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1 **Test-retest Reliability of a Commercial Linear Position Transducer**
2 **(GymAware PowerTool) to Measure Velocity and Power in the Back Squat**
3 **and Bench Press**

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16

17 *Brief running head:* Reliability of the GymAware PowerTool

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19 in the public, commercial, or not-for-profit sectors.

20

21 **ABSTRACT**

22 This study examined the test-retest reliability of the GymAware PowerTool (GYM) to measure
23 velocity and power in the free-weight back squat and bench press. Twenty-nine academy rugby
24 league players (age: 17.6 ± 1.0 years; body mass: 87.3 ± 20.8 kg) completed two test-retest
25 sessions for the back squat followed by two test-retest sessions for the bench press. GYM
26 measured mean velocity (MV), peak velocity (PV), mean power (MP) and peak power (PP) at
27 20, 40, 60, 80 and 90% of one repetition maximum (1RM). GYM showed good reliability
28 (intraclass correlation coefficient [ICC] and standard error of measurement percentage
29 [SEM%], respectively) for the measurement of MV at loads of 40 (0.77, 3.9%), 60 (0.83, 4.8%),
30 80 (0.83, 5.8%) and 90% (0.79, 7.9%) of 1RM in the back squat. In the bench press, good
31 reliability was evident for PV at 40 (0.82, 3.9%), 60 (0.81, 5.1%) and 80% (0.77, 8.4%) of
32 1RM, and for MV at 80 (0.78, 7.9%) and 90% (0.87, 9.9%) of 1RM. The measurement of MP
33 showed good to excellent levels of reliability across all relative loads ($ICC \geq 0.75$). In
34 conclusion, GYM provides practitioners with reliable kinematic information in the back squat
35 and bench press, at least with loads of 40 to 90% of 1RM. This suggests that strength and
36 conditioning coaches can utilise the velocity data to regulate training load according to daily
37 readiness and target specific components of the force-velocity curve. However, caution should
38 be taken when measuring movement velocity at loads $<40\%$ of 1RM.

39 **Key words:** Velocity-based training; sports performance; strength and conditioning; rugby
40 league

41 INTRODUCTION

42 Velocity-based training (VBT) has received considerable academic and practitioner interest in
43 recent years. VBT is characterised by performing resistance training exercises with maximal
44 intended concentric velocity and regulating training load based on the resultant velocity data.
45 Indeed, objectively measuring velocity has been shown to effectively monitor temporal fatigue
46 and estimate the proximity of muscle failure during isoinertial loading (31). Recent data also
47 demonstrate that providing athletes with instantaneous velocity feedback improves motivation
48 and attenuates the loss in barbell velocity in the free-weight back squat (41). While prescribing
49 resistance training intensity based on velocity feedback appears to be a promising training
50 strategy, the successful implementation of VBT relies on instruments that are reliable enough
51 to detect small changes in barbell kinematics.

52 In laboratory-based environments, force platforms and three-dimensional motion capture
53 systems are widely used to measure movement velocity and are generally considered the
54 reference methods for comparison with other measurement tools (1, 14, 34, 38). However,
55 transportation difficulties and high monetary costs limit the use of these techniques within
56 many applied settings. In addition, testing a large group of athletes with force plates or motion
57 capture systems can be time consuming and challenging in a training environment. This has
58 given rise to the recent development of portable kinematic devices, such as linear position
59 transducers (LPTs), to enhance the accessibility of VBT to strength and conditioning (S&C)
60 practitioners. LPTs directly measure the vertical displacement of a cable (that is attached to the
61 barbell) and determine velocity as the change in barbell position with respect to time (17).
62 These kinematic data are then coupled with the system mass (i.e. external load plus body mass)
63 to provide estimations of power through processes of double differentiation (9).

64 A commercially available LPT that continues to grow in popularity among researchers and
65 practitioners is the GymAware PowerTool (GYM). GYM offers additional features such as
66 instantaneous kinematic feedback, wireless transmission to a tablet computer and automated
67 summary reports on a cloud-based system. Importantly, previous research suggests that GYM
68 is highly valid at measuring velocity and power in resistance training exercises. Drinkwater et
69 al. (11) demonstrated very high correlations between GYM and an advanced video system for
70 the measurement of power in the free-weight bench press, Smith machine back squat and Smith
71 machine bench throw exercises. More recently, good correlations between GYM and a
72 laboratory-based device (consisting of four LPTs and a force plate) have been reported for the
73 measurement of velocity and power in the free-weight back squat (5). Ostensibly due to the
74 high validity and usability of GYM, a host of studies have used this device to quantify
75 concentric velocity and/or power in many training movements, in particular the bench press
76 (18, 28, 35) back squat (18, 41) and jump squat (2, 29).

77 Whilst the validity of GYM is reasonably well-established, there is limited information
78 available on the reliability of this particular LPT. Hori and Andrews (21) reported that the
79 reliability of GYM was high for the measurement of peak velocity in the jump squat using a
80 wooden pole (0.7 kg), weightlifting barbell (20 kg) and Smith machine (24.5 kg). However,
81 there are no published data concerning the reliability of GYM in other resistance training
82 exercises that are regularly used by S&C coaches. It is also currently unknown whether GYM
83 is reliable when greater external loads are lifted. Greater movement in the horizontal plane
84 often occurs concomitantly with increasing loads (24, 27). This extraneous horizontal motion
85 is a common source of error for methods relying exclusively on kinematic data because of an
86 inability to account for movement outside of the vertical plane (9). Furthermore, given that
87 GYM has been most widely used with rugby players (2, 29, 30, 35, 41), it would be prudent to
88 assess the device's reliability in a large cohort of these athletes. Therefore, the purpose of this

89 study was to evaluate the test-retest reliability of GYM to measure velocity and power during
90 the free-weight back squat and bench press in academy rugby league players. We aimed to
91 quantify the magnitude of measurement error to enable S&C practitioners to interpret whether
92 a change in performance between repeated trials is practically significant.

