

## Pooled Versus Individualized Load–Velocity Profiling in the Free-Weight Back Squat and Power Clean

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1 Original Investigation

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3 **Individualized vs. pooled load-velocity profiling in the back squat**  
4 **and power clean**

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46 ABSTRACT

47 Purpose: This study compared pooled against individualized load-velocity profiles (LVPs) in  
48 the free-weight back squat and power clean. Methods: Ten competitive weightlifters  
49 completed baseline one repetition maximum (1RM) assessments in the back squat and  
50 power clean. Three incremental LVPs were completed and separated by 48–72 hours. Mean  
51 and peak velocity was measured via a linear-position transducer (Gymaware). Linear and  
52 non-linear (second-order polynomial) regression models were applied to all pooled and  
53 individualized LVP data. A combination of coefficient of variation (CV), intraclass-correlation  
54 coefficient (ICC) and limits of agreement (LOA) assessed between-subject variability and  
55 within-subject reliability. Acceptable reliability was defined a priori as  $ICC > 0.7$  and  $CV <$   
56  $10\%$ . Results: Very high to practically perfect inverse relationships were evident in back  
57 squat ( $r = 0.83-0.96$ ) and power clean ( $r = 0.83-0.89$ ) for both regression models, however  
58 stronger correlations were observed in the individualized LVPs for both exercises ( $r = 0.85-$   
59  $0.99$ ). Between-subject variability was moderate to large across all relative loads in the back  
60 squat ( $CV = 8.2\%-27.8\%$ ), but smaller in the power clean ( $CV = 4.6\%-8.5\%$ ). The power  
61 clean met our criteria of acceptable reliability across all relative loads, however, the back  
62 squat revealed large CVs in loads  $\geq 90\%$  1RM ( $13.1\%-20.5\%$ ). Conclusions: Evidently, load-  
63 velocity characteristics are highly individualized, with acceptable levels of reliability observed  
64 in the power clean, but not the back squat ( $\geq 90\%$  1RM). If practitioners want to adopt load-  
65 velocity profiling as part of their testing and monitoring procedures, an individualized LVP  
66 should be utilized over pooled LVPs.

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**Key Words:** Velocity-based training, load-velocity relationship, maximal strength, resistance exercise, strength and conditioning

## 76 INTRODUCTION

77 Training intensity is typically derived from direct assessments (one repetition maximum  
78 (1RM)), followed by relative, submaximal load prescriptions (e.g. 85% 1RM).<sup>1</sup> Despite 1RMs  
79 showing good within-subject reliability,<sup>1,2</sup> it is hypothesized that this approach might struggle  
80 to account for acute changes in maximum strength or residual fatigue build-up.<sup>2</sup> Research has  
81 indicated that 1RM can significantly increase following acute bouts of resistance training (1 to  
82 4 weeks).<sup>3,4,5</sup> Significant decreases in 1RM as a result of residual fatigue (24 hours to 1 week  
83 in duration) are also evident,<sup>4,6</sup> potentially affecting the accuracy of prescriptions on a week-  
84 to-week basis. Regular 1RM assessments are possible however practitioners are faced with  
85 time constraints and logistical impracticalities. Such drawbacks have prompted the  
86 development of additional aids and approaches to maximal strength testing, such as the load-  
87 velocity profile (LVP).

88 Strong inverse relationships have been observed between load and barbell velocity in free-  
89 weight<sup>2,7,8,9</sup> ( $r > 0.93$ ) and Smith-machine exercises<sup>10,11,12,13,14</sup> ( $r > 0.90$ ). However, the  
90 application of this method has often been dictated by the procedures employed. For example,  
91 the inclusion of fixed-path (Smith) machines, pauses between eccentric and concentric  
92 phases, single-session methodologies, and a failure to investigate the reliability of velocity  
93 across a full spectrum of loads questions the practical representation of many of these studies  
94 to an applied setting by which free-weight and full isotonic exercises are utilized. Furthermore,  
95 different modalities of training (e.g. Smith machine vs. free-weight or concentric-only vs.  
96 eccentric-concentric) produce different kinematic outputs and LVPs<sup>12,15</sup>, highlighting the need  
97 for further research that investigates the reliability of velocity across a full spectrum of loads  
98 during multiple testing sessions in free-weight, full isotonic exercises.

