

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

THOMPSON, Steve <<http://orcid.org/0000-0001-7674-3685>>, LAKE, Jason, ROGERSON, David <<http://orcid.org/0000-0002-4799-9865>>, RUDDOCK, Alan <<http://orcid.org/0000-0002-7001-9845>> and BARNES, Andrew <<http://orcid.org/0000-0001-8262-5132>>

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

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4 **Steve W. Thompson<sup>1</sup>, Jason P. Lake<sup>2</sup>, David Rogerson<sup>1</sup>, Alan Ruddock<sup>1</sup>, Andrew Barnes<sup>1</sup>**

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6  
7 <sup>1</sup>Academy for Sport and Physical Activity, Sheffield Hallam University, Sheffield, United  
8 Kingdom

9 <sup>2</sup> Department of Sport and Exercise Sciences, Chichester University, Chichester, United  
10 Kingdom

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33  
34 Corresponding Author:  
35 Steve W. Thompson  
36 s.w.thompson@shu.ac.uk  
37 +44 1142252465

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42 **Running Head:** Kinetics and kinematics of back squat and jump squat

43  
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45 **ABSTRACT**

46 The study aim was to compare kinetics and kinematics of two, lower-body free-weight exercises,  
47 calculated from concentric and propulsion sub-phases, across multiple loads. Sixteen strength trained  
48 men performed back squat one-repetition maximum tests (1RM) (visit 1), followed by two incremental  
49 back squat and jump squat protocols (visit 2) (loads = 0% and 30-60%, back squat 1RM). Concentric  
50 and propulsion phase force-time-displacement characteristics were derived from force-plate-data and  
51 compared via analysis of variance and Hedges *g* effect sizes. Intra-session reliability was calculated via  
52 intraclass correlation coefficient (ICC) and coefficient of variation (CV). All dependent variables met  
53 acceptable reliability (ICC > 0.7; CV < 10%). Statistically significant three-way interactions (load × phase  
54 × exercise) and two-way main effects (phase × exercise) were observed for mean force, velocity (30-  
55 60% 1RM), power, work, displacement, and duration (0%, 30-50% 1RM) (*p* < 0.05). A significant two-  
56 way interaction (load × exercise) was observed for impulse (*p* < 0.001). Jump squat velocity (*g* = 0.94-  
57 3.80), impulse (*g* = 1.98-3.21), power (*g* = 0.84-2.93) and work (*g* = 1.09-3.56) were significantly larger  
58 across concentric and propulsion phases, as well as mean propulsion force (*g* = 0.30-1.06) performed  
59 over all loads (*p* < 0.001). No statistically significant differences were observed for mean concentric  
60 force. Statistically longer durations (*g* = 0.38-1.54) and larger displacements (*g* = 2.03-4.40) were  
61 evident for all loads and both sub-phases (*p* < 0.05). Ballistic, lower-body exercise produces greater  
62 kinetic and kinematic outputs than non-ballistic equivalents, irrespective of phase determination.  
63 Practitioners should therefore utilize ballistic methods when prescribing or testing lower-body  
64 exercises to maximize athlete's force-time-displacement characteristics.

65

66

67 **KEY WORDS**

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

## 70 INTRODUCTION

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

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

90 S&C practitioners utilize a variety of methods to develop underpinning mechanical qualities such as  
91 power, impulse, force and velocity, however literature comparing these strategies is somewhat  
92 limited (7,16,17,19,28,40). Increases in power have been observed from heavy strength training (e.g.,  
93 > 80% one repetition maximum (1RM)) through physiological adaptations (e.g., increases in motor  
94 unit recruitment and intramuscular co-ordination) that influence the force end of the force-velocity

95 curve (5,7,16,37). Nevertheless, these are often more effective with untrained or weaker athletes, or  
96 during the initial stages of a periodized programme (8,43). Further power development, therefore,  
97 typically requires the inclusion of additional lighter (e.g., 30-60% (1RM), more mechanically specific  
98 training methods that optimize movement velocity as dictated by the force-velocity-power  
99 relationship (9,10,27). In practice, methods to implement these faster velocity-type adaptations  
100 usually include ballistic (e.g., jump squat) or explosive non-ballistic (e.g., 'speed' back squat) exercises,  
101 with the main biomechanical difference being the projection of the body, system or object into free  
102 space during the ballistic task (14). However, comparisons of the underpinning mechanical demands  
103 of both training strategies are limited yet are vital for practitioners to make informed programming  
104 decisions.

