sub-phase, therefore, has been offered as a reason for non-ballistic exercises having limited application when performed with maximal intent under submaximal loading, particularly for the purpose of increasing force, velocity, power or impulse (6,31).

This sub-phase of negative acceleration is of practical relevance to the S&C practitioner. Typically, incremental protocols such as load- and force-velocity profiling begin with light to moderate loads (0-60% 1RM) in non-ballistic exercises (e.g., back squat, deadlift, bench press), with metrics calculated across the full concentric phase (34,39). Our data, however, demonstrates that force-velocity characteristics are significantly lower during non-ballistic exercise when compared with ballistic, and therefore underestimating an individual's maximal capabilities. Therefore, researchers and practitioners should incorporate ballistic equivalents (e.g., jump squat, trap-bar jumps, bench press throw) when performing loads < 60% 1RM during athlete testing and profiling (force- and load-velocity) to ensure a valid assessment of mechanical capabilities.

Researchers have suggested that the demands of biomechanically similar non-ballistic and ballistic exercises are more comparable when the kinetics and kinematics are calculated over only the propulsion phase and therefore removing the impact of any negative acceleration (15,23). Our data refutes this notion as the jump squat exhibited significantly greater mechanical demands in all output and driver metrics (power, velocity (30-60% 1RM), impulse, force and work), irrespective of the phase of interest, with moderate to very large standardized mean effects observed for all propulsion metrics (Figure 2). Despite the proposed underestimation of non-ballistic kinetics and kinematics when calculated across the full concentric phase (15,23), the system still accelerates over a significantly larger displacement and longer duration when a movement ends in a point of projection, directly influencing driver and output metrics based on Newtonian laws ($F = ma$). This therefore supports the inclusion of ballistic-type exercises to target specific neuromuscular adaptations at appropriate times of a periodized cycle.

Our data highlighted significantly longer periods of acceleration and larger displacements in the jump squat vs. back squat across all loads (figure 2), corroborating earlier findings in upper and lower body exercises (15,23,31). In contrast to previous literature that reported significantly longer periods of acceleration in the bench throw vs. bench press (15-60% 1RM) (15), comparable displacements and durations were observed in our study when considering the propulsion sub-phase as a proportion of the concentric phase (Table 2). However, when comparing propulsion displacement to total descent displacement, the jump squat was noticeably higher (> 100%) (Table 2). Similarly, significantly more propulsion work in the jump squat was evident, indicating ballistic training with light to moderate loads promotes a larger range of motion of positive acceleration, potentially eliciting adaptations across a longer length-tension relationship.

It is important to consider mechanical principia when understanding the underpinnings of human movement. Impulse was significantly greater in the jump squat exercises across all loads, which is a direct result of significantly greater forces being produced over significantly longer durations (figure 2). Change in momentum (mass × velocity) is directly proportional to impulse, meaning larger forces and longer acceleration results in higher velocities. Similarly, significantly greater power outputs were evident in the jump squat due to significantly greater work (power = work / Δ time; work = force x displacement). The interaction between these variables, therefore, provide insight into the demands of certain exercises. Whilst typically force, velocity and power seem to be the most sought-after metrics (8,41), coaches, practitioners and researchers should also consider the underpinning mechanics to understand the strategies and drivers of human movement.

Understanding the mechanics of human movement is important when creating training interventions. Output variables such as power, velocity and impulse can be effective feedback for athletes, however, are often dictated by specific strategies and drivers. For example, impulse could be of use to a coach, however, understanding how impulse is derived and/or changes from session-to-session or exercise-to-exercise is more useful. An increase in force produced (driver), or duration of force application (strategy) can both increase impulse (Δ force × Δ time). Maximizing force production in the shortest duration possible is therefore thought to be one of the most effective strategies for improving sport performance, suggesting practitioners should select the most appropriate output, driver and strategy metrics to provide a detailed and nuanced overview of how individuals perform tasks and improve following training interventions.

Although our research provides an in-depth and unique comparison of ballistic and non-ballistic lower-body exercise, it is not without its limitations. Specifically, not including any loads > 60% 1RM limits the application and interpretation of our data across the full load spectrum. Previous research has observed greater performance (e.g., strength and sprinting) and mechanical (e.g., power and force) improvements from heavy strength training, compared to lower-load ballistic training (5,7,16). And whilst this study did not assess chronic adaptations, a comparison between light and heavy loads in both exercises would provide a greater level of detail for practitioners to make appropriate decisions and should therefore be an avenue for future research. Secondly, this study did not consider the impact of the eccentric or descent strategy on subsequent kinetics and kinematics of the propulsion and concentric phases. For example, if an athlete were to apply a longer unweighting phase during the ballistic movement, this would determine the rate and magnitude of the force required during the braking phase and would likely influence the resultant impact of the stretch-shortening cycle on propulsion variables (29). Despite an attempt to standardize the descent phase of both lifts, without numerical data to support this, understanding the impact is difficult and therefore warrants further investigation.