93 **METHODS**

94 **Experimental Approach to the Problem**

95 This study protocol has been described previously (33). Briefly, all participants made five
96 separate visits to the performance suite in a repeated measures design. In the first visit, one
97 repetition maximums (1RMs) were determined for the free-weight back squat and bench press
98 and participants were familiarised with executing the concentric phase of each repetition with
99 maximal intended velocity. Visits two and three to the performance suite involved test and
100 retest sessions for the back squat, whereas visits four and five were test and retest sessions for
101 the bench press. Each of these testing sessions involved the completion of repetitions at 20%,
102 40%, 60%, 80% and 90% of 1RM. GYM (Kinetic Performance Technologies, Canberra,
103 Australia) was used to measure mean velocity (MV), peak velocity (PV), mean power (MP)
104 and peak power (PP) of each repetition. These metrics were chosen because they are commonly
105 reported in VBT research and utilised by S&C practitioners (5, 13). All testing sessions took
106 place in-season; ~72 hours after a competitive match and 24 hours following a low-intensity
107 'recovery' training session. Before each testing session, participants were instructed to refrain
108 from caffeine for ≥ 12 hours, leisure-time or training-related physical activity for 24 hours, to
109 maintain habitual dietary habits, and to arrive in a fully hydrated state.

110 **Subjects**

111 Twenty-nine male rugby league players were recruited from a Super League club's academy
112 playing in the Under-19s competition. Baseline characteristics of study participants are

113 presented in Table 1. All players were free from injury and typically engaged in eight training
114 sessions across four days per week, including resistance training, rugby league skills and
115 conditioning. Specifically, players reported engaging in structured resistance training 4.3 ± 0.5
116 times per week for the last 3.1 ± 1.3 years. Participants were informed of the experimental
117 procedures to be undertaken and potential risks and benefits prior to signing an institutionally
118 approved informed consent document to participate in the study. Parental or guardian signed
119 consent was also obtained for participants aged <18 years. Ethical approval for the study was
120 granted by the Sport, Health and Exercise Science Ethics Committee at the University of Hull.

121 **[INSERT TABLE 1 ABOUT HERE]**

122 **Procedures**

123 **1RM assessment**

124 1RM testing was consistent with recognised guidelines established by the National Strength
125 and Conditioning Association (16). An S&C coach accredited by the United Kingdom Strength
126 and Conditioning Association and a Certified Strength and Conditioning Specialist (CSCS)
127 were present at all times to ensure correct technique and adherence to the 1RM protocol.
128 Briefly, participants performed a standardised warm-up consisting of dynamic stretching and
129 preparatory exercises lasting approximately 5-10 minutes. Five repetitions of the given exercise
130 were then completed at $\sim 50\%$ of participants' perceived 1RM, followed by two sets of 2-3
131 repetitions at loads corresponding to $\sim 60-80\%$ of perceived 1RM. Thereafter, the load was
132 progressively increased and participants performed 3-5 maximal trials (one repetition sets) for
133 1RM determination. Three minutes of rest was given between attempts, and a five minute rest
134 period was provided between exercises after the 1RM was established. For the back squat, the
135 Olympic barbell (Eleiko, Halmstad, Sweden) was placed in a high-bar position inside an
136 adjustable power rack (Perform Better Ltd, Southam, UK). Participants descended downwards

137 until the top of the thigh was at least parallel to the floor before returning to an upright standing
138 position. The depth of the squat was monitored by an S&C coach positioned laterally to the
139 power rack. Participants were required to maintain constant downward force on the barbell so
140 it did not leave the shoulders, and to keep their feet in contact with the floor during all
141 repetitions. Safety bars were placed 5-10 cm below the lowest point of the squat movement
142 and a two-person spot was provided for each attempt. For the bench press, 1RM testing was
143 performed on a solid flat bench (Perform Better Ltd, Southam, UK) secured inside the power
144 rack. Participants unracked the barbell using a self-selected grip width and lowered the barbell
145 until the chest was briefly touched, approximately 3 cm superior to the xiphoid process, before
146 executing full elbow extension. The attempt was considered successful if the participant's head,
147 upper back, and buttocks remained firmly placed on the bench and both feet stayed flat on the
148 floor. Any trials that involved the barbell bouncing off the chest were discarded and a one-
149 person spot was provided for each attempt. Participants performed the eccentric phase of both
150 exercises in a controlled manner at a self-selected velocity and completed the concentric phase
151 as fast as possible (with the aid of verbal encouragement).

152 **Test-retest sessions**

153 All test and retest sessions were conducted at the same time of day (7 a.m.) and were separated
154 by seven days. Following the same standardised warm-up protocol performed in the
155 familiarisation session, participants completed three consecutive repetitions at loads of 20%,
156 40%, 60% and 80% of 1RM, and two repetitions at 90% of 1RM. Different loading conditions
157 were separated by three minutes of passive rest. These relative intensities were chosen to test
158 the reliability of GYM across the full loading spectrum. Participants were verbally encouraged
159 to complete each repetition with maximal concentric velocity, although no objective velocity
160 feedback was provided to participants. Additional repetitions were performed if technical

161 lifting requirements were not met or submaximal effort was used, as determined by a consensus
162 from the S&C coaches.

