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Orange, Sam, Metcalfe, James W., Liefeyth, Andreas, Marshall, Phil, Madden, Leigh A., Fewster, Connor R. and Vince, Rebecca V. (2018) Validity and Reliability of a Wearable Inertial Sensor to Measure Velocity and Power in the Back Squat and Bench Press. Journal of Strength and Conditioning Research.

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1 **Validity and Reliability of a Wearable Inertial Sensor to Measure Velocity**
2 **and Power in the Back Squat and Bench Press**

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16

17 *Brief running head:* Validity and reliability of an inertial sensor

18 *Disclosure statement:* This research did not receive any specific grant from funding agencies in the
19 public, commercial, or not-for-profit sectors.

20

21 ABSTRACT

22 This study examined the validity and reliability of a wearable inertial sensor to measure
23 velocity and power in the free-weight back squat and bench press. Twenty-nine youth rugby
24 league players (18 ± 1 years) completed two test-retest sessions for the back squat followed by
25 two test-retest sessions for the bench press. Repetitions were performed at 20%, 40%, 60%,
26 80% and 90% of one repetition maximum (1RM) with mean velocity (MV), peak velocity (PV),
27 mean power (MP) and peak power (PP) simultaneously measured using an inertial sensor
28 (PUSH™) and a linear position transducer (GymAware PowerTool). PUSH™ only
29 demonstrated good validity (Pearson product-moment correlation coefficient [r]) and
30 reliability (intraclass correlation coefficient [ICC]) for measurements of MP ($r = 0.91$; ICC =
31 0.83) and PP ($r = 0.90$; ICC = 0.80) at 20% of 1RM in the back squat. However, it may be more
32 appropriate for athletes to jump off the ground with this load to optimise power output. Further
33 research should therefore evaluate the usability of inertial sensors in the jump squat exercise.
34 In the bench press, good validity and reliability were only evident for the measurement of MP
35 at 40% of 1RM ($r = 0.89$; ICC = 0.83). PUSH™ was unable to provide a valid and reliable
36 estimate of any other criterion variable in either exercise. Practitioners must be cognisant of
37 the measurement error when using inertial sensor technology to quantify velocity and power
38 during resistance training, particularly with loads other than 20% of 1RM in the back squat and
39 40% of 1RM in the bench press.

40 **Key words:** Linear position transducer, rugby league, sports performance, strength and
41 conditioning.

42 INTRODUCTION

43 The use of velocity-based feedback has recently emerged as an effective strategy to monitor
44 loading intensity (10, 17) and estimate the proximity of repetition failure (29) during resistance
45 training. A progressive decline in repetition velocity is also representative of acute
46 neuromuscular fatigue during isoinertial loading (33). Furthermore, objectively measuring
47 mechanical power during resistance training enables the strength and conditioning (S&C)
48 practitioner to determine the load that elicits optimal power output and quantify training-
49 induced adaptations (40). The accurate measurement of velocity and power is contingent on
50 the development of valid and reliable instruments that are usable in the field (2).

51 Force platforms are widely considered the gold standard for the direct acquisition of kinetic
52 data (14). This technique may be less appropriate for measuring barbell velocity, however,
53 because force platforms are unable to account for barbell movements that occur independent
54 of the body (12). In addition, force platforms are generally not available for use within a
55 practical setting (11). Linear position transducers (LPTs) are portable kinematic systems that
56 directly measure the vertical displacement of a cable (that is attached to the barbell) and
57 determine velocity and power through double differentiation processes (12). GymAware
58 PowerTool (GYM) is a commercially available LPT that provides immediate kinematic
59 feedback and automated summary reports on a cloud-based system. GYM has recently been
60 shown to accurately assess velocity and power output in the free-weight back squat (6) and
61 bench press (15) compared to laboratory-based criterion measures. However, the relatively
62 high monetary cost of GYM (~£1700 per unit) limits its widespread application to all sporting
63 organisations. The requirement of a cable attachment to the barbell also restricts the number of
64 resistance exercises it can accurately measure. This has given rise to the increased popularity
65 of various wearable devices to improve the accessibility of tracking kinematic and kinetic
66 variables during resistance training.

67 A wearable inertial sensor has recently been developed (PUSH™) to quantify movement
68 velocity and power output in resistance training exercises. The device is relative economical
69 (~£220 per unit) and is worn inconspicuously on the forearm. Good correlations between
70 PUSH™ and a LPT have previously been reported for the measurement of mean and peak
71 velocity in the Smith machine back squat (5). Sato et al. (35) also suggested that PUSH™ is
72 highly valid at measuring movement velocity in the dumbbell biceps curl and dumbbell
73 shoulder press. However, the Pearson correlation analyses employed in both studies (5, 35)
74 involved combining all repetitions performed by each individual. That is, all participants
75 provided multiple data points in each paired measure. This statistical technique, although a
76 widespread practice, violates the assumption of independence of error between observations in
77 the Pearson correlation analysis (4). Analysing non-independent data with techniques that
78 assume independence often produces specious results (1, 26). Combining all repetitions for
79 analysis also does not elucidate whether the validity of the inertial sensor is load dependent.

80 In the only other study evaluating the validity of PUSH™ to date, Banyard and colleagues (6)
81 compared PUSH™ to a laboratory-based testing device in the free-weight back squat. Ten
82 resistance-trained males lifted loads of 20, 40, 60, 80, 90 and 100% of one repetition maximum
83 (1RM), with the fastest repetition from each load used for correlation analysis. Their results
84 suggested that the validity of PUSH™ to assess velocity and power in the back squat was
85 questionable (6). Although the data were appropriately analysed and provide useful
86 information, the applicability of these results to athlete populations is somewhat limited
87 because the study involved a small sample of recreationally-trained men. Athletic populations
88 require sessional and weekly training loads to be monitored with increased precision because
89 of a typically greater training burden and the need to prepare for competition. Within-subject
90 variation is also likely to differ between athlete and recreational populations (21). To determine

91 the usability of PUSHTM within professional sport, it is essential to evaluate its validity in a
92 larger sample of professional athletes.