105 Performing non-ballistic exercise with maximal intent at loads that optimize the trade-off between  
106 force and velocity (e.g., 30-60% 1RM) has been suggested as an appropriate strategy for inducing  
107 adaptations that underpin power and rate of force development (RFD) (4,6,42). However, inherent  
108 within non-ballistic exercise is a period of negative acceleration, commonly referred to as the  
109 '*deceleration sub-phase*' (velocity maxima to displacement maxima). The contribution of this sub-  
110 phase (e.g., 10-50% of the full '*concentric phase*' (displacement minima to displacement maxima) in  
111 loads of 30-81% 1RM) can result in a reduction in kinetic and kinematic output and muscle activation  
112 (11,31,36), potentially reducing adaptive stimuli and limiting dynamic correspondence to key sporting  
113 actions such as jumping and sprinting (6,8).

114 Ballistic exercises typically produce higher mechanical outputs than their non-ballistic counterparts as  
115 they exhibit a longer period of positive acceleration (displacement minima to velocity maxima),  
116 referred to as the '*propulsion sub-phase*' (8,14,26). As a result, when compared with non-ballistic  
117 equivalents, ballistic exercises exhibit higher velocities and larger forces, power and muscle activity,  
118 often making them the preferred choice for S&C coaches when designing 'power-type' training blocks  
119 (6,11,23,26,31). Despite this, ballistic exercise such as the jump squat must contain a landing phase.  
120 Previous researchers have observed significant increases in ankle range of motion (disproportionate

121 to knee and hip), ankle eccentric work contribution (% of total eccentric work) and slight increases in  
122 ankle landing joint moments because of longer landing durations caused by increasing loads (13,25).  
123 This change in landing strategy, therefore, must be a consideration for S&C coaches, particularly those  
124 working with athletes undertaking return to play protocols or during in-season prescription for  
125 athletes that participate in sports where a high number of jumps are common (e.g., 60-100 jumps in  
126 a competitive game of basketball) (12,33). However, practitioners must be sure that the appropriate  
127 neuromuscular adaptations would still occur if opting for alternative methods to traditional ballistic  
128 exercise.

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

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

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

## 154 **METHODS**

### 155 ***Experimental approach to the problem***

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

### 168 ***Subjects***

169 Sixteen healthy, strength-trained males (age:  $26.2 \pm 4.1$  years; body mass:  $83.2 \pm 9.3$  kg; stature:  $174.7$   
170  $\pm 4.3$  cm) volunteered for this study after providing informed consent and completing a medical pre-  
171 screening questionnaire. A sample size of sixteen subjects was calculated *a priori* (G\*Power, version  
172 3.1.9.7, Dusseldorf, Germany) using an alpha level of 0.05, statistical power of 0.95 and an effect size  
173 of 0.48 (Cohen's *f*) for a repeated measures design. Cohen's *f* was determined from Rossetti et al. (35)  
174 by taking the smallest Cohen's *d* values from the dependent variables that were collected in the  
175 present study and then divided by two. This approach to calculating effect size was based on parity  
176 between exercise modes and outcomes between Rossetti et al. (35) and the present study. Ethical  
177 approval was granted via the institution's ethics board (ER13605026) in accordance with the seventh  
178 revision (2013) of the declaration of Helsinki. Subjects were required to have a maximal back squat of



179 > 1.5 x body mass, be resistance trained for a minimum of 12 months, be technically competent in the  
180 free-weight back squat and jump squat exercises and be injury free.