163 **Data analysis**

164 GYM is a commercially available LPT consisting of a floor unit, made up of a spring-powered
165 retractable cable that is wound on a cylindrical spool coupled to the shaft of an optical encoder
166 (11). The floor unit was placed on the floor perpendicular to the right collar of the barbell. The
167 other end of the cable was vertically attached to the barbell (immediately proximal to the right
168 collar) using a Velcro strap (33) (see Supplemental Digital Content 1). Vertical displacement
169 of the barbell was measured from the rotational movement of the spool. GYM also incorporates
170 a sensor measuring the angle that the cable leaves the spool, which enables vertical-only
171 displacement to be measured by correcting for any motion in the horizontal plane (using basic
172 trigonometry) (17). Displacement data were time-stamped at 20 millisecond time points to
173 obtain a displacement-time curve for each repetition, which was down-sampled to 50 Hz for
174 analysis. The sampled data were not filtered. Instantaneous velocity was determined as the
175 change in barbell position with respect to time. Acceleration data were calculated as the change
176 in barbell velocity over the change in time for each consecutive data point. Instantaneous force
177 was determined by multiplying the system mass with acceleration, where system mass was the
178 barbell load plus the relative body mass of the participant (5, 9). Power was then calculated as
179 the product of force and velocity. Data obtained from GYM were transmitted via Bluetooth to
180 a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.1.1 app. GYM does not
181 require a calibration process.

182 The participant's body mass and the barbell load used were entered into the GymAware app
183 prior to each repetition. Values of MV and MP obtained by GYM were determined as the
184 average of all the instantaneous data collected during the concentric phase of each repetition.

185 PV and PP were calculated as the maximum value registered during the same concentric period.
186 The maximum value of each set of repetitions performed at each load (fastest mean concentric
187 velocity) was used for analysis.

188 **Statistical analyses**

189 In order to determine the test-retest reliability of GYM across the loading spectrum, each
190 relative load was analysed separately (i.e. 20%, 40%, 60%, 80%, and 90% of 1RM). Relative
191 reliability was determined using the intraclass correlation coefficient (ICC). ICC estimates and
192 their 95% confidence intervals (95% CIs) were calculated using SPSS for Windows (IBM
193 SPSS, version 24.0, Chicago, IL) based on a single-rating, absolute agreement, two-way
194 random effects model [i.e. ICC (2,1)] (26, 39). ICC estimates of <0.5, 0.50 to 0.74, 0.75 to
195 0.89, and ≥ 0.9 were considered poor, moderate, good and excellent, respectively (26). All other
196 data were analysed using custom-designed Microsoft Excel spreadsheets (Microsoft
197 Corporation, Redmond, Washington, USA) (20). Absolute reliability was examined with the
198 standard error of measurement (SEM) and mean bias with 95% limits of agreement (LOA).
199 The SEM was calculated as the standard deviation (SD) of the difference between trials divided
200 by $\sqrt{2}$ (19). SEM was also expressed as a percentage of the mean (SEM%) using the formula:
201 $([SEM/mean] \times 100)$. The smallest worthwhile change (SWC), calculated as the between-
202 subject SD multiplied by 0.2 (19), represented the smallest difference between repeated trials
203 that was not due to measurement error or individual variation. The following criteria were used
204 to rate the standardised mean bias: trivial (<0.2), small, (0.2 to 0.59), moderate (0.6 to 1.19),
205 large (1.2 to 1.99), very large (2.0 to 3.99) and extremely large (≥ 4.0) (20). The level for all
206 confidence intervals (CI) was set at 95%.

207 **RESULTS**

208 Figure 1 presents raw velocity and power data obtained in the second test-retest session.

209 Absolute SEM and SWC data for the back squat and bench press are presented in Table 2.

210 **[INSERT FIGURE 1 ABOUT HERE]**

211 **[INSERT TABLE 2 ABOUT HERE]**

212 **Back squat**

213 GYM showed good reliability (ICC, SEM%, respectively) for the measurement of MV at loads
214 of 40 (0.77, 3.9%), 60 (0.83, 4.8%), 80 (0.83, 5.8%) and 90% (0.79, 7.9%) of 1RM, and for PV
215 at 20 (0.77, 4.5%), 40 (0.78, 4.3%), and 60% (0.79, 4.2%) of 1RM. Good levels of reliability
216 were found in all measurements of MP (ICC \geq 0.75) and for PP at 20 (0.81, 8.0%), 40 (0.84,
217 7.1%) and 60% (0.77, 6.5%) of 1RM. The standardised mean bias showed only trivial or small
218 differences between repeated trials for the measurement of all criterion variables (Table 3),
219 which were also evidenced by the narrow 95% LOA (Figures 2 to 5).

220 **[INSERT TABLE 3 ABOUT HERE]**

221 **Bench press**

222 Good reliability (ICC, SEM%, respectively) was evident for the measurement of MV at 80
223 (0.78, 7.9%) and 90% (0.87, 9.9%) of 1RM, and for PV at 40 (0.82, 3.9%), 60 (0.81, 5.1%)
224 and 80% (0.77, 8.4%) of 1RM. The measurement of MP showed good to excellent reliability
225 across all relative loads (ICC \geq 0.75) (Figure 4). GYM also showed good to excellent reliability
226 for PP at loads of 20 (0.87, 8.0%), 40 (0.91, 5.6%), 60 (0.89, 5.6%) and 80% (0.77, 9.3%) of
227 1RM. Similar to the back squat, the standardised mean bias showed trivial or small differences
228 for the measurement of all criterion variables.

229 **[INSERT FIGURE 2 ABOUT HERE]**

230 **[INSERT FIGURE 3 ABOUT HERE]**

231 [INSERT FIGURE 4 ABOUT HERE]

232 [INSERT FIGURE 5 ABOUT HERE]

233 **DISCUSSION**

234 This study examined the test-retest reliability of GYM to measure velocity and power in free-
235 weight resistance training exercises. GYM demonstrated good reliability for the measurement
236 of MV at 40 to 90% of 1RM in the back squat. In the bench press, good reliability was evident
237 for PV at 40 to 80% of 1RM, and for MV at 80 to 90% of 1RM. Furthermore, good to excellent
238 levels of reliability were found in all measurements of MP. This suggests that GYM can
239 provide practitioners with reliable kinetic and kinematic information during resistance training,
240 at least with loads of 40 to 90% of 1RM.