93 Despite receiving considerable academic and practitioner interest in recent years, the test-retest
94 reliability of the PUSHTM device is yet to be determined. Previous studies have either not
95 employed a repeated measures design that permits a test-retest analysis (5, 35) and/or have not
96 reported any reliability statistics (6, 35). Similarly, the smallest difference between repeated
97 trials that is not due to measurement error or variation within individual performance, termed
98 the smallest worthwhile change (SWC) (22), has not been established. Therefore, the purpose
99 of this study was to evaluate the concurrent validity and test-retest reliability of a wearable
100 inertial sensor to measure velocity and power output during the free-weight back squat and
101 bench press in professional youth rugby league players.

102 **METHODS**

103 **Experimental Approach to the Problem**

104 Using a repeated measures design, participants visited the laboratory on five separate occasions.
105 The first visit was a familiarisation session where 1RMs were determined for the free-weight
106 back squat and bench press. Participants were also familiarised with executing the concentric
107 phase of each repetition with maximal intentional velocity. Visits two and three to the
108 laboratory involved test and retest sessions for the back squat, whereas visits four and five were
109 test and retest sessions for the bench press. Each of these testing sessions involved the
110 completion of repetitions at 20%, 40%, 60%, 80% and 90% of 1RM. Mean velocity (MV),
111 peak velocity (PV), mean power (MP) and peak power (PP) of each repetition were
112 simultaneously recorded using a commercially available LPT (GymAware PowerTool [GYM],
113 Kinetic Performance Technologies, Canberra, Australia) and a wearable inertial sensor

114 (PUSH™, PUSH Inc., Toronto, Canada). Before each visit to the laboratory, participants were
115 instructed to refrain from caffeine for ≥ 12 hours and strenuous physical activity for ≥ 24 hours.

116 **Subjects**

117 Twenty-nine professional male youth rugby league players (age: 18 ± 1 years [range: 16 to 19
118 years]; height: 1.73 ± 0.83 m; body mass: 87.3 ± 20.8 kg) from an English Super League club's
119 academy volunteered to participate in this study. Players reported engaging in structured
120 resistance training 4.3 ± 0.5 times per week for 3.1 ± 1.3 years before the commencement of
121 the study. Player strength characteristics are presented in Table 1. All participants were
122 informed of the experimental procedures to be undertaken prior to signing an institutionally
123 approved informed consent document to participate in the study. Parental or guardian signed
124 consent was also obtained for participants aged < 18 years. Ethical approval for the study was
125 granted by the Sports, Health and Exercise Science Ethics Committee at the University of Hull.

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

127 **Procedures**

128 **1RM testing**

129 1RM testing was consistent with recognised guidelines established by the National Strength
130 and Conditioning Association (18). A UKSCA accredited S&C coach and a Certified Strength
131 and Conditioning Specialist (CSCS) were present at all testing sessions to ensure correct
132 technique and adherence to the 1RM protocol. For the back squat, an Olympic barbell was
133 placed on the trapezius in a high-bar position. With their feet externally rotated $5-10^\circ$ and
134 placed shoulder-width apart, participants started in an upright bipedal position and descended
135 downwards until the top of the thigh was at least parallel to the floor before returning to the
136 starting position. Participants were required to maintain constant downward pressure on the
137 barbell (13) and keep their feet in contact with the floor during all repetitions. Bench press

138 1RM testing was performed on a solid flat bench secured in position inside an adjustable power
139 rack (Perform Better Ltd, Southam, UK). The position of the bench was individually adjusted
140 so that the vertical trajectory of the barbell was in line with participants' intermammary line.
141 Participants unracked the barbell using a self-selected grip width and lay supine on the bench
142 with their arms fully extended. Upon verbal command, participants lowered the barbell until
143 the chest was briefly touched, approximately 3 cm superior to the xiphoid process, before
144 executing full elbow extension. The attempt was considered successful if the participant's head,
145 upper back, and buttocks remained firmly placed on the bench and both feet stayed flat on the
146 floor. The barbell was not permitted to bounce off the chest. Participants performed the
147 eccentric phase of both exercises in a controlled manner at a self-selected velocity and
148 completed the concentric phase as fast as possible.

149 **Test-retest sessions**

150 All test and retest sessions were conducted at the same time of day (7 a.m.) and were separated
151 by seven days. Following a standardised warm-up protocol, participants completed three
152 consecutive repetitions at loads of 20%, 40%, 60% and 80% of 1RM, and two repetitions at
153 90% of 1RM. These loads were chosen to represent the full loading spectrum and to aid
154 comparisons with previous studies (5, 6). Three minutes of passive rest were provided between
155 different loading conditions and participants were verbally encouraged to execute each
156 repetition with maximal concentric velocity. Additional repetitions were performed if technical
157 lifting requirements were not met or submaximal effort was used, as determined by a consensus
158 from the UKSCA accredited S&C coach and CSCS. GYM was considered the criterion in this
159 study because the device has previously been shown to accurately assess velocity and power
160 in the back squat (6) and bench press (15).