### 181 ***Procedures***

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

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

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

### 200 *1RM Testing (Visit 1)*

201 Informed consent, pre-screening questionnaire, body mass (kg) (from the force plate) and stature (cm)  
202 (Seca, Leicester, Hamburg, Germany) were recorded. An individualized, standardized warm-up was  
203 performed using a combination of static stretching, dynamic mobility, activation exercises, light

204 barbell exercises and unloaded squats and jumps. Habituation of 1 s of quiet standing before initiating  
205 movement and performing all concentric phases with '*maximal intent and velocity*' also occurred.

206 Subjects were guided through an incremental, 1RM protocol in the free-weight back squat that  
207 consisted of performing loads with 50% (5 repetitions), 70% (3 repetitions), 80% (2 repetitions), 85%,  
208 90% and 95% (1 repetition) of an estimated 1RM, followed by up to 5 attempts at finding a true 1RM.  
209 Five minutes rest was prescribed between loads (38,39).

#### 210 *Force Plate Testing (Visit 2)*

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

216 Before the experimental trials, subjects completed the standardized warm-up from visit one. Subjects  
217 also completed two bodyweight warm-up (using a wooden dowel with a mass of approximately 0.7  
218 kg) sets of both exercises. The following incremental loads [repetition ranges] were then performed  
219 simultaneously in both exercises, with the order of each exercise counterbalanced across participants:  
220 0% [5], 30% [3], 40% [3], 50% [2], 60% [2]. Five minutes and three minutes rest was provided between  
221 loads and exercises (sets) at each load, respectively. Subjects were instructed to perform all  
222 repetitions with '*maximal intent and velocity*'.

#### 223 *Data Analysis*

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

229 of time and displacement spent in the propulsion phase relative to the concentric and descent phases  
230 were calculated and expressed as percentages.

231 \*\* Insert Table 1 \*\*

232 Dependent variables were selected based on three categories: output, driver and strategy variables.

233 Output variables (power, velocity and impulse) refer to instantaneous feedback that might be

234 presented and useful to an athlete or a coach; driver variables (force and work) refer to the

235 underpinning mechanics that help to determine athletic movement; and strategy variables (duration

236 and displacement) refer to a specific approach an individual may undertake to complete a task. The

237 combination of these variables helps provide a clear picture of the demands of both exercises.

238 The repetition start for both exercises was calculated from an initial 1 s of pre-movement quiet

239 standing. The mean force from this 1 s was used to calculate body weight (system weight for loaded

240 trials), and force standard deviation (SD) was also calculated from this period and the mean  $\pm$  5 SD

241 was used as the start threshold on a trial-by-trial basis (32). A graphical representation of the

242 propulsion, concentric and '*descent*' phase (start point to displacement minima) is explained in figure

243 1.

244 \*\* Insert Figure 1 \*\*

## 245 ***Statistical Analyses***

246 Data were checked for normality via the assessment of skewness, kurtosis, and univariate outliers.

247 Mean and standard deviations were calculated for all dependent variables. Three-way repeated

248 measures analysis of variance (ANOVA) was utilized to assess the load  $\times$  phase  $\times$  exercise interactions

249 for force, velocity, power, work, displacement and duration, simple two-way interactions were then

250 calculated, followed by simple main effects using the Bonferroni post-hoc correction. Impulse was

251 analyzed via a two-way repeated measures ANOVA (load  $\times$  exercise), with simple main effects

252 assessed also using Bonferroni corrections. Mean differences and 95% confidence intervals were

253 calculated between the two exercises for each load. Meaningful between-exercise differences were

254 assessed using Hedges  $g$ , with magnitudes interpreted as: trivial ( $< 0.2$ ); small (0.2-0.59); moderate  
255 (0.6-1.19); large (1.2-2.0); very large ( $> 2.0$ ) (18). The proportion of time and displacement (as a  
256 percentage ratio) spent in the propulsion phase compared to the concentric and descent phase were  
257 also calculated. Intra-session reliability was assessed on the two best repetitions (those with the  
258 highest peak velocity in each session) via intraclass-correlation (ICC) and coefficient of variation (CV),  
259 with 95% confidence intervals also calculated. ICC thresholds were set as poor ( $< 0.5$ ), moderate (0.5-  
260 0.74), good (0.75-0.9) and excellent ( $> 0.9$ ), with CV thresholds set as poor ( $> 10\%$ ), moderate (5-10%)  
261 and good ( $< 5\%$ ) (2,21).