99 A paucity of research, however, has begun to investigate more practically representative  
100 training methods such as free-weight exercises that utilize the stretch-shortening cycle.  
101 Banyard et al.<sup>2,7</sup> observed high intraclass correlation coefficients (ICC) ( $\geq 0.81$ ), low coefficient

102 of variation (CV) ( $\leq 9.1\%$ ) and small standard error of measurements ( $\leq 0.07 \text{ m}\cdot\text{s}^{-1}$ ) between  
103 three separate LVP trials in loads  $\leq 90\%$  1RM, and a strong relationship between load and  
104 velocity ( $r \geq 0.93$ ) in the free-weight back squat. Similar values were found in the free-weight  
105 prone bench pull, bench press and deadlift.<sup>8,10,9</sup> Recent data, however, has highlighted that  
106 the reliability of LVPs is potentially load dependent;<sup>16</sup> that large between-subject variability at  
107 submaximal loads (CVs  $> 10\%$ ) is evident;<sup>11,7</sup> and poor reliability of velocity at 1RM ( $V_{1\text{RM}}$ )  
108 (ICC = 0.19 - 0.66; CV = 15.7 - 22.5%) can also be observed across a range of  
109 exercises.<sup>2,8,10,9,7</sup> Moreover, individualized LVPs seemingly provide stronger relationships  
110 between load and velocity.<sup>10,11,7</sup> With clear uncertainties about the most effective way to  
111 construct LVPs, further research in free-weight exercises investigating the individuality of load-  
112 velocity characteristics is needed.

113 LVPs are traditionally fitted with either linear regression<sup>7</sup> or non-linear equivalents such as  
114 second-order polynomials.<sup>13,14</sup> A small number of studies have compared the two statistical  
115 models,<sup>2,8,10</sup> however these have often been limited to smith-machine or upper body exercises.  
116 Nevertheless, Banyard et al.<sup>2</sup> did investigate this comparison during the free-weight back  
117 squat and found no statistical differences, however, the small number of loads (6) used to  
118 construct the LVP may account for this. Therefore, further clarification is required to assess  
119 the most appropriate statistical model to apply when constructing a full LVP ( $> 6$  loads and  $<$   
120  $20\%$  increments). Further investigation is also needed into the strength of the load-velocity  
121 relationship when utilizing more practically representative methods such as free-weight,  
122 isotonic exercises, constructing the profile individually and when employing more explosive  
123 movements such as weightlifting derivatives.

124 Weightlifting derivatives such as the power clean are common in strength and conditioning  
125 (S&C) interventions as they train important movement patterns such as the triple extension<sup>17</sup>  
126 and are strongly linked to physical characteristics such as sprinting and jumping.<sup>18</sup>  
127 Weightlifting stimulates high levels of force generation, rate of force development (RFD) and  
128 impulse,<sup>17,19</sup> requiring greater acceleration of heavier loads in comparison to biomechanically

129 similar exercises such as loaded squat jumps.<sup>20</sup> High levels of inter- and intra-session  
130 reliability in experienced, novice and youth lifters (ICC > 0.98; TE = 2.9 kg and smallest  
131 detectable differences (SDD) = 3.76 kg)<sup>19,21,22</sup> have also been reported when performing this  
132 exercise incrementally to 1RM. The explosive nature of the power clean and the technical  
133 competency required to perform this lift might impact load-velocity characteristics. The margin  
134 for error to successfully execute this exercise therefore may be smaller than the back squat,  
135 and it is proposed that heavier relative loads are likely to be performed at faster velocities and  
136 in smaller increments. Importantly, limited research is available that fully assesses LVPs in  
137 the power clean. Naclerio et al.<sup>23</sup> investigated the LVP in this exercise, but only measured  
138 peak velocity and did not assess reliability or evaluate the most appropriate method to  
139 construct the profile. Moreover, our study is the first to evaluate these important considerations  
140 when wanting to implement LVP in weightlifting exercises.

141 Therefore, the primary aim of this study was to investigate the load-velocity relationship of the  
142 free-weight back squat and power clean exercises, comparing pooled vs. individualized LVPs  
143 and linear vs. non-linear regression models. Secondary aims were to determine between-  
144 subject variability and within-subject reliability at each relative load for both exercises.