161 **Data analysis**

162 GYM is a commercially available LPT consisting of a floor unit, made up of a steel cable that
163 is wound on a cylindrical spool coupled to the shaft of an optical encoder (15). The floor unit
164 was placed on the floor perpendicular to the right collar of the barbell. In line with
165 manufacturer's instructions, the other end of the cable was vertically attached to the barbell
166 (immediately proximal to the right collar) using a Velcro strap. GYM measures the vertical
167 displacement of its cable in response to changes in barbell position. The displacement data
168 were time-stamped at 20 millisecond time points and down-sampled to 50 Hz for analysis. The
169 sampled data were not filtered. Instantaneous velocity was determined as the change in barbell
170 position with respect to time. Acceleration data were calculated as the change in barbell
171 velocity over the change in time for each consecutive data point. Instantaneous force was
172 determined by multiplying the system mass with acceleration, where system mass was the
173 barbell load plus the relative body mass of the participant (6). Power was then calculated as the
174 product of force and velocity. Data obtained from GYM were transmitted via Bluetooth to a
175 tablet (iPad, Apple Inc., California, USA) using the GymAware v2.1.1 app.

176 PUSHTM is a wearable inertial sensor consisting of a 3-axis accelerometer and a gyroscope that
177 provides six degrees in its coordinate system. The device was worn on the participant's right
178 forearm, 1-2 cm distal to the elbow crease, with the main button located proximally as per
179 manufacturer's instruction. The acceleration data were smoothed using a Butterworth filter,
180 and vertical velocity was calculated by the integration of acceleration with respect to time.
181 Similarly to GYM, instantaneous force was calculated as the product of acceleration and the
182 system mass, and power was determined by multiplying force with velocity. Data obtained
183 from PUSHTM were recorded at a sampling rate of 200 Hz and transmitted to the PUSHTM
184 v3.1.2 app via a Bluetooth connection with a tablet. PUSHTM and GYM do not require
185 calibration processes.

186 The participant's body mass and the barbell load used were entered into both apps prior to each
187 repetition. Values of MV and MP obtained by the PUSHTM and GYM were determined as the
188 average of all the instantaneous data collected during the concentric phase of each repetition.
189 PV and PP were calculated as the maximum value registered during the same concentric period.
190 The maximum value of each set of repetitions performed at each load (fastest mean concentric
191 velocity as determined by GYM) was used for analysis.

192 **Statistical analysis**

193 All data were analysed using custom-designed Microsoft Excel spreadsheets (Microsoft
194 Corporation, Redmond, Washington, USA) (24). The concurrent validity and test-retest
195 reliability of PUSHTM were determined by examining each relative load separately (i.e. 20%,
196 40%, 60%, 80%, and 90% of 1RM). Validity of PUSHTM was assessed using the Pearson
197 product-moment correlation coefficient (Pearson's r) and mean bias with 95% limits of
198 agreement (95% LOA). The standardised mean bias was rated as: trivial (<0.2), small, (0.2 to
199 0.59), moderate (0.6 to 1.19), large (1.2 to 1.99), very large (2.0 to 3.99) and extremely large
200 (≥ 4.0) (24). Relative reliability was determined using the intraclass correlation coefficient
201 (ICC). Absolute reliability was examined using the standard error of measurement (SEM) and
202 the smallest worthwhile change (SWC). SEM was calculated using the formula $SD_{diff}/\sqrt{2}$ (22)
203 and was also expressed as a percentage of the mean (SEM%). The SWC was calculated as the
204 between-subject SD multiplied by 0.2 (22). The following criteria were used to interpret the
205 strength of the Pearson's r used to assess validity and the ICC estimates used to assess
206 reliability: poor (<0.5), moderate (0.50 to 0.74), good (0.75 to 0.89) and excellent (≥ 0.9) (27).
207 The level for all confidence intervals (CI) was set at 95%.

208 **RESULTS**

209 Figure 1 presents velocity and power data across each relative intensity. The reliability (ICC,
210 SEM%) of MV measurements obtained by GYM ranged from 0.72 to 0.87 and 3.9 to 9.9%,
211 respectively.

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

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

214 **Back squat**

215 The standardised mean bias showed small differences between PUSHTM and GYM devices for
216 the measurement of PV and MP at 20% of 1RM. There were moderate to very large
217 underestimations of all other criterion variables (see Table, Supplemental Digital Content 1),
218 which were also evidenced by the 95% LOA (Figures 2 to 5). Despite the evidence of
219 systematic bias, good to excellent correlations ($r \geq 0.75$) were found between PUSHTM and
220 GYM methods for MP and PP measurements at loads of 20% to 80% of 1RM. Good
221 correlations were also found for MV at 20%, 60%, and 80% of 1RM, and PV at 20% and 80%
222 of 1RM.

223 PUSHTM only demonstrated good reliability for the measurement of MP (ICC = 0.83, 95% CI:
224 0.66 to 0.91) and PP (ICC = 0.80, 95% CI: 0.62 to 0.90) at 20% of 1RM. The SEM% and ICC
225 estimates tended to worsen as the relative intensity increased (Figures 2 to 5). Absolute SEM
226 and SWC data for all measurements obtained by PUSHTM are presented in Table 2.

227 **Bench press**

228 The standardised mean bias showed that there were no obvious under- or over-estimations of
229 PV at 60% to 90% of 1RM and MP at 60% of 1RM. Small systematic biases were evident for
230 the measurements of MV at 60% of 1RM, PV and MP at 20% and 40% of 1RM, and PP at 90%
231 of 1RM. There were moderate differences between PUSHTM and GYM for all other criterion

232 variables (see Table, Supplemental Digital Content 1). Good correlations between PUSHTM
233 and GYM were found for the measurement of MV at 40% of 1RM ($r = 0.84$, 95% CI: 0.68 to
234 0.92), and for MP at 40% ($r = 0.89$, 95% CI: 0.77 to 0.95) and 80% ($r = 0.76$, 95% CI: 0.53 to
235 0.88) of 1RM.