241 GYM is a commercially available LPT that continues to grow in popularity among researchers
242 and practitioners. Despite the widespread use of GYM throughout the recent literature (2, 18,
243 28, 29, 35, 41), the present study is the first to determine the reliability of this kinematic device
244 in the free-weight back squat. There was evidence of good reliability for the measurement of
245 MV at loads of 40 to 90% of 1RM. All SEM_% data for MV were <8% and standardised mean
246 differences were either trivial or small (i.e. <0.6). For measurements of PV, GYM showed good
247 reliability at 20 to 60% of 1RM. The ICC estimates for PV at 80 and 90% of 1RM, however,
248 only indicated a moderate level of reliability. This is problematic when prescribing loads that
249 target maximal strength development and suggests that MV may be a more appropriate variable
250 when using heavy loads in the back squat. It is generally thought that MV better represents the
251 overall expression of velocity through the entire concentric phase of non-aerial movements like
252 the back squat (4, 13, 23), while PV is relevant for ballistic exercises such as jump squats and
253 bench throws (29).

254 The SEM represents the typical variation in performance between repeated trials and can be
255 used as a threshold to identify whether changes in the measurement are practically significant
256 (19). Based on the SEM presented in this study, the measurement error for MV obtained by
257 GYM ranges from 0.03 to 0.05 m·s⁻¹ in the free-weight back squat. The SEM for PV ranged
258 from 0.06 to 0.09 m·s⁻¹ (Table 2). To put these magnitudes of measurement error into context,
259 it has been shown recently that for every 5% increment in relative load, MV decreases by 0.05
260 to 0.10 m·s⁻¹ (8, 37) while PV decreases by 0.06 to 0.07 m·s⁻¹ (37). As noted by Sánchez-
261 Medina et al. (37), when an athlete increases their MV attained against a given absolute load
262 by this value (i.e. 0.05 to 0.10 m·s⁻¹), this represents a 5% increase in strength. The same
263 reasoning is applicable to changes in PV of 0.06 to 0.07 m·s⁻¹. This suggests that the
264 measurement error in MV recorded by GYM is small enough to detect subtle changes in lifting
265 performance, apart from at 20% of 1RM (SEM = 0.05 m·s⁻¹). This supports the assertion that
266 MV is a reliable metric to monitor training load in the back squat, at least with loads of 40 to
267 90% of 1RM. Even so, practitioners must still be cognisant of the magnitude of measurement
268 error when interpreting changes in MV. That is, if MV is >0.05 m·s⁻¹ outside the target
269 movement velocity, coaches should consider adjusting the barbell load. A change in MV of
270 0.05 m·s⁻¹ or less may simply be a product of noise in the measurement. These data also suggest
271 that the measurement error present in PV may be too large to detect small yet important changes
272 in performance. Caution should therefore be taken if PV data are used to adjust sessional
273 training loads in the back squat.

274 For a more conservative estimate of absolute reliability, practitioners may refer to the 95%
275 LOA. These data provide an approximate range that differences between test-retest
276 measurements would fall 95% of the time. The main difference between this statistic and the
277 SEM is that the 95% LOA calculate the test-retest differences for 95% of a population, whereas
278 the SEM estimates the typical measurement error for an average individual in the sample (3).

279 Numerically, this difference equates to a factor of approximately three. However, Hopkins (19)
280 suggests that this degree of certainty about a meaningful change in athletic performance is
281 unrealistic. Minor changes in performance are often meaningful for professional athletes, and
282 therefore the 95% LOA may be too strict for S&C practitioners to base their decisions on.

283 In the bench press, GYM showed good reliability for the measurement of MV at 80 (ICC =
284 0.78) and 90% (ICC = 0.87) of 1RM. ICC estimates of PV at 40 to 80% of 1RM were also
285 indicative of good reliability. This suggests that PV may be the most appropriate metric when
286 lifting moderate to heavy loads in the bench press, whereas MV appears to be the most reliable
287 at near maximal loads. This finding may be related to changes in the vertical acceleration-time
288 curve with increasing intensities. In the ascent phase of a bench press, lifting loads of $\leq 80\%$ of
289 1RM is characterised by a large acceleration of the barbell followed by a substantial
290 deceleration phase. In other words, the acceleration-time curve shows one positive acceleration
291 region and one negative acceleration region (27). In contrast, the bar path at loads of $\geq 90\%$ of
292 1RM fluctuates between periods of acceleration and deceleration throughout the concentric
293 movement. This is caused by a sticking point in the ascent phase, usually occurring at $\sim 30\%$ of
294 total bar displacement (12), which causes the barbell to decelerate before reaccelerating
295 through a 'maximum strength region' and eventually decelerating again to stop at the end of
296 the range (12, 27). It is conceivable that taking a mean value of velocity at $\geq 90\%$ of 1RM may
297 be a more reliable metric to represent the fluctuations in barbell kinematics that occur at near
298 maximal loads. On the other hand, PV may better capture the rapid acceleration observed at
299 loads of $\leq 80\%$ of 1RM. However, further research is required to substantiate this reasoning
300 and provide more firm practitioner recommendations.

301 Despite some ICC estimates not reaching our threshold for good reliability (i.e. $ICC \geq 0.75$),
302 the SEM data suggest a small magnitude of absolute measurement error. Similar to the back
303 squat, previous work has identified a consistent relationship between load and velocity in the

304 bench press (6). For each 5% increment in bench press load, MV decreases by 0.07 to 0.09
305 $\text{m}\cdot\text{s}^{-1}$ (13, 15, 36) and PV decreases by 0.13 to 0.14 $\text{m}\cdot\text{s}^{-1}$ (13). All absolute SEM data reported
306 in this study are smaller than the above values, with the exception of 20% of 1RM for both MV
307 (SEM = 0.09 $\text{m}\cdot\text{s}^{-1}$) and PV (SEM = 0.13 $\text{m}\cdot\text{s}^{-1}$). Therefore, measurements of MV and PV
308 obtained by GYM at 40 to 90% of 1RM appear sensitive to subtle changes in bench press
309 performance. This notion is supported by the trivial to small systematic biases found between
310 repeated measurements.