PRACTICAL APPLICATIONS

S&C coaches should look to optimize mechanical output throughout a periodized plan via appropriate exercise choice. The most effective way to maximize power, impulse and RFD is through the combination of training modalities across the full force-velocity spectrum, however, when focusing on specific ‘power’ training blocks, loaded ballistic exercises (0-60% 1RM) should be utilized over non-ballistic exercises of comparable loads. However, this approach could still be ‘contrasted’ with heavy load exercises (> 80% 1RM) to ensure maximal force production does not decrease. Practitioners would therefore need to select these exercises at appropriate times of a competitive season (e.g., away from fixture congestion) to minimize any unwanted impact of landing. Furthermore, given the greater mechanical outputs observed in the jump squat, it seems logical to replace the lighter and moderate loads in profiling type activities with their ballistic equivalents to provide a valid reflection of an individual’s force-velocity capabilities. Finally, when collecting and analyzing force kinetic and kinematic data, practitioners should utilize metrics that detail an athlete’s strategy (e.g., duration and displacement) to a task and the mechanical drivers (e.g., force and work) of said task in addition to the more popular feedback or output variables (e.g., power, velocity and impulse).

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REFERENCES

1. Andersen, LL and Aagaard, P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology* 96: 46–52, 2006.
2. Banyard, HG, Nosaka, K, and Haff, GG. Reliability and Validity of the Load-Velocity Relationship to Predict the 1RM Back Squat. *Journal of Strength and Conditioning Research* 31: 1897–1904, 2017.
3. Bird, SP, Tarpenning, KM, and Marino, FE. Designing resistance training programmes to enhance muscular fitness: A review of the acute programme variables. *Sports Medicine* 35: 841–851, 2005.
4. Brandon, R, Howatson, G, Strachan, F, and Hunter, AM. Neuromuscular response differences to power vs strength back squat exercise in elite athletes. *Scandinavian Journal of Medicine and Science in Sports* 25: 630–639, 2015.
5. Cormie, P, McCaulley, GO, and McBride, JM. Power versus strength-power jump squat training: Influence on the load-power relationship. *Medicine and Science in Sports and Exercise* 39: 996–1003, 2007.
6. Cormie, P, Mccaulley, GO, Triplett, NT, and Mcbride, JM. Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports and Exercise* 39: 340–349, 2007.
7. Cormie, P, McGuigan, MR, and Newton, RU. Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise* 42: 1582–1598, 2010.
8. Cormie, P, McGuigan, MR, and Newton, RU. Developing maximal neuromuscular power: Part 2 training considerations for improving maximal power production. *Sports Medicine* 41: 125–146, 2011.

9. Cronin, JB, McNair, PJ, and Marshall, RN. The role of maximal strength and load on initial power production. *Medicine and Science in Sports and Exercise* 32: 1763–1769, 2000.

10. Cronin, JB, McNair, PJ, and Marshall, RN. Force-velocity analysis of strength-training techniques and load: Implications for training strategy and research. *Journal of Strength and Conditioning Research* 17: 148–155, 2003.

11. Elliott, BC, Wilson, GJ, and Kerr, GK. A biomechanical analysis of the sticking region in the bench press. *Medicine and Science in Sports and Exercise* 21: 450–462, 1989.

12. Fox, JL, Stanton, R, Sargent, C, O’Grady, CJ, and Scanlan, AT. The impact of contextual factors on game demands in starting, semiprofessional, male basketball players. *International Journal of Sports Physiology and Performance* 15: 450–456, 2020.

13. Fritz, J, Stallegger, J, Fessl, I, Schwameder, H, and Kröll, J. Jumping with barbell load: Assessment of lower limb joint kinematics and kinetics during landing. *Journal of Biomechanics* 120, 2021.

14. Frost, DM, Cronin, J, and Newton, RU. A biomechanical evaluation of resistance: Fundamental concepts for training and sports performance. Sports Medicine. 40: 303–326, 2010.

15. Frost, DM, Cronin, JB, and Newton, RU. Have we underestimated the kinematic and kinetic benefits of non-ballistic motion? *Sports Biomechanics* 7: 372–385, 2008.

16. Harris, NK, Cronin, JB, Hopkins, WG, and Hansen, KT. Squat jump training at maximal power loads vs. heavy loads: Effect on sprint ability. *Journal of Strength and Conditioning Research* 22: 1742–1749, 2008.

17. Hoffman, JR, Ratamess, NA, Cooper, JJ, Kang, J, Chilakos, A, and Faigenbaum, AD. Comparison of loaded and unloaded jump squat training on strength/power performance in college football players. *Journal of Strength and Conditioning Research* 19: 810–815, 2005.

18. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. Medicine and Science in Sports and Exercise. 41: 3–12, 2009.

19. Jones, J V., Pyne, DB, Haff, GG, and Newton, RU. Comparison of ballistic and strength training on swimming turn and dry-land leg extensor characteristics in elite swimmers. *International Journal of Sports Science and Coaching* 13: 262–269, 2018.

20. Knudson, D V. Correcting the use of the term “power” in the strength and conditioning literature. Journal of Strength and Conditioning Research. 23: 1902–1908, 2009.

21. Koo, TK and Li, MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine* 15, 2016.

22. Kraemer, WJ and Ratamess, NA. Fundamentals of Resistance Training: Progression and Exercise Prescription. Medicine and Science in Sports and Exercise. 36: 674–688, 2004.

23. Lake, J, Lauder, M, Smith, N, and Shorter, K. A comparison of ballistic and nonballistic lower-body resistance exercise and the methods used to identify their positive lifting phases. *Journal of Applied Biomechanics* 28: 431–437, 2012.

24. Lake, JP, Mundy, PD, and Comfort, P. Power and impulse applied during push press exercise. *Journal of Strength and Conditioning Research* 28: 2552–2559, 2014.

25. Lake, JP, Mundy, PD, Comfort, P, McMahon, JJ, Suchomel, TJ, and Carden, P. Effect of barbell load on vertical jump landing force-time characteristics. *Journal of Strength and conditioning research* 35: 25–32, 2021.