236 PUSHTM only showed good reliability for the measurement of MP (ICC = 0.83, 95% CI: 0.67
237 to 0.92) and PP (ICC = 0.88, 95% CI: 0.76 to 0.94) at 40% of 1RM.

238 [INSERT FIGURE 2 ABOUT HERE]

239 [INSERT FIGURE 3 ABOUT HERE]

240 [INSERT FIGURE 4 ABOUT HERE]

241 [INSERT FIGURE 5 ABOUT HERE]

242

243 **DISCUSSION**

244 This study examined the validity and reliability of a wearable inertial sensor (PUSHTM) to
245 measure velocity and power in the back squat and bench press. Our data are the first to
246 demonstrate that the reliability and validity of PUSHTM are contingent on the exercise and the
247 external load lifted. The device was reliable and valid for the measurements of MP at 20% of
248 1RM in the back squat. In the bench press, PUSHTM provided a reliable and valid measurement
249 of MP at 40% of 1RM.

250 This study is the first to determine the test-retest reliability of PUSHTM. In the free-weight back
251 squat, there was evidence of good reliability for the measurement of MP (ICC = 0.83, 95% CI:
252 0.66 to 0.91) and PP (ICC = 0.80, 95% CI: 0.62 to 0.90) at 20% of 1RM. The 95% CIs of these
253 ICC estimates suggest that the true reliability for this population likely ranges from moderate
254 to excellent. Interestingly though, our data demonstrated that the reliability of the device tended

255 to decrease as the external load increased, as evidenced by both the SEM% and ICC data
256 (Figures 2 to 5). This finding aligns well with a recent study (8) reporting a trend of greater
257 between-subject variation in MV and MP with increasing relative intensities in the back squat.
258 This inverse relationship between reliability and intensity may be attributed to alterations in
259 lower body kinematics with increasing loads. Kellis and colleagues (25) reported a 16° increase
260 in forward trunk inclination between 40-70% of 1RM in the free-weight back squat. Hay and
261 colleagues (20) also found that the absolute angle of the hip increased significantly by 22° when
262 the external load was increased from 40% to 80% of 4RM, possibly due to greater involvement
263 of the hip musculature and a concomitant reduction in knee extensor torque (20). Although
264 technique and squat depth were vigilantly monitored throughout testing, this intrinsic change
265 in lower body kinematics would conceivably alter the pathway and orientation of the inertial
266 sensor during the squat movement. Similarly, in the bench press, horizontal displacement of
267 the barbell has been shown to significantly increase from 86 ± 36 mm at 70% of 1RM to 123
268 ± 38 mm at 100% of 1RM (28). Greater horizontal displacement of the barbell at heavier loads
269 may result from an increased effort to reduce the moment arm about the shoulder axis (16, 28),
270 which would alter the position of the forearm relative to the barbell during the concentric phase.
271 Caution should therefore be taken when measuring velocity and power at heavier loads in free-
272 weight resistance exercises.

273 We have provided absolute measures of reliability to enable practitioners to interpret whether
274 training-induced changes in velocity and/or power are practically significant. The SEM
275 represents the typical variation in performance from repeated trials and displays measurement
276 error in the same units as the original measurement (22). It is important for coaches to minimise
277 the SEM in order to detect subtle yet meaningful changes in performance. Sánchez-Medina et
278 al. (34) have eloquently shown that differences in MV between each 5% increment in relative
279 load vary between 0.05 and 0.10 m·s⁻¹ in the back squat. Their data also show that for each 10%

280 increase in load, the concomitant change in MV varies between 0.11 and 0.18 m·s⁻¹ (34). Based
281 on the SEM values for MV reported in this study (Table 2), the inertial sensor appears reliable
282 enough to detect 10%, but not 5%, changes in relative load. S&C practitioners must judge
283 whether the magnitude of measurement error is acceptable based on the specific needs of their
284 athletes. Clearly, an appropriate balance must be struck between usability, cost, practicality,
285 and reliability of the testing method.

286 Two previous studies have supported the use of PUSHTM to accurately measure movement
287 velocity during resistance training. Sato and colleagues (35) reported good correlations
288 between PUSHTM and a 3D motion analysis capture system for the measurement of MV and
289 PV in the dumbbell biceps curl (MV: $r = 0.86$; PV: $r = 0.80$) and shoulder press (MV: $r = 0.88$;
290 PV: $r = 0.92$). Using a LPT as the criterion measure, Balsalobre-Fernández and colleagues (5)
291 also suggested that PUSHTM was highly valid at measuring MV ($r = 0.85$) and PV ($r = 0.91$) in
292 the Smith machine back squat. Unlike the free-weight back squat though, the Smith machine
293 restricts barbell displacement to a fixed linear path, which eliminates measurement error
294 resulting from extraneous horizontal motion (12). Furthermore, the Pearson correlation
295 analyses employed in both studies (5, 35) involved combining all repetitions performed by each
296 individual. For example, participants in the Balsalobre-Fernández et al. (5) study performed
297 three repetitions at loads of 20, 40, 50, 60 and 70kg, with each repetition used in the validity
298 analyses. Therefore, all participants provided 15 data points in each paired sample. This
299 technique violates the assumption of independence in the Pearson correlation analysis and is
300 likely to produce erroneous results (4).