311 The large within-subject variability in movement velocity at 20% of 1RM may have been
312 caused by an intrinsic limitation to maximally generate force through the entire concentric
313 phase. When lifting light loads in the back squat (with maximal intended velocity), the athlete
314 must decelerate considerably in order to keep their feet in contact with the ground. Similarly,
315 in the bench press, the barbell must decelerate prior to achieving zero velocity at the end of the
316 ascent phase. The amount of time spent in the deceleration phase (as a percentage of total ascent
317 time) increases with lighter barbell loads because there is less inertia to overcome, which results
318 in greater initial acceleration at the start of the concentric movement (27). Indeed, power output
319 in the jump squat and bench throw has been shown to be approximately twofold greater
320 compared with the back squat and bench press, respectively (10, 32). Thus, practitioners should
321 avoid using GYM at 20% of 1RM to regulate training load in traditional (non-aerial) resistance
322 exercises. GYM has previously shown high within- and between-session reliability for the
323 measurements of PV and PP in the jump squat using a 20 kg barbell (coefficient of variation =
324 1.3 to 9.4%) (21). Further research should endeavour to establish the reliability of GYM in
325 other ballistic exercises such as the bench throw and push press.

326 GYM samples and time-stamps displacement data at 20 millisecond time points, which is
327 down-sampled to 50 Hz for analysis. The measurement error in GYM is largely comparable to
328 other commercially available LPTs sampling at higher frequencies (6, 40). For example, the

329 Tendo Weightlifting Analyser (Tendo Sports Machines, Trencin, Slovak Republic), sampling
330 data at 1000 Hz, has been shown to measure PV at 20 to 90% of 1RM in the bench press with
331 a similar measurement error ($SEM = 0.05$ to $0.12 \text{ m}\cdot\text{s}^{-1}$; $SEM_{\%} = 3.1$ to 12.6%) (40) to that
332 recorded by GYM in the present study ($SEM = 0.05$ to $0.13 \text{ m}\cdot\text{s}^{-1}$; $SEM_{\%} = 3.9$ to 12.9%). More
333 recently (6), the combination of four commercial LPTs (each sampling at 1000 Hz) recorded
334 MV at 20 to 90% of 1RM in the back squat with a SEM that ranged from 0.02 to $0.03 \text{ m}\cdot\text{s}^{-1}$,
335 which is marginally smaller than GYM (0.03 to $0.05 \text{ m}\cdot\text{s}^{-1}$). Bardella and colleagues (7) suggest
336 that a sampling rate of 25 Hz is more than adequate to measure velocity and power during
337 resistance training, even during explosive exercises. Therefore, LPTs with higher sampling
338 frequencies may not provide the practitioner with appreciably greater recording precision.

339 GYM calculates power through processes of double differentiation. Notwithstanding the
340 extensive data manipulation involved in differentiation procedures, good to excellent reliability
341 was found in all measurements of MP, with the lower 95% CI of the ICC estimates also
342 exceeding the threshold for moderate reliability. This suggests that practitioners can use GYM
343 to provide a reliable estimate of power production across the loading spectrum in both the back
344 squat and bench press. Interestingly, measurements of MP appeared to be more reliable than
345 PP especially at heavy loads. This was evidenced by the 95% LOA in particular, which were
346 much wider for measurements of PP. GYM calculates MP as the average rate of doing work
347 over the entire concentric phase, whereas PP is determined as the maximum instantaneous
348 value registered during the same concentric period. Given that GYM time-stamps displacement
349 data at 20 millisecond time points, PP may result from a sharp spike in the rate of doing work
350 lasting one-fiftieth of a second. Therefore, PP may only represent a small sample of the overall
351 concentric phase of the lift and be more susceptible to error. Hori et al. (22) have previously
352 suggested that PP is less reliable than MP because of problems associated with data smoothing,

353 differentiation and integration. Ostensibly based on this reasoning, the manufacturers of GYM
354 (Kinetic Performance Technologies) also recommend the use of MP rather than PP (25).

355 In conclusion, GYM is a practical field-based device that provides a reliable estimate of
356 movement velocity in the ascent phase of resistance training exercises. Specifically, GYM
357 showed good reliability for the measurement of MV at loads of 40 to 90% of 1RM in the back
358 squat. In the bench press, good reliability was evident for PV at 40 to 80% of 1RM, and for
359 MV at 80 to 90% of 1RM. The small standardised mean bias and errors of measurement
360 reported in this study also suggest that GYM is sensitive to subtle changes in lifting
361 performance. Furthermore, good to excellent reliability was found in all measurements of MP,
362 indicating that practitioners can utilise GYM to quantify the expression of concentric muscle
363 power in resistance training exercises.

364 **PRACTICAL APPLICATIONS**

365 GYM provides reliable kinematic information at loads of 40 to 90% of 1RM in the back squat
366 and bench press. This suggests that S&C coaches can use the velocity data to regulate sessional
367 training load according to daily readiness and target specific components of the hyperbolic
368 force-velocity curve (at 40 to 90% of 1RM) depending on the stage of season and training
369 objective. Even so, practitioners must be cognisant of the magnitude of measurement error
370 when interpreting changes in movement velocity. That is, coaches should consider adjusting
371 the barbell load if the change in velocity exceeds the measurement error. Our data also suggest
372 that MV may be a more reliable measurement than PV, at least in the back squat. Furthermore,
373 practitioners employing VBT methods should avoid using GYM at 20% of 1RM because of
374 the large within-subject variability present at this load.