26. Loturco, I, Pereira, LA, Kobal, R, and McGuigan, MR. Power output in traditional and ballistic bench press in elite athletes: Influence of training background. *Journal of Sports Sciences* 37: 277–284, 2019.

27. Lynn, SK and Noffal, GJ. Lower extremity biomechanics during a regular and counterbalanced squat. *Journal of Strength and Conditioning Research* 26: 2417–2425, 2012.

28. McBride, JM, Nimphius, S, and Erickson, TM. The acute effects of heavy-load squats and loaded countermovement jumps on sprint performance. *Journal of Strength and Conditioning Research* 19: 893–897, 2005.

29. McMahon, JJ, Suchomel, TJ, Lake, JP, and Comfort, P. Understanding the key phases of the countermovement jump force-time curve. *Strength and Conditioning Journal* 40: 96–106, 2018.

30. Mundy, PD, Smith, NA, Lauder, MA, and Lake, JP. The effects of barbell load on countermovement vertical jump power and net impulse. *Journal of Sports Sciences* 35: 1781–1787, 2017.

31. Newton, RU, Kraemer, WJ, Häkkinen, K, Humphries, BJ, and Murphy, AJ. Kinematics, kinetics, and muscle activation during explosive upper body movements. *Journal of Applied Biomechanics* 12: 31–43, 1996.

32. Owen, NJ, Watkins, J, Kilduff, LP, Bevan, HR, and Bennett, MA. Development of a criterion method to determine peak mechanical power output in a countermovement jump. *Journal of Strength and Conditioning Research* 28: 1552–1558, 2014.

33. Ransdell, LB, Murray, T, Gao, Y, Jones, P, and Bycura, D. A 4-Year Profile of Game Demands in Elite Women's Division I College Basketball. *Journal of strength and conditioning research* 34: 632–638, 2020.

34. Rivière, JR, Rossi, J, Jimenez-Reyes, P, Morin, JB, and Samozino, P. Where does the One-Repetition Maximum Exist on the Force-Velocity Relationship in Squat? *International Journal of Sports Medicine* 38: 1035–1043, 2017.

35. Rossetti, ML, Munford, SN, Snyder, BW, Davis, SE, and Moir, GL. The Effects of Multiple Sets of Squats and Jump Squats on Mechanical Variables. *Journal of strength and conditioning research* 34: 1017–1023, 2020.

36. Sánchez-Medina, L, González-Badillo, JJ, Pérez, CE, and Pallarés, JG. Velocity- and power-load relationships of the bench pull vs Bench press exercises. *International Journal of Sports Medicine* 35: 209–216, 2014.

37. Suchomel, TJ, Nimphius, S, and Stone, MH. The Importance of Muscular Strength in Athletic Performance. Sports Medicine. 46: 1419–1449, 2016.

38. Thompson, S, Rogerson, D, Dorrell, H, Ruddock, A, and Barnes, A. The Reliability and Validity of Current Technologies for Measuring Barbell Velocity in the Free-Weight Back Squat and Power Clean. *Sports* 8: 94, 2020.

39. Thompson, SW, Rogerson, D, Ruddock, A, Banyard, HG, and Barnes, A. Pooled Versus Individualized Load–Velocity Profiling in the Free-Weight Back Squat and Power Clean. *International journal of sports physiology and performance* 16: 825–833, 2021.Available from: https://doi.org/10.1123/ijspp.2020-0534.

40. Tricoli, V, Lamas, L, Carnevale, R, and Ugrinowitsch, C. Short-term effects on lower-body functional power development: Weightlifting vs. vertical jump training programs. *Journal of Strength and Conditioning Research* 19: 433–437, 2005.

41. Turner, AN, Comfort, P, McMahon, J, Bishop, C, Chavda, S, Read, P, et al. Developing powerful athletes, part 1: Mechanical underpinnings. *Strength & Conditioning Journal* 42: 30–39, 2020.

42. De Villarreal, ESS, Izquierdo, M, and Gonzalez-Badillo, JJ. Enhancing jump performance after combined vs. maximal power, heavy-resistance, and plyometric training alone. *Journal of Strength and Conditioning Research* 25: 3274–3281, 2011.

43. Wilson, GJ, Murphy, AJ, and Walshe, AD. Performance benefits from weight and plyometric training: effects of initial strength level. *Coaching & Sport Science Journal* 2: 3–8, 1997.

44. Winter, EM, Abt, G, Brookes, FBC, Challis, JH, Fowler, NE, Knudson, D V., et al. Misuse of “power” and other mechanical terms in sport and exercise science research. Journal of Strength and Conditioning Research. 30: 292–300, 2016.

45. Winter, EM and Fowler, N. Exercise defined and quantified according to the Système International d’Unités. Journal of Sports Sciences. 27: 447–460, 2009.

Table 1. Definitions, Système Internationale (SI) units and calculation methods for all dependent variables from the concentric and propulsion phases.

Dependent Variable (SI Unit)	**Calculation**
Force (N)	Average of raw vertical ground reaction force data
Velocity (m.s^{-1})	Integrated acceleration data with respect to time (acceleration = net force / body mass (system mass for loaded trials) Mean: Average of velocity data
Impulse (N.s)	Mean net force: Average of force less body weight (system weight for loaded trials) Integrated mean net force with respect to time
Power (W)	Force x velocity
Duration (s)	Timepoint at phase end – timepoint at phase start
Displacement (m)	Velocity x change in time Change in position (end position – start position)
Work (J)	Power x time

All integration occurred via the trapezium method (24)

Table 2. Duration and displacement propulsion-concentric and propulsion-descent ratios calculate as a percentage (%).