301 To satisfy the assumption of independence, we analysed each relative load separately using the
302 fastest repetition at each load. Our data demonstrated good to excellent correlations between
303 PUSHTM and GYM for MP and PP measurements at loads of 20% to 80% of 1RM. We also
304 found good correlations for measurements of MV at 20%, 60% and 80% of 1RM and for PV

305 at 20% and 80% of 1RM. Similarly, Banyard and colleagues (6) recently reported that PUSHTM
306 was highly valid for the measurement of MV at light to moderate loads (i.e. <60% of 1RM)
307 and for measuring PV at light loads (i.e. 20% of 1RM). However, they considered all MP and
308 PP data obtained by PUSHTM to be invalid. Differences between these results and our data are
309 readily explained by the different validity criteria used. We employed Pearson's *r* to determine
310 thresholds of acceptable validity, whereas Banyard and colleague's (6) included Pearson's *r*,
311 coefficient of variation (CV) and the effect size in their validity criteria. Interestingly, if the
312 CV was not used in their (6) analyses, the validity of PUSHTM to measure MP and PP would
313 have been considered high for all loads except for 90% and 100% of 1RM (i.e. the same results
314 as the present study). Although the CV is commonly used to assess the validity of variables
315 pertinent to sports medicine (3), it has been suggested that this statistic may be more
316 representative of variability within an individual, rather than within a sample of individuals
317 (30). This appears logical given the CV can only be directly calculated from repeated
318 measurements on a single case (32). Additional differences between studies include the
319 criterion measure used, the number of repetitions performed per load, and the sample
320 population (and therefore the sample heterogeneity).

321 Though the inertial sensor was valid and reliable for measuring MP at 20% of 1RM in the back
322 squat, the practical applications of prescribing this load are questionable. We instructed
323 participants to keep their feet in contact with the floor during all repetitions in order to
324 standardise technique between each load. Due to the inherent limitation of applying maximal
325 force to the ground when using light loads in the back squat (34), it may be more appropriate
326 for athletes to jump off the ground with 20% of 1RM. Indeed, peak power output in the jump
327 squat has been shown to be approximately twofold greater compared with the back squat (13).
328 Lighter loads ($\leq 30\%$ of 1RM) also elicit the highest PP output in the jump squat exercise (36).

329 Therefore, further research should evaluate the validity and reliability of inertial sensors to
330 measure power in the jump squat.

331 In agreement with previous reports (5), we found evidence of systematic bias between the
332 inertial sensor and LPT in the back squat. Specifically, the standardised mean bias showed
333 moderate to very large underestimations of most criterion variables, which were also evidenced
334 by the 95% LOA. This bias is likely underpinned by differences in calculation techniques.

335 GYM is a portable LPT that directly measures the vertical displacement of its cable. Movement
336 velocity and power output are calculated as derivatives of the displacement data through double
337 differentiation processes. Conversely, the inertial sensor is worn on the forearm and
338 encompasses a 3-axis accelerometer with a gyroscope. Differentiation of the acceleration data
339 then permits the calculation of velocity and power. The differentiation procedures used by both
340 systems, although based on well-established mathematical principles, require extensive data
341 manipulation and therefore result in the amplification of noise and the consequential risk of
342 erroneous data (12). Inertial sensors and LPTs also use different sampling frequencies and
343 methods to correct for motion in the horizontal plane, which may further contribute to the
344 systematic bias. The lack of agreement between PUSHTM and GYM suggests that S&C
345 practitioners should not use these two devices interchangeably and should take caution when
346 comparing data obtained by inertial sensors to normative data obtained by LPTs in the literature.

347 The inertial sensor showed good reliability for the measurement of MP (ICC = 0.83, 95% CI:
348 0.67 to 0.92) and PP (ICC = 0.88, 95% CI: 0.76 to 0.94) at 40% of 1RM in the bench press. In
349 addition, a good correlation between PUSHTM and GYM was found at 40% of 1RM for the
350 measurement of MP ($r = 0.89$, 95% CI 0.77 to 0.95), with the lower 95% CI of the Pearson
351 correlation also exceeding the threshold for good validity. Furthermore, the mean bias with 95%
352 LOA for this measurement were relatively narrow (32.3 ± 95.3 W), with the standardised mean
353 bias demonstrating only a small underestimation (0.31) compared to GYM. Therefore, these

354 data suggest that PUSHTM provides a reliable and valid measurement of MP at 40% of 1RM. It
355 is important to note that maximal MP and PP output were also achieved at 40% of 1RM (Figure
356 1), which is in agreement with previous research demonstrating that power production in the
357 bench press is optimised at moderate loads (37). This finding indicates that S&C coaches are
358 able to prescribe 40% of 1RM in the bench press to accurately quantify and develop the power-
359 generating capabilities of their athletes.

360 The criteria for ICC estimates of reliability used in this study were based on recent guidelines
361 for selecting and reporting ICCs (27). For example, an ICC estimate of 0.75 or above was
362 considered a good level of reliability. We also used the same thresholds for Pearson correlations
363 to improve clarity in the interpretation of our data. Many studies (19, 31, 38, 39) have used a
364 correlation threshold of ≥ 0.50 to denote a strong level of validity and/or reliability based on
365 criteria put forward by Cohen (9) and Hopkins (23). On the other hand, some authors have
366 chosen an analytic goal of r being above 0.70 (6, 7). We have provided mean estimates with
367 95% CIs for all correlation coefficients to enable the reader to make their own interpretation of
368 the data.

369 In conclusion, these data show that the reliability and validity of the inertial sensor are
370 contingent on the exercise and the external load lifted. The PUSHTM device was reliable and
371 valid for the measurement of MP at light relative loads (e.g. 20% of 1RM) in the back squat.
372 However, the practical applications of using this load are questionable because of the intrinsic
373 limitation of applying maximal force to the ground when lifting light loads in the back squat.
374 In the bench press, PUSHTM obtained a valid and reliable measurement of MP at 40% of 1RM,
375 although a small systematic bias between PUSHTM and GYM devices was present. Practitioners
376 must be cognisant of the measurement error when evaluating changes in performance between
377 repeated trials.