## 145 METHODS

### 146 Design

147 A repeated-measures, within-subject design investigated the reliability of pooled (all subject  
148 data combined) and individualized (one profile for one subject) LVPs in the free-weight back  
149 squat and power clean. 1RM assessments were conducted in each exercise, followed by three  
150 incremental LVPs utilizing loads of: 30%, (back squat only), 40-80% (in 10% increments) and  
151 85% to 100% (in 5% increments), with mean and peak velocity recorded for each repetition.

### 152 Subjects

153 Ten (8 male, 2 female) healthy competitive Weightlifters (age:  $25.0 \pm 5.6$  y; body mass:  $73.6$   
154  $\pm 13.9$  kg; stature:  $169.6 \pm 6.6$  cm), who had competed at a minimum of regional level within  
155 the previous 12 months and possessed appropriate relative strength levels (squat  $> 1.5$  x body  
156 mass and power clean  $> 1.15$  x body mass) were recruited. Subjects' relative (absolute)  
157 strength values were:  $2.1 \pm 0.3$  ( $157.0 \pm 35.8$  kg) and  $1.4 \pm 0.2$  ( $104.4 \pm 22.8$  kg) for the back  
158 squat and power clean, respectively. Informed consent was provided prior to data collection  
159 with ethical approval granted by the local institutional ethics committee in accordance with 7<sup>th</sup>  
160 revision (2013) of the declaration of Helsinki.

### 161 Methodology

162 Subjects attended four separate sessions, each separated by 48-72 hours. Each session  
163 occurred at the same time of day with participants asked to perform no additional exercise  
164 during data collection. Body mass (kg) (InBody 720, Biospace, Korea), stature (cm)  
165 (Harpenden, Holtain Ltd, Wales) and rack height (cm) were all recorded during the initial visit.  
166 Subjects undertook a standardized, individualized warm-up that included 5 minutes on a cycle  
167 ergometer (Ergomedic 874E, Monark, Sweden) at 100W followed by a combination of body  
168 weight movements, mobility exercises and light barbell lifts. Baseline 1RM assessments were  
169 then conducted in the power clean (AM) followed by the back squat (PM). A calibrated

170 International Weightlifting Federation's (IWF) approved 20kg Olympic barbell and bumper  
171 plates (Werksan, Turkey), and portable squat rack (Mirafit, UK) were used throughout the  
172 study. The 1RM protocols started at an estimated 50% 1RM and increased incrementally until  
173 1RM was reached. Multiple repetitions were performed at warm-up loads (5 reps @ 50% 1RM;  
174 3 reps @ 70% & 80% 1RM) with single repetitions for all remaining loads (85%, 90%, 95%  
175 and 100% 1RM). Up to five attempts were allowed to determine a true 1RM, with loads being  
176 increased by 0.5 to 5 kg. Rest periods were 3-5 minutes between all sets. Subjects were  
177 habituated to performing lighter loads with maximal intent and velocity during this visit.

178 The three subsequent LVP sessions were identical in procedure and consisted of incremental  
179 protocols for the power clean, followed by the back squat with loads being determined from  
180 baseline 1RM. Three repetitions were performed for lighter loads (30% to 60% 1RM), two  
181 repetitions for moderate loads (70% & 80% 1RM) and one repetition for heavy loads (85% to  
182 100% 1RM). Up to five attempts were permitted to achieve the 100% 1RM load. Rest periods  
183 were 3-5 minutes between all sets.

184 Power clean and back squat repetitions were required to meet the IWF, International  
185 Powerlifting Federation's (IPF) regulations guidelines, as well as previous research.<sup>2,17,21,24,25</sup>  
186 A power clean was deemed successful if upon catch, the greater trochanter of the hip was  
187 superior to the lateral epicondyle of the knee and the subject was able to fully extend the lower  
188 limbs.<sup>17,21</sup> The back squat required subjects to descend, ensuring the greater trochanter was  
189 inferior to the lateral epicondyle of the knee at full descent and the subject could fully extend  
190 the lower limbs on ascent.<sup>2,24</sup> Technical competency of both exercises was evaluated via a  
191 simple 2d video assessment (iPhone 7, Apple, USA) and an experienced S&C coach. Subjects  
192 were instructed to perform the ascents of both lifts as '*quickly*' and '*explosively*' as possible for  
193 all loads, and the descent at a natural speed.