Load (% 1RM)	Exercise	Duration Propulsive-Concentric ratio (%)	Displacement Propulsive-Concentric ratio (%)	Displacement Propulsive-Descent ratio (%)
0	Back Squat	54.8 ± 5.6	56.1 ± 6.0	64.7 ± 9.3
	Jump Squat	53.4 ± 3.6	54.0 ± 3.3	105.3 ± 3.1
30	Back Squat	67.8 ± 3.7	69.3 ± 3.8	81.4 ± 8.1
	Jump Squat	68.7 ± 1.8	68.6 ± 2.0	104.3 ± 5.8
40	Back Squat	72.5 ± 2.3	73.5 ± 2.9	85.1 ± 7.0
	Jump Squat	72.7 ± 1.7	72.3 ± 2.2	102.8 ± 2.0
50	Back Squat	76.6 ± 1.9	76.6 ± 2.5	86.2 ± 10.0
	Jump Squat	76.9 ± 1.3	75.2 ± 1.9	105.9 ± 5.1
60	Back Squat	80.4 ± 2.4	79.2 ± 2.5	91.0 ± 6.8
	Jump Squat	80.6 ± 1.3	77.5 ± 2.0	103.4 ± 2.6

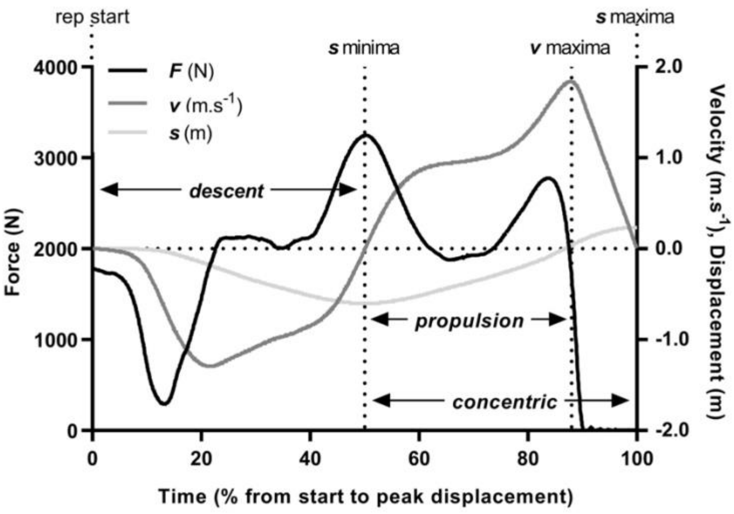
1RM 1 repetition maximum

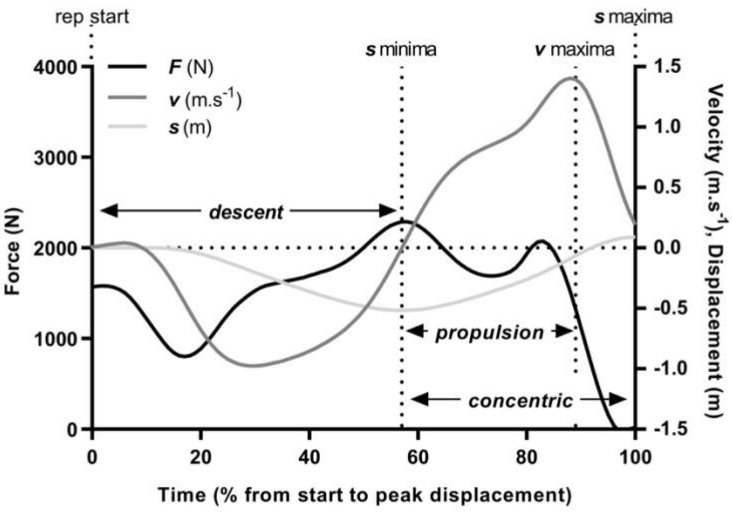
Figure 1. Example calculation methods for the determination of descent (negative displacement, positive and negative acceleration phase), concentric (positive displacement, positive and negative acceleration phase) and propulsion (positive displacement, positive acceleration) phases. Left figure = jump squat, right figure = back squat.

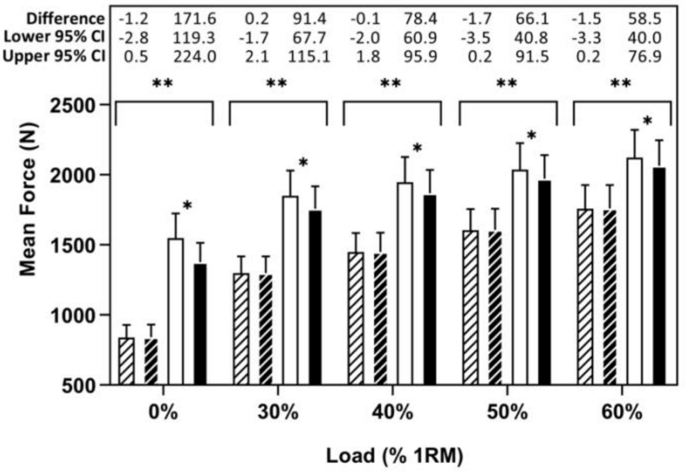
F, Force; *v*, velocity; *s*, displacement