## 262 RESULTS

263 All data were normally distributed and met assumptions for parametric analysis. Mean back squat  
264 1RM was  $158.8 \pm 19.2$  kg ( $1.92 \pm 0.3$  kg.bm<sup>-1</sup>). The ICC and CV reliability data is presented in the  
265 supplementary files. The mean (SD), differences (95% confidence intervals) and statistical significance  
266 for all dependent variables are presented in Figure 2.

267 \*\* Insert Figure 2 \*\*

268 Three-way repeated measures ANOVA revealed statistically significant load  $\times$  phase  $\times$  exercise  
269 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 ( $F_{(1.24,$   
270  $18.64)} = 82.13, P < 0.001$ ), work ( $F_{(1.81, 27.19)} = 7.74, P = 0.003$ ), duration ( $F_{(4, 60)} = 48.60, P < 0.001$ ) and  
271 displacement ( $F_{(1.98, 29.71)} = 136.40, P < 0.001$ ). Statistically significant simple two-way interactions  
272 (phase  $\times$  exercise) were observed for force ( $F_{(1, 15)} = 31.74-88.53, P < 0.001$ ), power ( $F_{(1, 15)} = 53.09-$   
273  $115.67, P < 0.001$ ), displacement ( $F_{(1, 15)} = 31.91-216.87, P < 0.001$ ), and work ( $F_{(1, 15)} = 10.45-136.32, P$   
274  $= 0.006 - < 0.001$ ) across all five loads. Whereas significant simple two-way interactions were only  
275 observed for velocity across loads of 30-60% 1RM ( $F_{(1, 15)} = 19.27-36.13, P = 0.001 - < 0.001$ ) and  
276 duration across loads of 0% and 30-50% 1RM ( $F_{(1, 15)} = 10.91-176.33, P = 0.005 - < 0.001$ ).

277 Simple main effects revealed significantly higher velocities ( $F_{(1, 15)} = 34.05-213.24, P < 0.001, g = 1.43-$   
278  $3.80$ ), larger power ( $F_{(1, 15)} = 34.81-194.42, P < 0.001, g = 0.84-2.54$ ), more work ( $F_{(1, 15)} = 64.99-282.09,$   
279  $P < 0.001, g = 1.09-3.02$ ), larger displacements ( $F_{(1, 15)} = 71.70-298.51, P < 0.001, g = 2.54-4.40$ ) and  
280 longer durations ( $F_{(1, 15)} = 9.03-125.56, P = 0.009 - < 0.001, g = 0.45-2.21$ ) in the jump squat compared  
281 to the back squat across all five loads, but no differences for mean force ( $F_{(1, 15)} = 0.02-3.55, P = 0.08-$   
282  $0.90, g = -0.01-0.00$ ) when calculated over the concentric phase. Similarly, significantly larger force  
283 ( $F_{(1, 15)} = 30.48-91.13, P < 0.001, g = 0.30-1.06$ ), higher velocities ( $F_{(1, 15)} = 21.28-70.04, P < 0.001, g =$   
284  $0.94-3.10$ ), larger power ( $F_{(1, 15)} = 42.48-144.40, P < 0.001, g = 0.98-2.93$ ), more work ( $F_{(1, 15)} = 86.76-$   
285  $282.09, P < 0.001, g = 1.30-3.56$ ), larger displacements ( $F_{(1, 15)} = 72.42-197.49, P < 0.001, g = 2.03-3.40$ )  
286 and longer durations ( $F_{(1, 15)} = 6.58-7302.09, P = 0.022 - < 0.001, g = 0.38-1.05$ ) were observed in the

287 jump squat compared to back squat across all five loads when calculated over the propulsion subphase  
288 (Figure 2).