378 **PRACTICAL APPLICATIONS**

379 Though the inertial sensor was considered valid and reliable for measuring MP at 20% of 1RM
380 in the back squat, it may be more appropriate for athletes to jump off the ground with this load
381 in order to optimise power output. Further research should therefore evaluate the validity and
382 reliability of inertial sensors to measure power in the jump squat exercise. Measuring MP at
383 40% of 1RM provides S&C coaches with a reliable and valid measurement of power output in
384 the bench press. However, inertial sensors and LPTs should not be used interchangeably
385 because of the systematic bias between the two systems. Practitioners should acknowledge the
386 magnitude of measurement error between repeated trials when using inertial sensor technology
387 to quantify velocity and power in resistance training exercises.

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389

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485

486 **Figure and Table Captions**

487 **Table 1.** Baseline strength characteristics of study participants.

488 **Table 2.** Absolute reliability of the wearable inertial sensor in the back squat and bench press

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

492 **Figure 2.** Validity and reliability of the wearable inertial sensor to measure mean velocity in
493 the back squat and bench press. Validity was assessed using Pearson product-moment
494 correlation coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was
495 determined using the intraclass correlation coefficient (C) and standard error of measurement
496 as a percentage of the mean (D). Area shaded in grey represents a good level of
497 validity/reliability. 1RM = one repetition maximum. Data are presented as means \pm 95%
498 confidence intervals.

499 **Figure 3.** Validity and reliability of the wearable inertial sensor to measure peak velocity in
500 the back squat and bench press. Validity was assessed using Pearson product-moment
501 correlation coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was
502 determined using the intraclass correlation coefficient (C) and standard error of measurement
503 as a percentage of the mean (D). Area shaded in grey represents a good level of
504 validity/reliability. 1RM = one repetition maximum. Data are presented as means \pm 95%
505 confidence intervals.

506 **Figure 4.** Validity and reliability of the wearable inertial sensor to measure mean power in the
507 back squat and bench press. Validity was assessed using Pearson product-moment correlation
508 coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was determined
509 using the intraclass correlation coefficient (C) and standard error of measurement as a

510 percentage of the mean (D). Area shaded in grey represents a good level of validity/reliability.

511 1RM = one repetition maximum. Data are presented as means \pm 95% confidence intervals.

512 **Figure 5.** Validity and reliability of the wearable inertial sensor to measure peak power in the

513 back squat and bench press. Validity was assessed using Pearson product-moment correlation

514 coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was determined

515 using the intraclass correlation coefficient (C) and standard error of measurement as a

516 percentage of the mean (D). Area shaded in grey represents a good level of validity/reliability.

517 1RM = one repetition maximum. Data are presented as means \pm 95% confidence intervals.

518

519 **Supplemental Digital Content 1.** Standardised mean bias between PUSHTM and GYM
520 methods

Table 1. Baseline strength characteristics of study participants

| Back Squat (kg) | | Bench Press (kg) | |
|-----------------|--------------|------------------|--------------|
| 1RM | Relative 1RM | 1RM | Relative 1RM |
| 145.5 ± 24.4 | 1.71 ± 0.35 | 100.8 ± 16.4 | 1.18 ± 0.26 |

1RM = one repetition maximum; relative 1RM = one repetition maximum normalised to body mass. Data are presented as means ± SD.

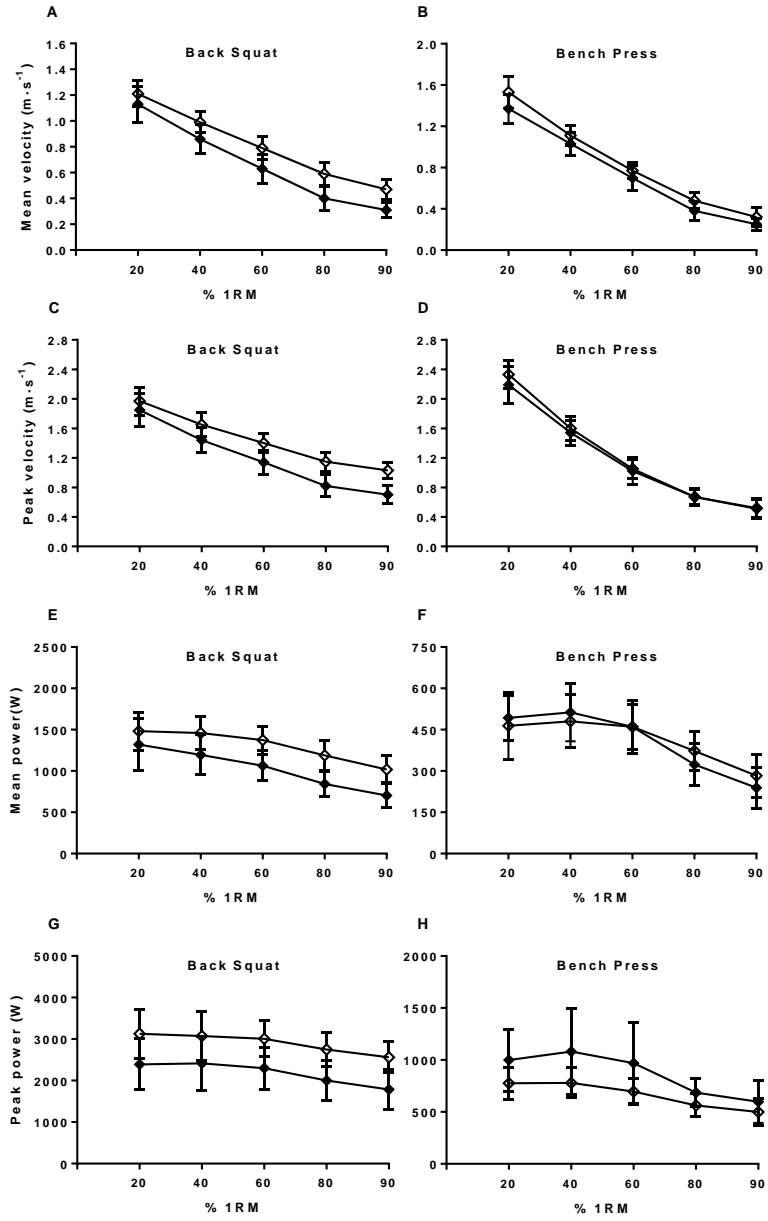
Table 2. Absolute reliability of the wearable inertial sensor in the back squat and bench press