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496 **Table and Figure Captions**

497 **Table 1.** Baseline characteristics of study participants.

498 **Table 2.** Absolute reliability of the GymAware PowerTool in the back squat and bench press.

499 **Table 3.** Standardised mean bias between repeated trials

500 **Figure 1.** Values for mean velocity (panels A and B), peak velocity (panels C and D), mean
501 power (panels E and F) and peak power (panels G and H) in the back squat and bench press.
502 Data are presented as means \pm SD.

503 **Figure 2.** Reliability of the GymAware PowerTool to measure mean velocity in the back squat
504 and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard
505 error of measurement as a percentage of the mean (SEM%, panel B), and the mean bias with
506 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good
507 correlation coefficient. 1RM = one repetition maximum. Data are presented as means \pm 95%
508 confidence intervals.

509 **Figure 3.** Reliability of the GymAware PowerTool to measure peak velocity in the back squat
510 and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard
511 error of measurement as a percentage of the mean (SEM%, panel B), and the mean bias with
512 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good
513 correlation coefficient. 1RM = one repetition maximum. Data are presented as means \pm 95%
514 confidence intervals.

515 **Figure 4.** Reliability of the GymAware PowerTool to measure mean power in the back squat
516 and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard
517 error of measurement as a percentage of the mean (SEM%, panel B), and the mean bias with
518 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good

519 correlation coefficient. 1RM = one repetition maximum. Data are presented as means \pm 95%
520 confidence intervals.

521 **Figure 5.** Reliability of the GymAware PowerTool to measure peak power in the back squat
522 and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard
523 error of measurement as a percentage of the mean (SEM%, panel B), and the mean bias with
524 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good
525 correlation coefficient. 1RM = one repetition maximum. Data are presented as means \pm 95%
526 confidence intervals.

527

ACCEPTED

528 **Supplemental Digital Content 1.** Photograph of a GymAware setup on a free-weight bench

529 press

ACCEPTED

Table 1. Baseline characteristics of study participants

Characteristic	n = 29
Age (years)	17.6 ± 1.0
Body mass (kg)	87.3 ± 20.8
Height (cm)	173.3 ± 18.3
Back squat 1RM (kg)	
Absolute	145.5 ± 24.4
Relative	1.71 ± 0.35
Bench press 1RM (kg)	
Absolute	100.8 ± 16.4
Relative	1.18 ± 0.26

1RM = one repetition maximum. Data are presented as means ± SD.

Table 2. Absolute reliability of the GymAware PowerTool in the back squat and bench press.

		Back Squat					Bench Press				
		20%	40%	60%	80%	90%	20%	40%	60%	80%	90%
MV	SEM	0.05	0.04	0.04	0.03	0.04	0.09	0.05	0.04	0.04	0.03
(m·s⁻¹)	SWC	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.01	0.02	0.02
PV	SEM	0.09	0.07	0.06	0.06	0.06	0.13	0.06	0.05	0.06	0.07
(m·s⁻¹)	SWC	0.04	0.03	0.03	0.02	0.02	0.05	0.03	0.02	0.02	0.02
MP	SEM	102.5	79.6	73.0	76.7	76.2	52.8	27.4	27.1	28.2	29.6
(W)	SWC	45.7	37.4	32.8	34.5	32.1	26.5	19.1	15.8	13.5	14.9
PP	SEM	250.4	219.1	196.4	217.0	202.7	60.9	43.2	38.7	51.8	78.0
(W)	SWC	112.8	105.3	80.1	70.9	66.6	33.3	29.4	24.4	21.4	25.5

MV = mean velocity; PV = peak velocity; MP = mean power; PP = peak power; SEM = standard error of measurement; SWC = smallest worthwhile change.

Table 3. Standardised mean bias between repeated trials

	Back Squat					Bench Press				
	20%	40%	60%	80%	90%	20%	40%	60%	80%	90%
MV (m·s⁻¹)	0.21	0.22	0.06	0.22	0.11	0.56	0.27	0.09	0.13	0.00
PV (m·s⁻¹)	0.08	0.08	0.13	0.33	0.42	0.27	0.21	0.12	0.24	0.03
MP (W)	0.19	0.12	0.07	0.23	0.20	0.33	0.20	0.07	0.11	0.00
PP (W)	0.04	0.02	0.04	0.43	0.50	0.14	0.16	0.16	0.14	0.06

MV = mean velocity; PV = peak velocity; MP = mean power; PP = peak power. Standardised mean bias of <0.2, 0.2 to 0.59, 0.6 to 1.19, 1.2 to 1.99, 2.0 to 3.99 and ≥ 4.0 were considered trivial, small, moderate, large, very large and extremely large, respectively (20).