289 Two-way repeated measures ANOVA revealed a statistically significant load  $\times$  exercise interaction  
290 between the two exercises for impulse ( $F_{(2,20, 32.93)} = 21.20, P < 0.001$ ), with simple main effects  
291 indicating larger impulse in the jump squat compared with the back squat across all five loads ( $F_{(1, 15)}$   
292  $= 102.26-293.42, P = < 0.001, g = 1.88-3.21$ ) (Figure 2).

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

298 \*\* Insert Table 2 \*\*

299

## 300 **DISCUSSION**

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

310 Significantly larger force, impulse, power, work, displacement, higher velocities and longer durations  
311 were observed in the jump squat compared to the back squat across all five loads (Figure 2), regardless  
312 of the phase of interest (propulsion vs. concentric). Our data, in part, agrees with the limited available  
313 data comparing ballistic and non-ballistic squat-based exercise (6,23,35). Significantly more power  
314 (6,35), higher velocities (6,23,35), larger forces (35) and displacements (35) have previously been  
315 reported across multiple loads (0-85% 1RM) in the free-weight jump squat compared to the back squat  
316 when calculated over the full concentric phase (8). As ballistic exercise is accelerative, of high velocity  
317 and culminates in the projection of the body, system or projectile into free space, there is a reduced  
318 requirement to perform negative acceleration at the end of the concentric phase in comparison to  
319 non-ballistic exercise (14). Further, this period of negative acceleration has been reported to  
320 contribute from 21.9-47.7% of the concentric phase when performed across incremental loads (15-  
321 90% 1RM) in the free-weight bench press (15,23). This sub-phase, therefore, has been offered as a  
322 reason for non-ballistic exercises having limited application when performed with maximal intent  
323 under submaximal loading, particularly for the purpose of increasing force, velocity, power or impulse  
324 (6,31).

325 This sub-phase of negative acceleration is of practical relevance to the S&C practitioner. Typically,  
326 incremental protocols such as load- and force-velocity profiling begin with light to moderate loads (0-  
327 60% 1RM) in non-ballistic exercises (e.g., back squat, deadlift, bench press), with metrics calculated  
328 across the full concentric phase (34,39). Our data, however, demonstrates that force-velocity  
329 characteristics are significantly lower during non-ballistic exercise when compared with ballistic, and  
330 therefore underestimating an individual's maximal capabilities. Therefore, researchers and  
331 practitioners should incorporate ballistic equivalents (e.g., jump squat, trap-bar jumps, bench press  
332 throw) when performing loads < 60% 1RM during athlete testing and profiling (force- and load-  
333 velocity) to ensure a valid assessment of mechanical capabilities.

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

346 Our data highlighted significantly longer periods of acceleration and larger displacements in the jump  
347 squat vs. back squat across all loads (figure 2), corroborating earlier findings in upper and lower body  
348 exercises (15,23,31). In contrast to previous literature that reported significantly longer periods of  
349 acceleration in the bench throw vs. bench press (15-60% 1RM) (15), comparable displacements and  
350 durations were observed in our study when considering the propulsion sub-phase as a proportion of



351 the concentric phase (Table 2). However, when comparing propulsion displacement to total descent  
352 displacement, the jump squat was noticeably higher (> 100%) (Table 2). Similarly, significantly more  
353 propulsion work in the jump squat was evident, indicating ballistic training with light to moderate  
354 loads promotes a larger range of motion of positive acceleration, potentially eliciting adaptations  
355 across a longer length-tension relationship.

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

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

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

## 391 **PRACTICAL APPLICATIONS**

392 S&C coaches should look to optimize mechanical output throughout a periodized plan via appropriate  
393 exercise choice. The most effective way to maximize power, impulse and RFD is through the  
394 combination of training modalities across the full force-velocity spectrum, however, when focusing on  
395 specific 'power' training blocks, loaded ballistic exercises (0-60% 1RM) should be utilized over non-  
396 ballistic exercises of comparable loads. However, this approach could still be 'contrasted' with heavy  
397 load exercises (> 80% 1RM) to ensure maximal force production does not decrease. Practitioners  
398 would therefore need to select these exercises at appropriate times of a competitive season (e.g.,  
399 away from fixture congestion) to minimize any unwanted impact of landing. Furthermore, given the  
400 greater mechanical outputs observed in the jump squat, it seems logical to replace the lighter and