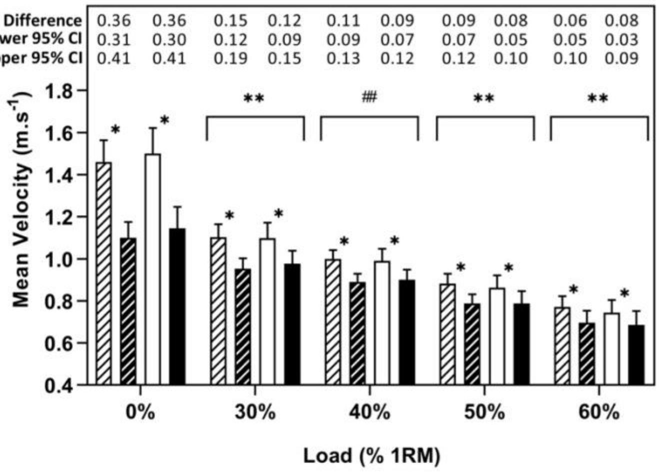
Figure 2. Means and SDs (error bars) for force, velocity, power, work, displacement, duration and impulse across the five loads. White bars = jump squat data, black bars = back squat data. Striped bars = concentric phase, solid bars = propulsion phase. Data above demonstrates mean differences and 95% confidence limits between the jump squat – back squat.

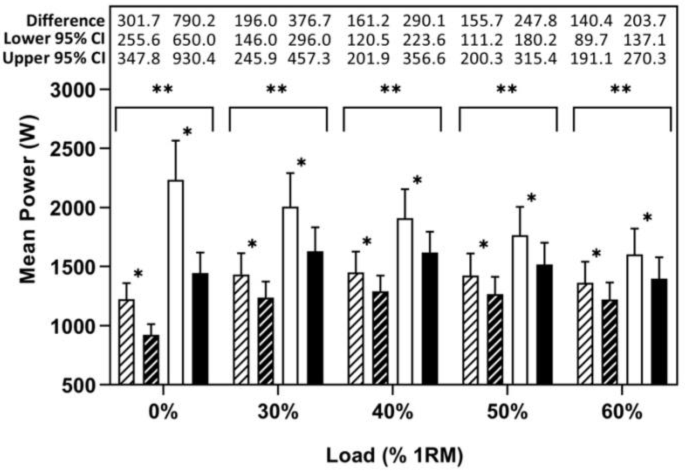
** indicates phase × exercise interactions ($P < 0.001$); $^{\#\#}$ indicates phase × exercise interactions ($P < 0.05$); * indicates significant main effect ($P < 0.001$).

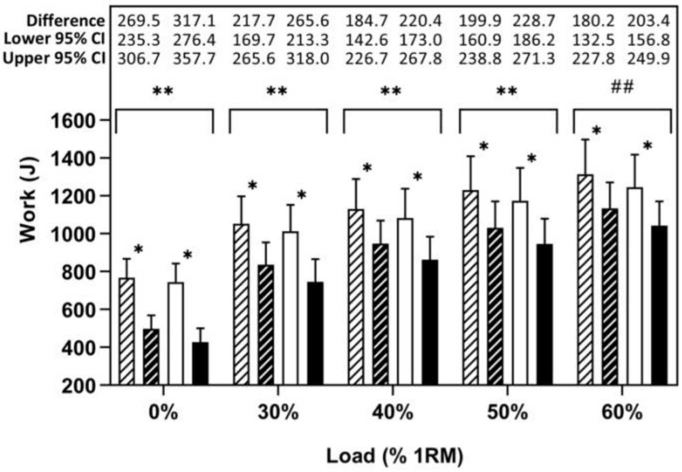

rep start
s minima
v maxima
s maxima
F (N)
v (m.s^{-1})
s (m)
descent
propulsion
concentric
Force (N)
4000
3000
2000
1000
0
Velocity (m.s^{-1}), Displacement (m)
2.0
1.0
0.0
-1.0
-2.0
0
20
40
60
80
100
Time (% from start to peak displacement)

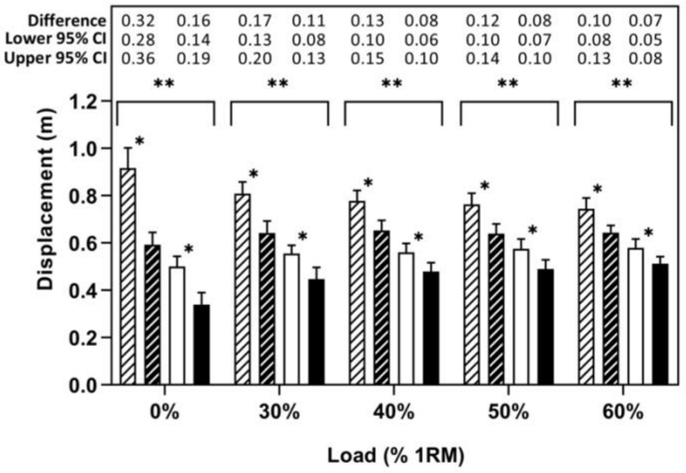

rep start
s minima
v maxima
s maxima
F (N)
v (m.s^{-1})
s (m)
descent
propulsion
concentric
Force (N)
4000
3000
2000
1000
0
Velocity (m.s^{-1}), Displacement (m)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
20
40
60
80
100
Time (% from start to peak displacement)