Figure 1

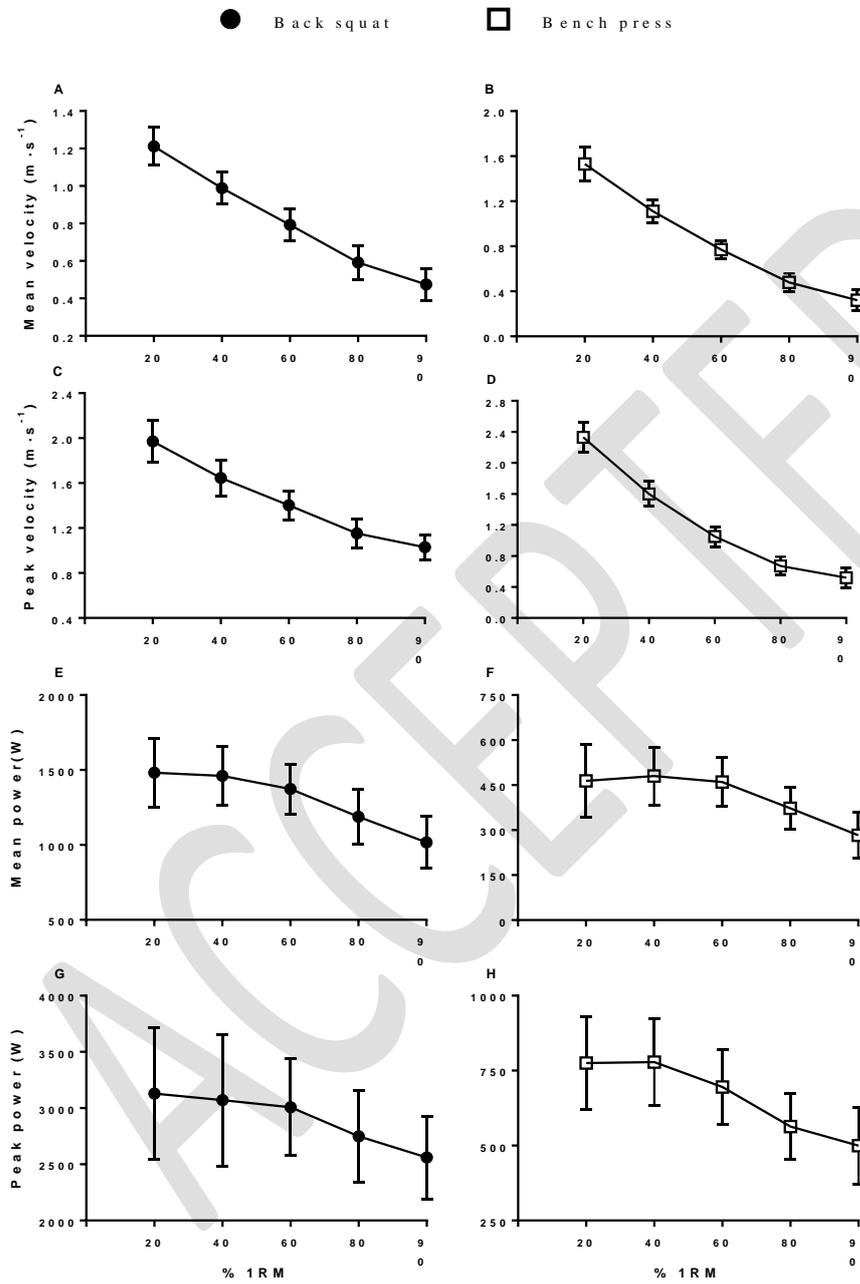


Figure 2

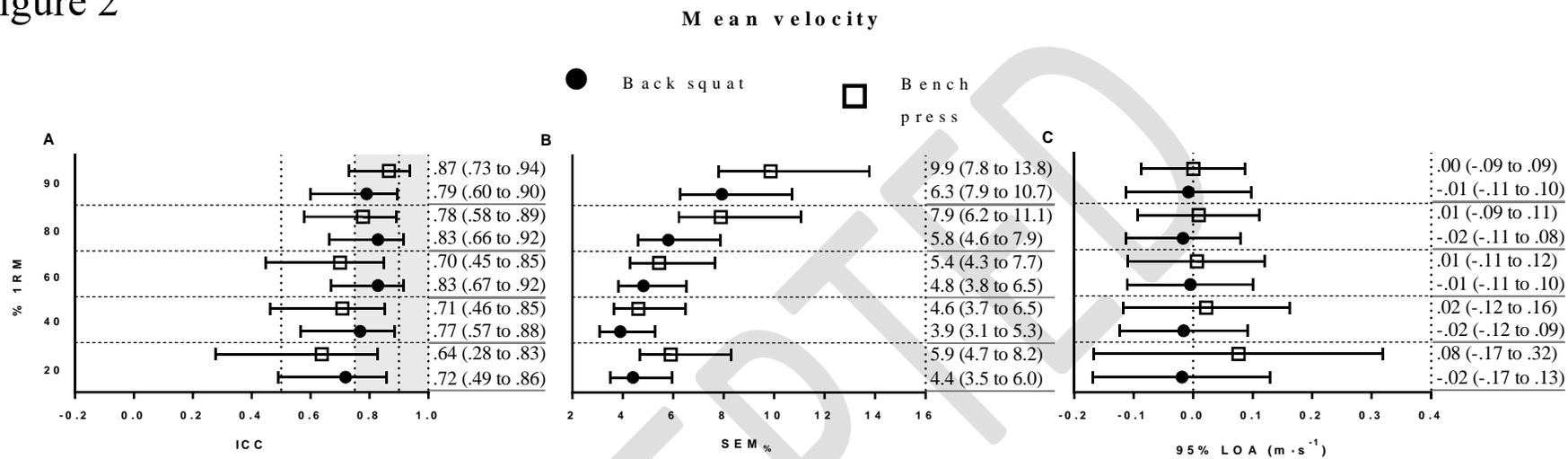


Figure 3

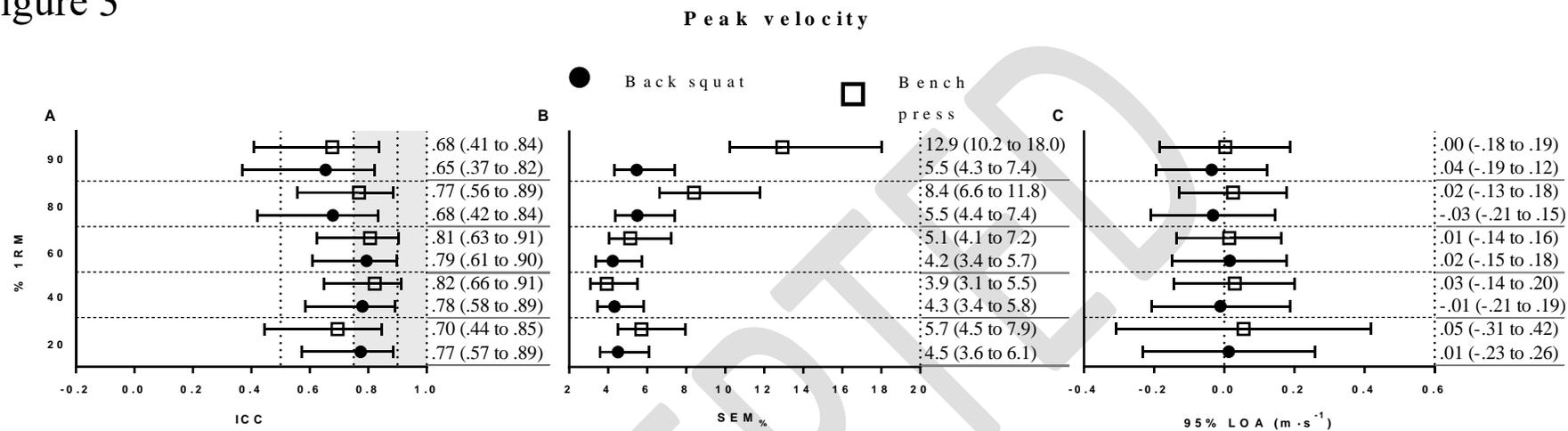


Figure 4