401 moderate loads in profiling type activities with their ballistic equivalents to provide a valid reflection  
402 of an individual's force-velocity capabilities. Finally, when collecting and analyzing force kinetic and  
403 kinematic data, practitioners should utilize metrics that detail an athlete's strategy (e.g., duration and  
404 displacement) to a task and the mechanical drivers (e.g., force and work) of said task in addition to  
405 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, Tarpinning, 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, Mccauley, 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/ijssp.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, Syst me 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 <sup>-1</sup> )	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	Displacement	Displacement
		Propulsive-Concentric ratio (%)	Propulsive-Concentric ratio (%)	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

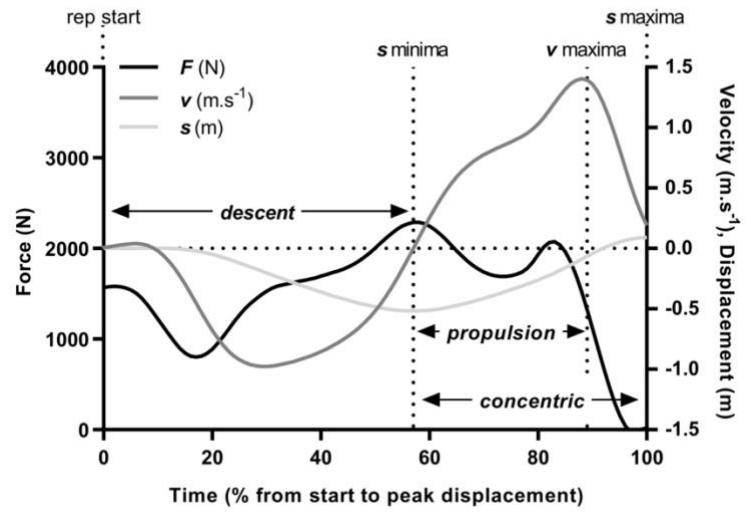
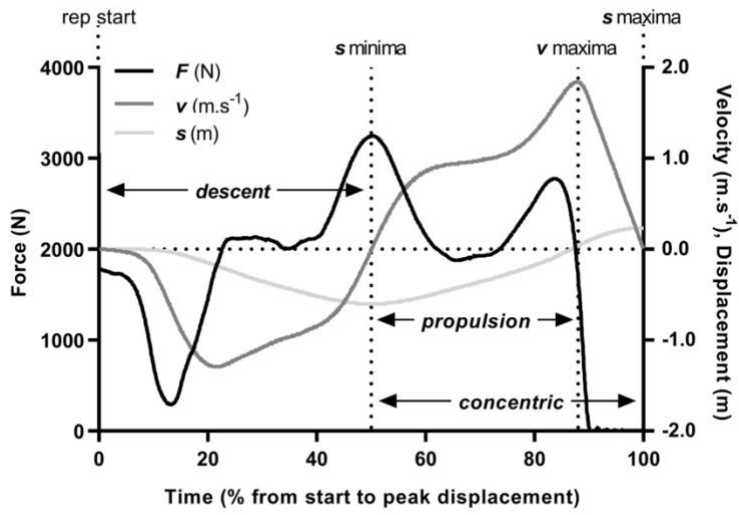
1RM 1 repetition maximum