| | | Back Squat | | | | | Bench Press | | | | |
|---------------------------|-----|------------|-------|-------|-------|-------|-------------|-------|-------|-------|-------|
| | | 20% | 40% | 60% | 80% | 90% | 20% | 40% | 60% | 80% | 90% |
| MV | SEM | 0.08 | 0.07 | 0.06 | 0.06 | 0.06 | 0.11 | 0.08 | 0.08 | 0.06 | 0.05 |
| (m·s⁻¹) | SWC | 0.03 | 0.02 | 0.02 | 0.02 | 0.01 | 0.03 | 0.02 | 0.02 | 0.02 | 0.01 |
| PV | SEM | 0.12 | 0.18 | 0.11 | 0.11 | 0.12 | 0.21 | 0.11 | 0.12 | 0.08 | 0.10 |
| (m·s⁻¹) | SWC | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.05 | 0.04 | 0.04 | 0.02 | 0.02 |
| MP | SEM | 128.3 | 121.5 | 105.9 | 129.5 | 117.0 | 70.6 | 33.8 | 51.6 | 51.3 | 45.7 |
| (W) | SWC | 59.1 | 41.6 | 32.4 | 32.9 | 30.0 | 19.0 | 20.3 | 18.2 | 15.6 | 15.5 |
| PP | SEM | 261.2 | 345.8 | 279.4 | 345.4 | 359.5 | 221.9 | 151.0 | 273.0 | 137.5 | 131.9 |
| (W) | SWC | 112.3 | 115.6 | 95.9 | 80.7 | 87.5 | 71.1 | 84.2 | 69.2 | 40.0 | 40.8 |

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

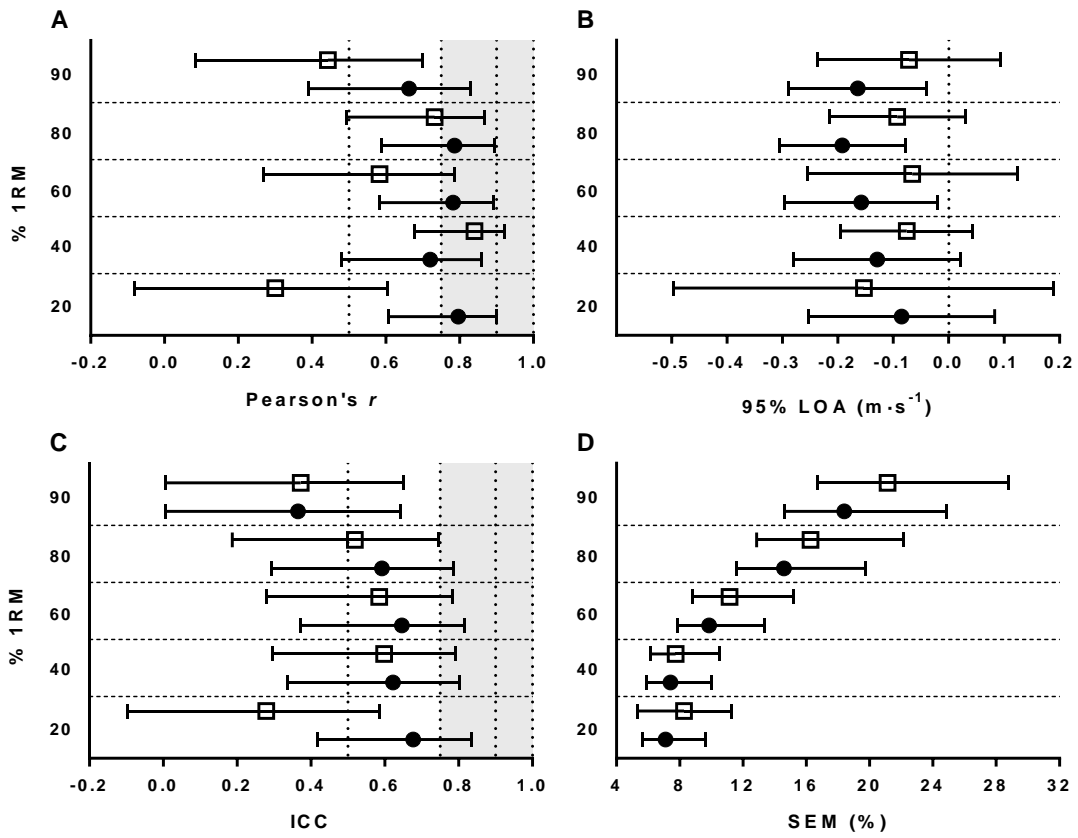
= smallest worthwhile change.