194 The Gymaware was used to measure mean and peak velocities during each repetition and  
195 has previously been shown to be reliable and valid when measuring barbell velocity.<sup>26</sup> Mean



196 velocity refers to the velocity recorded across the full concentric phase of the lift (propulsive  
197 and braking phases), with peak referring to the instantaneous maximum velocity recorded  
198 during the concentric phase. The tether of the device was attached to the right-hand collar of  
199 the barbell, 100 mm from the end of the bar. The unit was placed directly under the bar for  
200 each repetition, with a tether angle of  $0 \pm 5^\circ$ .

## 201 Statistical Analysis

202 Normal distribution and relevant assumptions were assessed prior to analysis. Linear and non-  
203 linear (second-order polynomial) regression models were fitted to the pooled and  
204 individualized data to assess the relationship between load and mean or peak velocities.  
205 Fisher's  $r$  to  $z$ -transformations were used to determine significant differences between linear  
206 vs. non-linear regression model correlation coefficients.<sup>2</sup>

207 Pearson product-moment correlations ( $r$ ) and standard error of the estimate (SEE) assessed  
208 the relationship between load and velocity. The strength of the correlations was determined  
209 using the following criteria: trivial ( $< 0.1$ ), small (0.1 to 0.3), moderate (0.3 to 0.5), high (0.5 to  
210 0.7), very high (0.7 to 0.9) or practically perfect ( $> 0.9$ ).<sup>27</sup> Between-subject variability at each  
211 relative load was analyzed using CV ( $CV (\%) = \frac{\text{Between-subject } SD}{\text{subject mean score}} \times 100$ ). Within-subject reliability  
212 at each relative load was assessed using ICC (model 3.1),  $CV (CV (\%) = \frac{\text{Within-subject } SD}{\text{subject mean score}} \times 100$ ),  
213 typical error of measurement (TE) and Bland-Altman's limits of agreement (LOA) (95%  
214 confidence). Within-subject reliability refers to the reliability between sessions. The reliability  
215 of the 1RM data were assessed via one-way repeated measures analysis of variance  
216 (ANOVA), partial eta squared effect sizes ( $\eta_p^2$ ), ICC, CV and TE. All three trials were used for  
217 all reliability analyses except for LOA. For LOA, trials one and three were utilized in order to  
218 allow for the largest impact of habituation and residual fatigue on the data. Statistical  
219 significance was set at  $p < 0.05$  for all relevant statistical tests. Magnitudes of the CVs were  
220 determined as: large ( $> 10\%$ ), moderate (5% to 10%) and small ( $< 5\%$ ).<sup>7</sup> Acceptable reliability

- 221 was defined *a priori* as: a very high correlation ( $> 0.70$ ) and a small to moderate CV ( $< 10\%$ ).<sup>2</sup>
- 222 Smallest worthwhile change (SWC) was calculated for each relative load of both exercises.

## 223 RESULTS

224 Data were normally distributed and met the assumptions for regression. A very high to  
225 practically perfect inverse relationship was found between velocity and load for both exercises  
226 (figure 1, table 1). The group's maximum load (kg) during each LVP session demonstrated an  
227 acceptable level of reliability in the back squat ( $p = 0.17$ ;  $\eta_p^2 = 0.18$ ; ICC = 0.99; CV = 1.8%;  
228 TE = 2.69 kg) and power clean ( $p = 0.99$ ;  $\eta_p^2 = 0.001$ ; ICC = 0.99; CV = 2.0%; TE = 1.84 kg),  
229 indicating true 1RMs were observed each session and confounding variables such as residual  
230 fatigue were controlled for.

231 \*\*Insert Figure 1\*\*

232 \*\*Insert table 1\*\*

233 Linear regression and second order polynomials were fitted to the pooled LVPs of the sample  
234 and indicated very strong to practically perfect relationships between load and velocity for the  
235 back squat and power clean (table 1). Individualized LVPs were then analyzed using the same  
236 approaches. Individualized LVPs were stronger for all data sets, but substantially stronger for  
237 peak velocity in both lifts (table 1). All correlations were statistically significant ( $p = 0.001$ ).  
238 Fisher's  $r$  to  $z$ -transformations revealed no significant differences (back squat:  $p = 0.45$ ; power  
239 clean:  $p = 0.50$ ) between the linear and non-linear regression models (table 1). Large CVs for  
240 between-subject variability were present in the back squat ( $> 10\%$ ) for a number of relative  
241 intensities for mean (70-100% 1RM) and peak velocity (40-100% 1RM) (figures 2). The power  
242 clean presented CVs  $< 10\%$  for all relative loads (figure 3).