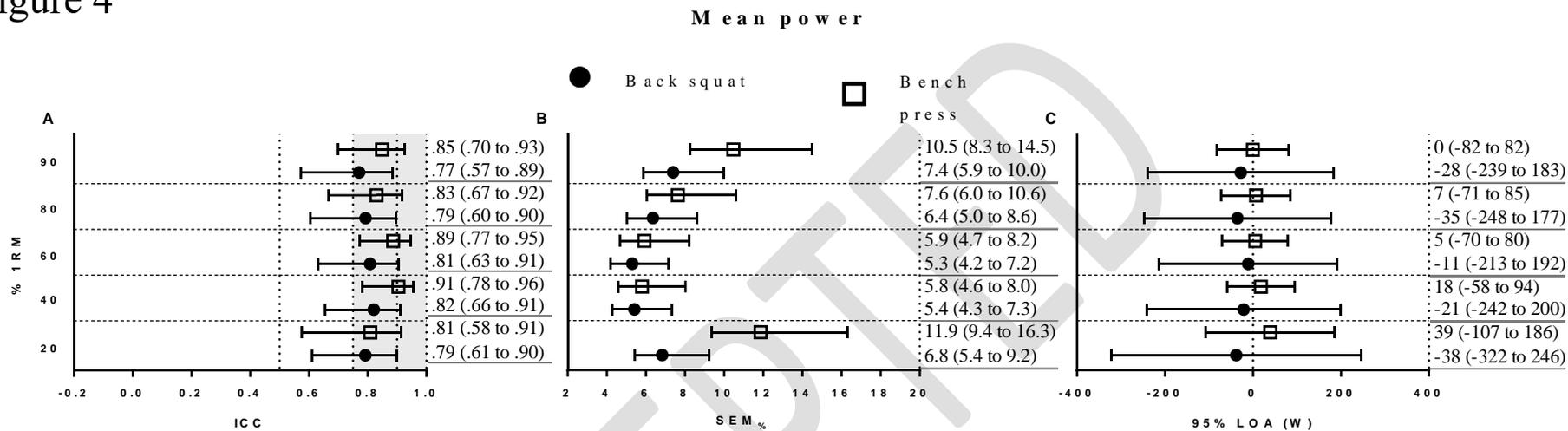
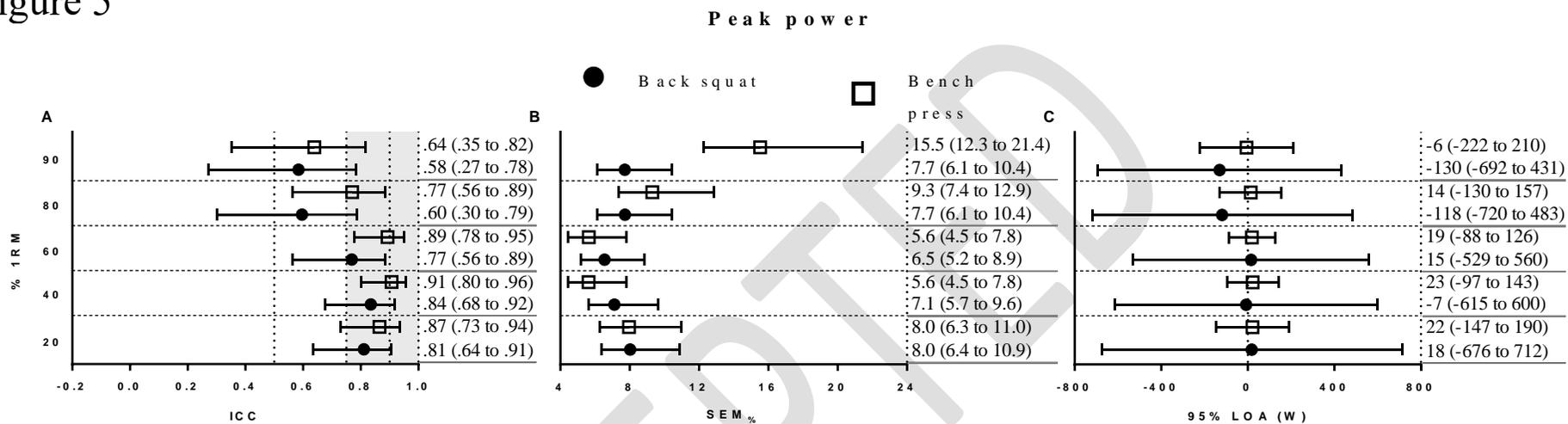


Figure 5



Supplemental Digital Content 1. Photograph of the GymAware setup on a free-weight bench press