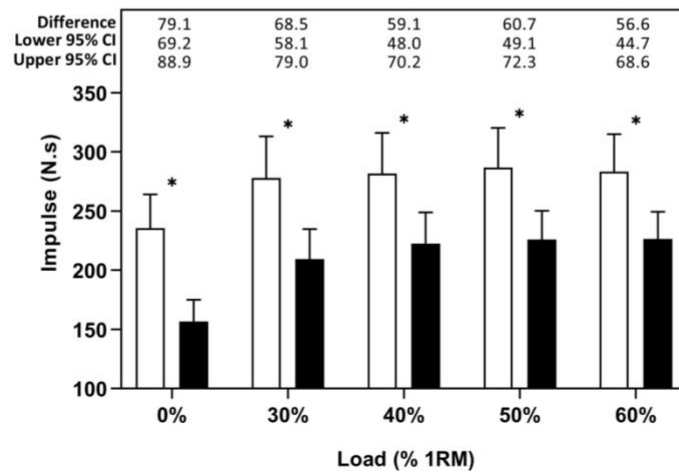
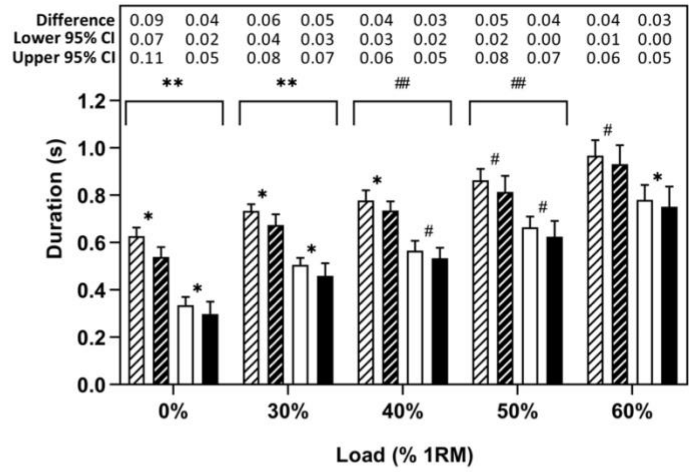
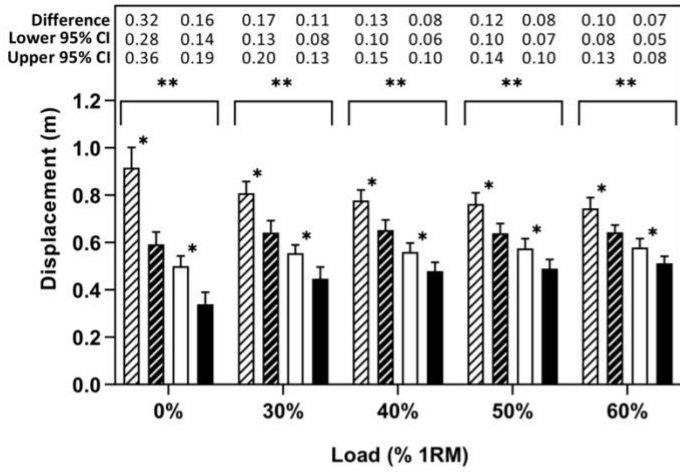
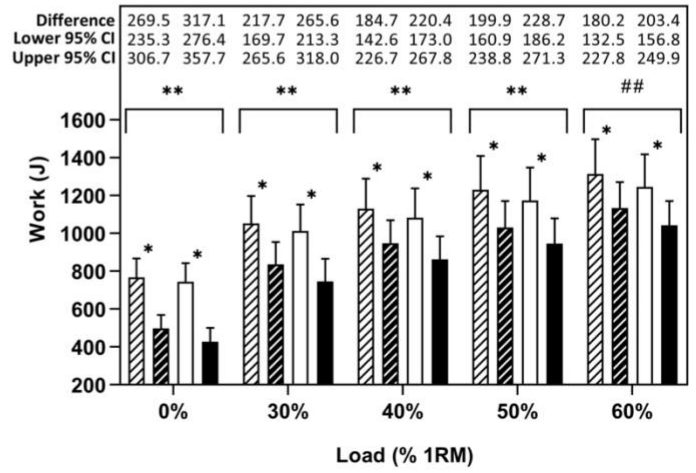
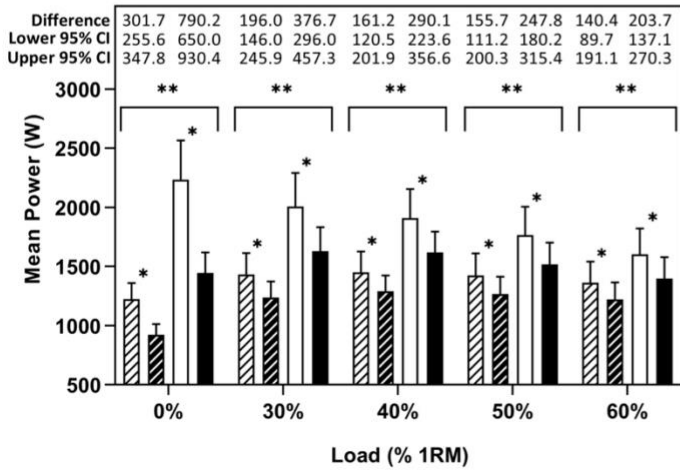
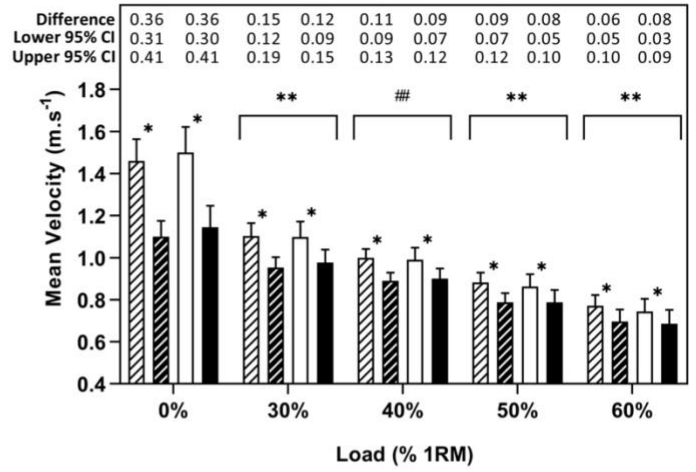
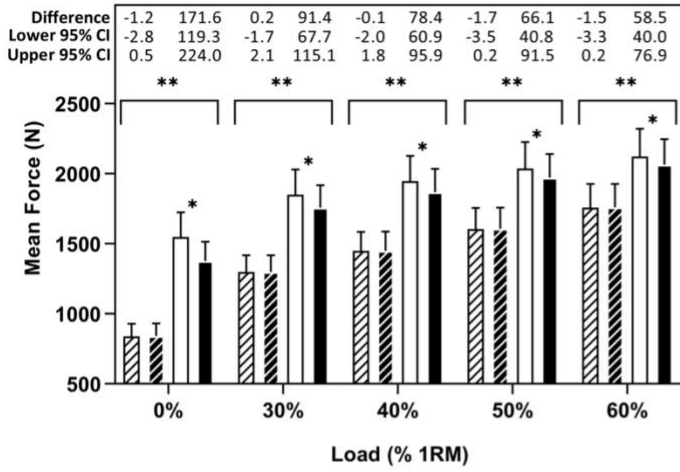
**Figure 1.** Example calculation methods for the determination of descent (negative displacement, positive and negative acceleration phase), concentric (positive displacement, positive and negative acceleration phase) and propulsion (positive displacement, positive acceleration) phases. Left figure = 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 ( $P < 0.001$ ).





## SUPPLEMENTARY TABLES

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

<b>Exercise</b>	<b>Load (% 1RM)</b>	<b>Mean Concentric Force</b>	<b>Mean Propulsion Force</b>	<b>Mean Concentric Velocity</b>	<b>Mean Propulsion Velocity</b>	<b>Mean Concentric Power</b>	<b>Mean Propulsion Power</b>	<b>Concentric Work</b>	<b>Propulsion Work</b>	<b>Mean Net Impulse</b>
Back	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)
squat	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	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)
Jump	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)
<b>Exercise</b>	<b>Load (% 1RM)</b>	<b>Concentric Duration</b>	<b>Propulsion Duration</b>	<b>Concentric Displacement</b>	<b>Propulsion Displacement</b>					
Back	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)					
squat	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	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)					
Jump	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	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean Net
	(% 1RM)	Concentric Force	Propulsion Force	Concentric Velocity	Propulsion Velocity	Concentric Power	Propulsion Power	Concentric Work	Propulsion Work	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	Concentric	Propulsion	Concentric	Propulsion
	(% 1RM)	Duration	Duration	Displacement	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