243 \*\*Insert Figures 2 and 3\*\*

244 The systematic bias and LOAs (95%) between trials 1 and 3 were:  $0.009 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$  (mean  
245 velocity) and  $-0.002 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$  (peak velocity) for the back squat and  $0.001 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$   
246 (mean velocity) and  $0.004 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$  (peak velocity) for the power clean (figure 4). Within-  
247 subject reliability can be seen in figures 5 and 6. Mean and peak velocity presented ICCs of

248 0.82 to 0.98, CVs of 2.1 to 4.9% and TEs of 0.03 to 0.07 m.s<sup>-1</sup> for all relative intensities in the  
249 power clean, meeting the criteria for acceptable reliability. The back squat, however, did not  
250 meet the criteria for acceptable reliability at relative intensities of  $\geq 95\%$  (ICC = 0.75 to 0.86;  
251 CV = 13.1 to 20.6%; TE = 0.03 to 0.06 m.s<sup>-1</sup>) and  $\geq 90\%$  (ICC = 0.87 to 0.91; CV = 11.8 to  
252 15.6%; TE = 0.10 to 0.14 m.s<sup>-1</sup>) for mean and peak velocity, respectively. Mean and peak  
253 velocity SWC for each relative load for both exercises can be seen in table 3.

254 \*\*Insert Figures 4, 5 and 6\*\*

255 \*\*Insert table 3\*\*

256

## 257 DISCUSSION

258 The primary aim of this study was to investigate the load-velocity relationship of the free-weight  
259 back squat and power clean exercises, comparing pooled vs. individualized LVPs and linear  
260 vs. non-linear regression models. The primary findings of this investigation were: 1) the back  
261 squat and power clean demonstrated strong, inverse relationships between load and velocity,  
262 with stronger relationships observed from individualized LVPs and no statistical differences  
263 observed between the two regression models; 2) the back squat demonstrated moderate-to-  
264 large between-subject variability whereas the power clean displayed much lower variability.

265 Very high to practically perfect, inverse relationships ( $r = 0.81$  to  $0.96$ ) were observed between  
266 load and velocity for both exercises (figure 1 and table 1), reflecting existing data in the free  
267 weight back squat ( $r$  and  $R^2 = 0.93$  to  $0.99$ ).<sup>2,7</sup> The impact of cross-bridge cycling on force  
268 production is thought to underpin this association. As the shortening of a muscle quickens,  
269 actin and myosin have less time for cross-bridges to form, inhibiting force production.<sup>28</sup>  
270 Comparable studies for the power clean are scarce, however, it is evident that the LVP of the  
271 power clean is unique (figure 1), indicating load-velocity relationships are exercise specific.  
272 Naclerio et al.<sup>23</sup> suggested only 46% of variance could be explained when using peak velocity  
273 to predict relative load (% 1RM). This suggests a much lower correlation compared to our  
274 data, potentially due to technical competency of the elite sample recruited for the present  
275 study. Similarly, comparisons to mean velocity with Naclerio's data are not possible, limiting  
276 the interpretation of their research. Furthermore, the application of the LVP when applied to  
277 the power clean may differ depending on the velocity characteristic of interest. Peak velocity  
278 is most likely to occur during the second pull phase,<sup>17</sup> providing greater insight into an  
279 individual's explosive strength whereas mean velocity may be a more stable metric to monitor  
280 and will largely be determined from the first pull and transition phases.

281 We observed large between-subject variability across relative loads in the back-squat  
282 exercise, with CVs of up to 24.2% and 27.8% for mean and peak velocity, respectively (figure

283 2). This finding reflects Balsalobre-Fernandez et al.<sup>11</sup> who observed CVs of up to 24.6% when  
284 performing a seated military press in a smith-machine, and Banyard et al.<sup>2</sup> who, reported large  
285 absolute differences between subjects across all loads (0.33 to 0.68 m.s<sup>-1</sup>) in the free-weight  
286 back squat. This variability could be a contributing factor to the poor application of pre-  
287 determine generalized predictive equations such as those developed by Gonzalez-Badillo et  
288 al.<sup>13</sup> Garcia-Ramos et al.<sup>29</sup> investigated the use of these predictive equations to estimate 1RM  
289 and observed large discrepancies from the measured maximal loads (2.8 kg to 11.4 kg) when  
290 using mean velocity. Furthermore, greater results were obtained when employing an  
291 individualized LVP (0.6 kg to 2.6 kg). Research has shown that individuals with similar 1RM  
292 values can produce different force-velocity profiles depending on their neuromuscular  
293 properties, such as fiber typing, recruitment patterns and synergistic coordination,<sup>1,28,30,31</sup>  
294 highlighting the need to profile athletes individually. This can facilitate the development of  
295 individualized training programs as well as optimizing the efficiency and effectiveness of a  
296 training intervention to elicit desired training effects.