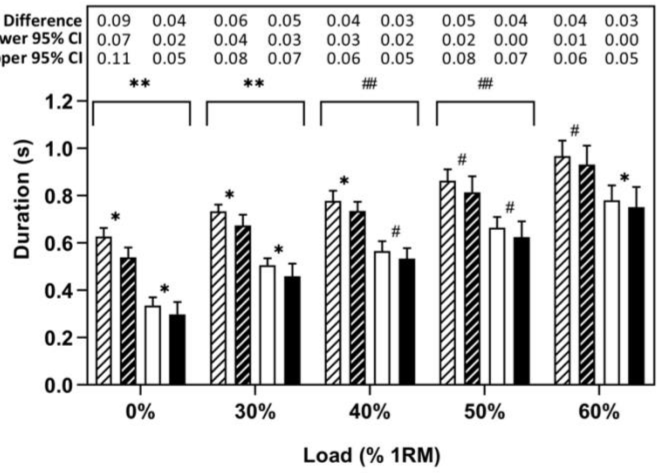

Difference -1.2 171.6 0.2 91.4 -0.1 78.4 -1.7 66.1 -1.5 58.5
Lower 95% CI -2.8 119.3 -1.7 67.7 -2.0 60.9 -3.5 40.8 -3.3 40.0
Upper 95% CI 0.5 224.0 2.1 115.1 1.8 95.9 0.2 91.5 0.2 76.9
**
Mean Force (N)
2500
2000
1500
1000
500
*
0%
30%
40%
50%
60%
Load (% 1RM)

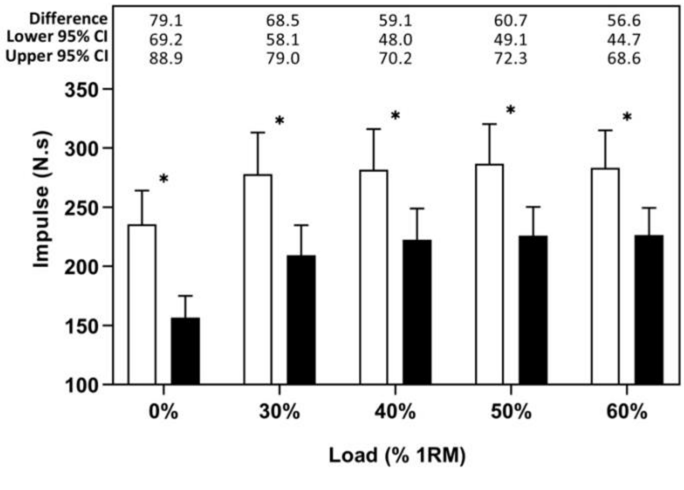

Difference 0.36 0.36 0.15 0.12 0.11 0.09 0.09 0.08 0.06 0.08
Lower 95% CI 0.31 0.30 0.12 0.09 0.09 0.07 0.07 0.05 0.05 0.03
Upper 95% CI 0.41 0.41 0.19 0.15 0.13 0.12 0.12 0.10 0.10 0.09
**
##
Mean Velocity (m.s-1)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
*
0%
30%
40%
50%
60%
Load (% 1RM)


Difference 301.7 790.2 196.0 376.7 161.2 290.1 155.7 247.8 140.4 203.7
Lower 95% CI 255.6 650.0 146.0 296.0 120.5 223.6 111.2 180.2 89.7 137.1
Upper 95% CI 347.8 930.4 245.9 457.3 201.9 356.6 200.3 315.4 191.1 270.3
**
Mean Power (W)
3000
2500
2000
1500
1000
500
*
0%
30%
40%
50%
60%
Load (% 1RM)


Difference 269.5 317.1 217.7 265.6 184.7 220.4 199.9 228.7 180.2 203.4
Lower 95% CI 235.3 276.4 169.7 213.3 142.6 173.0 160.9 186.2 132.5 156.8
Upper 95% CI 306.7 357.7 265.6 318.0 226.7 267.8 238.8 271.3 227.8 249.9
**
##
Work (J)
1600
1400
1200
1000
800
600
400
200
*
0%
30%
40%
50%
60%
Load (% 1RM)


Difference 0.32 0.16 0.17 0.11 0.13 0.08 0.12 0.08 0.10 0.07
Lower 95% CI 0.28 0.14 0.13 0.08 0.10 0.06 0.10 0.07 0.08 0.05
Upper 95% CI 0.36 0.19 0.20 0.13 0.15 0.10 0.14 0.10 0.13 0.08
**
Displacement (m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
*
0%
30%
40%
50%
60%
Load (% 1RM)


Difference 0.09 0.04 0.06 0.05 0.04 0.03 0.05 0.04 0.04 0.03
Lower 95% CI 0.07 0.02 0.04 0.03 0.03 0.02 0.02 0.00 0.01 0.00
Upper 95% CI 0.11 0.05 0.08 0.07 0.06 0.05 0.08 0.07 0.06 0.05
**
##
Duration (s)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
*
#
0%
30%
40%
50%
60%
Load (% 1RM)


Difference 79.1 68.5 59.1 60.7 56.6
Lower 95% CI 69.2 58.1 48.0 49.1 44.7
Upper 95% CI 88.9 79.0 70.2 72.3 68.6
Impulse (N.s)
350
300
250
200
150
100
*
0%
30%
40%
50%
60%
Load (% 1RM)

SUPPLEMENTARY TABLES

S1. Coefficient of Variation (95% Confidence Intervals) for all dependent variables.