297 Between-subject variability within the power clean was lower than that of the back squat (CVs  
298 of < 10%) (figure 3). Similarly, stronger correlations were found for an individualized LVP in  
299 comparison to the pooled profiles (table 1). Further, within-subject variability (CVs - figure 6)  
300 was lower than between-subject variability (CVs - figure 3) across all relative loads, indicating  
301 that individualized LVPs are favorable. This relationship has previously been reported for the  
302 bench press and prone bench pull,<sup>8,10,32</sup> reflecting our data, and indicating that individualized  
303 LVPs are a more accurate and reliable measurement when training and testing athletes.

304 Both exercises in this study exhibited strong, inverse relationships (figure 1). The use of non-  
305 linear regression models (second-order polynomials) have been proposed as a method of  
306 strengthening the predictive model.<sup>2,10</sup> Our data supports that of previous research showing  
307 no statistical differences are evident between the two regression models in either exercises ( $p$   
308 > 0.05) (table 1).<sup>2,10</sup> Therefore, either approach could be implemented dependent on the  
309 preference of the practitioner and the number of loads included in the profile.

310 The secondary aim of this study was to determine the within-subject reliability of the LVPs and  
311 velocity measures at each relative load. To our knowledge, this is the first study to examine  
312 the between-session reliability of load-velocity profiling in the power clean. Importantly, we  
313 observed high repeatability in the 1RM data (kg) across the three sessions in both exercises,  
314 indicating that 1RM testing is a reliable method for assessing maximal strength as well as  
315 demonstrating the robustness of our methodology. Despite this, previous research has  
316 indicated that 1RM can significantly change with respect to strength developments and fatigue  
317 build up over a short-time period,<sup>3,4,5,6</sup> and therefore frequent 1RM assessments to monitor  
318 changes in strength are not always desirable, particular during in-season competition.

319 When evaluating LVPs as a whole, we observed minimal systematic bias between trials in  
320 both exercises (-0.002 to 0.009 m.s<sup>-1</sup>), with 95% confidence intervals of 0.05 to 0.06 m.s<sup>-1</sup> and  
321 0.07 to 0.14 m.s<sup>-1</sup> for mean and peak velocity, respectively (figure 4). Given the scale of the  
322 unit of measure, the 95% confidence intervals could indicate important methodological  
323 considerations. For example, accurate manipulation of load could be compromised if the  
324 associated measurement error is not taken into account by practitioners. The SWC (table 2)  
325 provides practitioners with practical values in order for confidence to be assumed that  
326 meaningful changes are occurring throughout training interventions. The smaller SWCs  
327 observed for mean velocity in the present study compared to peak velocity suggests that mean  
328 velocity is perhaps the better metric to use in order to evaluate the effectiveness of training  
329 interventions.

330 Analyzing LVPs as a whole could limit its practical use given prescriptions typically occur from  
331 specific relative loads (e.g. 85% 1RM). The power clean produced acceptable levels of  
332 reliability across all relative loads in mean and peak velocity (figure 6), suggesting it could be  
333 utilized as an appropriate tool for practitioners to test and monitor the progress of their athletes.  
334 Conversely, the back squat did not meet the reliability criteria for loads  $\geq 95\%$  for mean velocity  
335 and  $\geq 90\%$  for peak velocity (CVs = 13.1% to 20.6%) (figure 5). This is in agreement with  
336 previous research that observed moderate ICCs (0.55 to 0.63) and large CVs (15.7% to

337 19.4%) at heavier loads (> 90%) when measuring mean velocity in the free-weight back squat  
338 and deadlift.<sup>2,9,7</sup> However, practitioners could look to utilize LVPs of 30% to 90% 1RM using  
339 mean velocity given the low to moderate CVs and TEs (3.0% to 6.1% and 0.03 m.s<sup>-1</sup> to 0.05  
340 m.s<sup>-1</sup>, respectively) (figure 5).

341 Small horizontal movements and the influence of the stretch-shortening cycle have previously  
342 been attributed to the poorer within-subject reliability at heavy loads.<sup>2,9,7</sup> Furthermore,  
343 biomechanical deviations could affect the path of the barbell, altering kinematic variables such  
344 as barbell velocity. For example, significant inter- and intra-individual variability in barbell  
345 velocity, and hip, knee and ankle angular velocity at 90% 1RM back squat have previously  
346 been reported.<sup>33</sup> Better within-subject reliability in the power clean observed in our study  
347 further reinforces this argument. The power clean is technically more complex, with a  
348 requirement to produce faster velocities to successfully complete a lift (figure 1). This smaller  
349 margin for error requires greater consistency in the biomechanical positioning achieved from  
350 repetition to repetition. For example, differences of  $\geq 8\text{cm}$  in forward barbell displacement,  $\leq$   
351  $0.19\text{ m.s}^{-1}$  in barbell velocity and  $\leq 33^\circ$  resultant acceleration angle in the second-pull phase  
352 can dictate the success of a repetition.<sup>17</sup> Therefore, movement variability could contribute to  
353 the poorer reliability evident at heavier loads in the back squat.

354 Despite favorable reliability data for the LVP, a full-individualized profile, if performed in a  
355 similar way to the present study, may still be time consuming and logistically difficult.  
356 Furthermore, if adopting such a method, it is advised that practitioners should aim to do so  
357 alongside more traditional 1RM testing given the acceptable reliability of the 1RM data  
358 observed in this study when free from confounding variables. This combination will ensure  
359 S&C coaches are able to accurately and reliably measure the maximum strength capabilities  
360 of their athletes (1RM) and optimally manipulate load session-to-session (LVP). Practitioners,  
361 however, must be cognizant of the limitations that surround the construction, application and  
362 utilization of LVPs if opting to employ them with their practices.



## 363 PRACTICAL APPLICATIONS

364 S&C practitioners wanting to profile an athlete's load-velocity characteristics should ensure an  
365 individualized approach is utilized. Practitioners should evaluate the need for profiling their  
366 athletes, the time and equipment available, and factor in the SWC associated with each  
367 relative load. S&C coaches should not replace traditional methods such as the 1RM with LVPs,  
368 but instead, consider the addition of LVPs to assist in testing and monitoring. For example,  
369 warm up sets of an incremental protocol utilized during a 1RM assessment could be used to  
370 form the light to moderate loads of an LVP. Despite this, practitioners should be cognizant to  
371 the logistical and time-related issues surrounding individualized LVPs and should adopt a  
372 method that will fit in to the scope of their practices. Finally, if undertaking LVPs in the free-  
373 weight back squat, practitioners should be mindful of the associated error when performing  
374 this method multiple times and adjust the approach accordingly.

## 375 CONCLUSIONS

376 Load and velocity demonstrate a very strong to practically perfect inverse relationship in the  
377 free-weight back squat and power clean. However, large between-subject variability, or a  
378 smaller within-subject to between-subject variability ratio, indicates that load-velocity  
379 characteristics are highly individualized. The back squat highlighted poor within-subject  
380 reliability in mean and peak velocity during the heavier loads ( $\geq 90\%$  1RM), perhaps due to  
381 greater movement variability, however, mean and peak velocity demonstrated high within-  
382 subject reliability across all relative loads in the power clean.



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494 TABLES

495 Table 1. Linear regression and second-order polynomials correlation coefficients ( $r$ ) with  
496 standard error of the estimates (SEE) for the back squat and power clean. Pooled vs.  
497 individualized data.

498 Table 2. Recommendations for the smallest worthwhile change (SWC) of mean and peak  
499 velocity for each relative load performed across both exercises.