Exercise	Load (% 1RM)	Mean Concentric Force	Mean Propulsion Force	Mean Concentric Velocity	Mean Propulsion Velocity	Mean Concentric Power	Mean Propulsion Power	Concentric Work	Propulsion Work	Mean Net Impulse
Back squat	0%	0.1 (0.1, 0.2)	3.0 (2.2, 4.6)	2.2 (1.6, 3.4)	3.1 (2.3, 4.9)	2.1 (1.6, 3.3)	2.7 (2.0, 4.2)	3.4 (2.5, 5.3)	5.0 (3.7, 7.9)	3.1 (2.3, 4.8)
	30%	0.1 (0.1, 0.2)	4.3 (3.1, 6.7)	1.9 (1.4, 2.9)	2.0 (1.5, 3.1)	1.8 (1.3, 2.8)	2.7 (2.0, 4.2)	2.1 (1.5, 3.2)	2.5 (1.9, 4.0)	2.0 (1.4, 3.1)
	40%	0.1 (0.1, 0.2)	3.2 (2.3, 4.9)	1.6 (1.1, 2.4)	2.2 (1.7, 3.5)	1.5 (1.1, 2.4)	2.4 (1.8, 3.7)	2.0 (1.5, 3.1)	2.4 (1.8, 3.7)	2.2 (1.7, 3.5)
	50%	0.1 (0.1, 0.2)	3.2 (2.4, 5.0)	2.6 (1.9, 4.0)	3.3 (2.4, 5.2)	2.6 (1.9, 4.0)	3.4 (2.5, 5.3)	3.5 (2.6, 5.4)	3.8 (2.8, 6.0)	3.2 (2.4, 5.0)
	60%	0.1 (0.0, 0.1)	3.9 (2.8, 6.2)	3.6 (2.6, 5.7)	3.3 (2.4, 6.7)	3.6 (2.6, 5.7)	4.3 (3.1, 7.2)	2.8 (2.1, 4.5)	3.2 (2.3, 5.2)	3.2 (2.3, 5.1)
Squat Jump	0%	0.2 (0.1, 0.3)	2.9 (2.1, 4.5)	2.3 (1.7, 3.6)	2.2 (1.6, 3.4)	2.2 (1.6, 3.5)	4.0 (2.9, 6.2)	3.4 (2.0, 4.2)	5.0 (2.1, 4.4)	2.0 (1.5, 3.1)
	30%	0.2 (0.1, 0.3)	2.3 (1.7, 3.5)	1.5 (1.1, 2.4)	1.1 (0.8, 1.7)	1.5 (1.1, 2.3)	1.8 (1.4, 2.9)	2.2 (1.6, 3.4)	2.2 (1.6, 3.4)	1.0 (0.8, 1.6)
	40%	0.1 (0.1, 0.2)	2.9 (2.1, 4.5)	1.8 (1.3, 2.8)	1.6 (1.2, 2.5)	2.7 (2.0, 4.2)	3.8 (2.8, 5.9)	1.7 (1.3, 2.6)	1.7 (1.2, 2.6)	1.1 (0.8, 1.6)
	50%	0.2 (0.1, 0.2)	3.6 (2.7, 5.6)	2.3 (1.7, 3.5)	2.2 (1.6, 3.4)	2.3 (1.7, 3.5)	3.0 (2.2, 4.6)	2.8 (2.1, 4.3)	2.9 (2.1, 4.5)	2.0 (1.5, 3.2)
	60%	0.1 (0.1, 0.2)	3.2 (2.4, 5.0)	3.5 (2.6, 5.4)	2.5 (1.8, 3.9)	3.4 (2.5, 5.3)	4.2 (3.1, 6.6)	3.4 (2.5, 5.3)	3.3 (2.4, 5.1)	2.1 (1.6, 3.3)

Exercise	Load (% 1RM)	Concentric Duration	Propulsion Duration	Concentric Displacement	Propulsion Displacement
Back squat	0%	2.1 (1.6, 3.3)	4.3 (3.1, 6.7)	3.4 (2.5, 5.3)	1.9 (1.4, 2.9)
	30%	1.6 (1.2, 2.5)	3.4 (2.5, 5.3)	2.1 (1.5, 3.3)	2.6 (1.9, 4.1)
	40%	1.3 (1.0, 2.0)	2.3 (1.7, 3.5)	2.0 (1.5, 3.1)	1.8 (1.3, 2.8)
	50%	3.3 (2.4, 5.1)	3.9 (2.9, 6.2)	3.5 (2.6, 5.5)	3.8 (2.8, 6.0)
	60%	2.8 (2.0, 4.4)	3.6 (2.6, 5.7)	3.8 (2.7, 6.0)	3.8 (2.7, 7.8)
Squat Jump	0%	1.4 (1.0, 2.2)	2.8 (2.1, 4.4)	2.8 (2.1, 4.4)	2.4 (1.7, 3.7)
	30%	1.6 (1.2, 2.6)	2.3 (1.7, 3.5)	2.2 (1.6, 3.5)	1.5 (1.1, 2.3)
	40%	2.9 (2.1, 4.5)	4.1 (3.0, 6.4)	1.7 (1.3, 2.7)	2.1 (1.5, 3.2)
	50%	3.0 (2.2, 4.7)	3.7 (2.7, 5.8)	2.9 (2.1, 4.5)	3.0 (2.2, 4.6)
	60%	3.7 (2.7, 5.9)	4.6 (3.3, 7.3)	3.5 (2.5, 5.4)	3.2 (2.4, 5.1)

1RM 1 repetition maximum

S2. Intraclass Correlation Coefficient (95% confidence intervals) for all dependent variables.