500



501 Table 1

		Linear Regression				Second-order Polynomial			
		Pooled		Individualized		Pooled		Individualized	
		<i>r</i>	SEE (m.s <sup>-1</sup> )	<i>r</i>	SEE (m.s <sup>-1</sup> )	<i>r</i>	SEE (m.s <sup>-1</sup> )	<i>r</i>	SEE (m.s <sup>-1</sup> )
Back	MV	0.96	0.09	0.98-0.99	0.02-0.06	0.96	0.09	0.98-0.99	0.02-0.05
Squat	PV	0.83	0.22	0.96-0.99	0.03-0.11	0.83	0.22	0.98-0.99	0.01-0.05
Power	MV	0.89	0.08	0.87-0.99	0.02-0.06	0.90	0.08	0.92-0.99	0.01-0.04
Clean	PV	0.83	0.16	0.85-0.99	0.02-0.10	0.83	0.16	0.85-0.99	0.01-0.09

502

503 Table 2

Load (% 1RM)	Back Squat		Power Clean	
	Mean Velocity	Peak Velocity	Mean Velocity	Peak Velocity
	(m.s <sup>-1</sup> )	(m.s <sup>-1</sup> )	(m.s <sup>-1</sup> )	(m.s <sup>-1</sup> )
30	0.02	0.04		
40	0.02	0.04	0.03	0.04
50	0.02	0.04	0.02	0.04
60	0.02	0.04	0.02	0.04
70	0.02	0.04	0.02	0.04
80	0.02	0.05	0.01	0.03
85	0.02	0.05	0.01	0.03
90	0.02	0.05	0.01	0.03
95	0.02	0.05	0.01	0.03
100	0.02	0.05	0.01	0.03

504

505 FIGURES

506 Figure 1. Group mean (SD) values from three load-velocity profiles for mean velocity (m.s<sup>-1</sup>)  
507 (▲) and peak velocity (m.s<sup>-1</sup>) (◆) for a) back squat and b) power clean. Linear regression (---  
508 ) and second-order polynomial (....) are presented with respective equations (located in box).  
509 *1RM* = one repetition maximum.

510 Figure 2. Between-subject variability for mean velocity (m.s<sup>-1</sup>) (A) and peak velocity (m.s<sup>-1</sup>) (B)  
511 for the back squat. Means (SD) are represented by the horizontal bar (error bars). Coefficients  
512 of Variation (CV) are displayed above each relative load in parentheses. *1RM* = one repetition  
513 maximum.

514 Figure 3. Between-subject variability for mean velocity (m.s<sup>-1</sup>) (A) and peak velocity (m.s<sup>-1</sup>) (B)  
515 for the power clean. Means (SD) are represented by the horizontal bar (error bars).  
516 Coefficients of Variation (CV) displayed above each relative load in parentheses. *1RM* = one  
517 repetition maximum.

518 Figure 4. Bland-Altman plots exhibiting variations in mean velocity (m.s<sup>-1</sup>) (A and C) and peak  
519 velocity (m.s<sup>-1</sup>) (B and D) between trials 1 and 3 measured in 10% increments (30 to 80%  
520 *1RM*) and 5% increments (85 to 100% *1RM*) for the back squat (A and B) (n = 100) and 10%  
521 increments (40 to 80% *1RM*) and 5% increments (85 to 100% *1RM*) for the power clean (n =  
522 90) (C and D). — represents mean systematic bias and --- represents Limits of Agreement  
523 (95% confidence intervals).

524 Figure 5. Within-subject reliability of mean velocity (m.s<sup>-1</sup>) (▲) and peak velocity (m.s<sup>-1</sup>) (◆) in  
525 the back squat at all submaximal relative loads. Forest plots displaying Intraclass Correlations  
526 (ICC) (A), Coefficient of Variation (CV) (B) and Technical Error of Measurement (TE) (C) with  
527 error bars indicating 95% confidence intervals. Right y axis details group mean and 95%  
528 confidence values. Grey shaded areas indicate the criteria for acceptable reliability defined a  
529 priori. *1RM* = one repetition maximum.

530 Figure 6. Within-subject reliability of mean velocity ( $\text{m}\cdot\text{s}^{-1}$ ) ( $\blacktriangle$ ) and peak velocity ( $\text{m}\cdot\text{s}^{-1}$ ) ( $\blacklozenge$ ) in  
531 the power clean at all submaximal relative loads. Forest plots displaying Intraclass  
532 Correlations (ICC) (A), Coefficient of Variation (CV) (B) and Technical Error of Measurement  
533 (TE) (C) with error bars indicating 95% confidence intervals. Right y axis details group mean  
534 and 95% confidence values. Grey shaded areas indicate the criteria for acceptable reliability  
535 defined a priori.  $1RM$  = one repetition maximum.

536