Exercise	Load (% 1RM)	Mean Concentric Force	Mean Propulsion Force	Mean Concentric Velocity	Mean Propulsion Velocity	Mean Concentric Power	Mean Propulsion Power	Concentric Work	Propulsion Work	Mean Net Impulse
Back squat	0%	1.00 (1.00, 1.00)	0.97 (0.93, 0.99)	0.93 (0.81, 0.97)	0.87 (0.68, 0.95)	0.97 (0.91, 0.99)	0.96 (0.89, 0.99)	0.96 (0.88, 0.98)	0.92 (0.79, 0.97)	0.94 (0.83, 0.98)
	30%	1.00 (1.00, 1.00)	0.95 (0.87, 0.98)	0.92 (0.78, 0.97)	0.94 (0.84, 0.98)	0.98 (0.95, 0.99)	0.96 (0.90, 0.99)	0.98 (0.95, 0.99)	0.98 (0.94, 0.99)	0.98 (0.94, 0.99)
	40%	1.00 (1.00, 1.00)	0.96 (0.88, 0.98)	0.92 (0.79, 0.97)	0.94 (0.83, 0.98)	0.98 (0.95, 0.99)	0.96 (0.88, 0.98)	0.98 (0.95, 0.99)	0.98 (0.94, 0.99)	0.97 (0.90, 0.99)
	50%	1.00 (1.00, 1.00)	0.93 (0.81, 0.97)	0.88 (0.68, 0.95)	0.87 (0.68, 0.95)	0.96 (0.89, 0.99)	0.94 (0.84, 0.98)	0.94 (0.84, 0.98)	0.94 (0.82, 0.98)	0.93 (0.81, 0.98)
	60%	1.00 (1.00, 1.00)	0.95 (0.86, 0.98)	0.83 (0.56, 0.94)	0.86 (0.64, 0.95)	0.94 (0.82, 0.98)	0.92 (0.78, 0.97)	0.97 (0.90, 0.99)	0.96 (0.88, 0.99)	0.94 (0.83, 0.98)
Squat Jump	0%	1.00 (1.00, 1.00)	0.97 (0.90, 0.99)	0.91 (0.77, 0.97)	0.94 (0.84, 0.98)	0.96 (0.90, 0.99)	0.93 (0.82, 0.98)	0.96 (0.90, 0.99)	0.92 (0.89, 0.99)	0.98 (0.93, 0.99)
	30%	1.00 (1.00, 1.00)	0.98 (0.94, 0.99)	0.93 (0.82, 0.98)	0.98 (0.94, 0.99)	0.99 (0.97, 1.00)	0.98 (0.96, 0.99)	0.98 (0.95, 0.99)	0.98 (0.95, 0.99)	0.99 (0.98, 1.00)
	40%	1.00 (1.00, 1.00)	0.97 (0.90, 0.99)	0.85 (0.63, 0.95)	0.95 (0.87, 0.98)	0.96 (0.88, 0.98)	0.93 (0.80, 0.97)	0.99 (0.97, 1.00)	0.99 (0.97, 1.00)	0.99 (0.98, 1.00)
	50%	1.00 (1.00, 1.00)	0.93 (0.82, 0.98)	0.85 (0.62, 0.95)	0.89 (0.71, 0.96)	0.97 (0.92, 0.99)	0.96 (0.88, 0.98)	0.97 (0.90, 0.99)	0.97 (0.90, 0.99)	0.97 (0.92, 0.99)
	60%	1.00 (1.00, 1.00)	0.93 (0.81, 0.97)	0.73 (0.38, 0.90)	0.86 (0.65, 0.95)	0.93 (0.82, 0.98)	0.91(0.75, 0.97)	0.95 (0.86, 0.98)	0.95 (0.87, 0.98)	0.97 (0.90, 0.99)

Exercise	Load (% 1RM)	Concentric Duration	Propulsion Duration	Concentric Displacement	Propulsion Displacement
Back squat	0%	0.91 (0.77, 0.97)	0.92 (0.79, 0.97)	0.87 (0.66, 0.95)	0.96 (0.90, 0.99)
	30%	0.95 (0.87, 0.98)	0.94 (0.84, 0.98)	0.93 (0.81, 0.98)	0.92 (0.80, 0.97)
	40%	0.96 (0.90, 0.99)	0.96 (0.89, 0.99)	0.92 (0.79, 0.97)	0.97 (0.91, 0.99)
	50%	0.88 (0.69, 0.96)	0.90 (0.74, 0.96)	0.72 (0.37, 0.89)	0.81 (0.53, 0.93)
	60%	0.92 (0.78, 0.97)	0.92 (0.77, 0.97)	0.74 (0.39, 0.91)	0.87 (0.65, 0.95)
Squat Jump	0%	0.95 (0.86, 0.98)	0.95 (0.85, 0.98)	0.92 (0.80, 0.97)	0.95 (0.86, 0.98)
	30%	0.87 (0.67, 0.95)	0.88 (0.69, 0.96)	0.91 (0.76, 0.97)	0.98 (0.93, 0.99)
	40%	0.79 (0.50, 0.92)	0.75 (0.42, 0.91)	0.94 (0.84, 0.98)	0.95 (0.87, 0.98)
	50%	0.80 (0.52, 0.93)	0.80 (0.51, 0.92)	0.84 (0.60, 0.94)	0.91 (0.75, 0.97)
	60%	0.75 (0.40, 0.91)	0.71 (0.33, 0.89)	0.72 (0.36, 0.89)	0.86 (0.65, 0.95)

1RM 1 repetition maximum