◇ GYM ◆ PUSH™



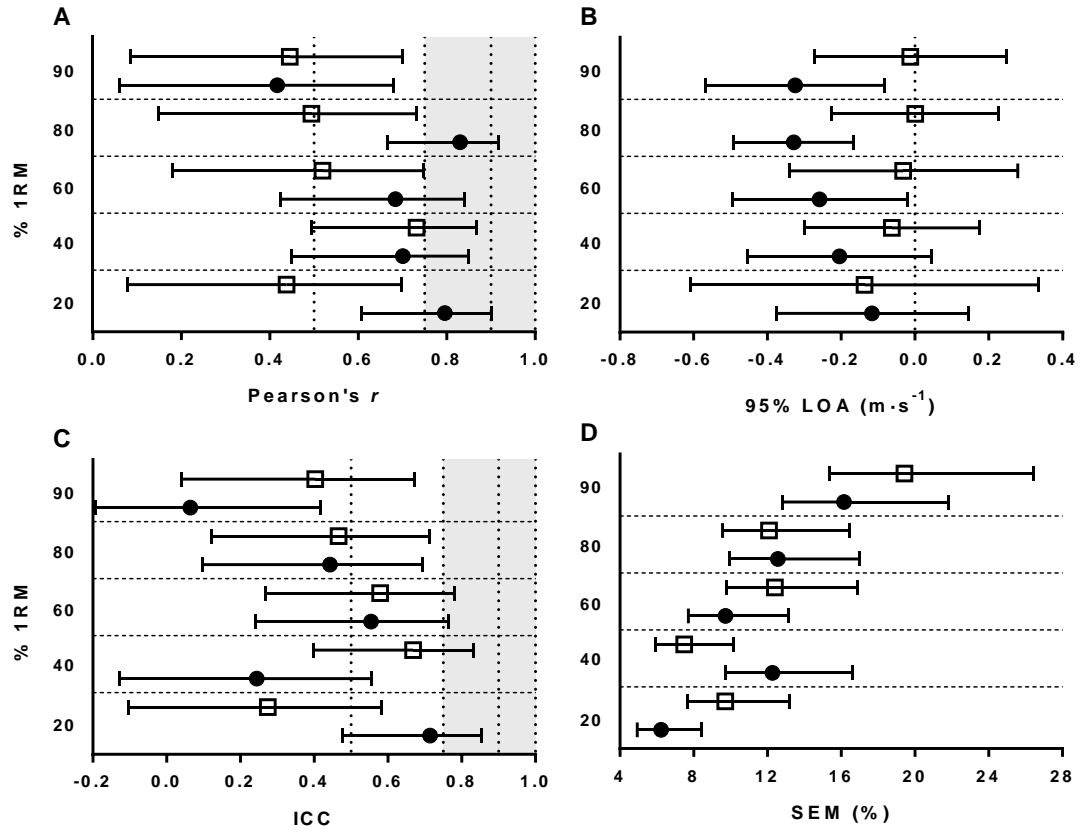
Mean velocity

● Back Squat □ Bench Press



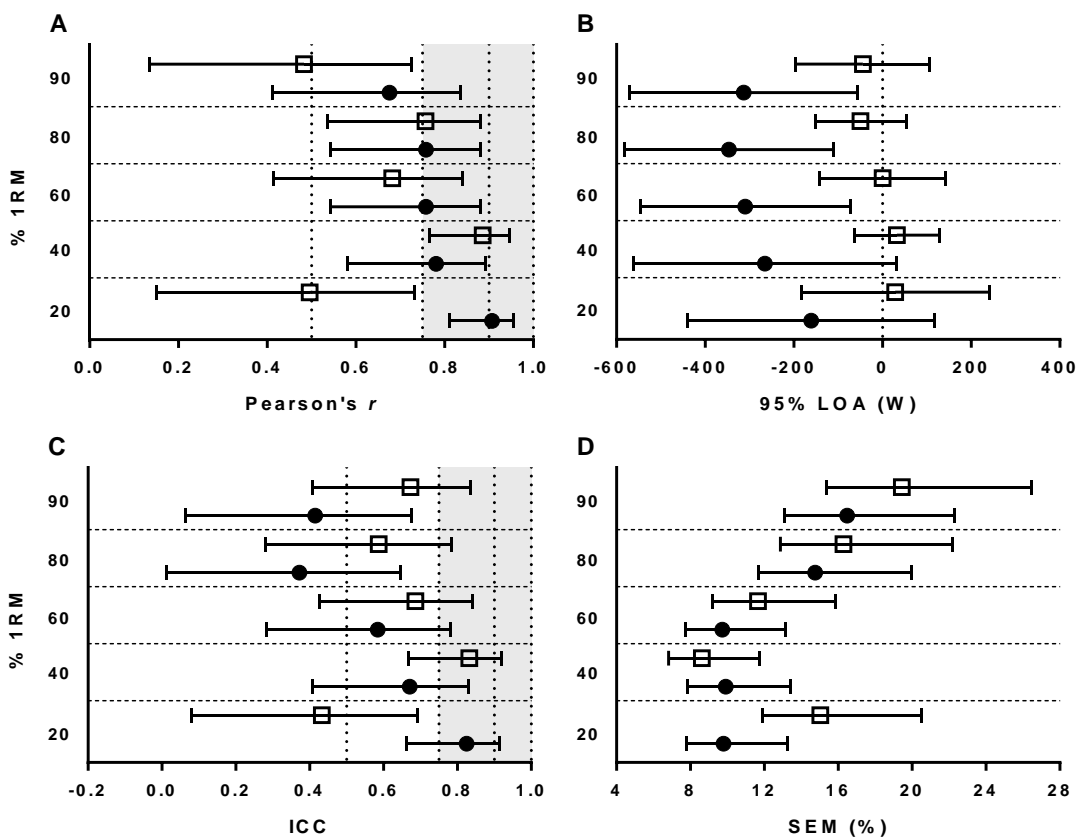
Peak velocity

● Back Squat □ Bench Press



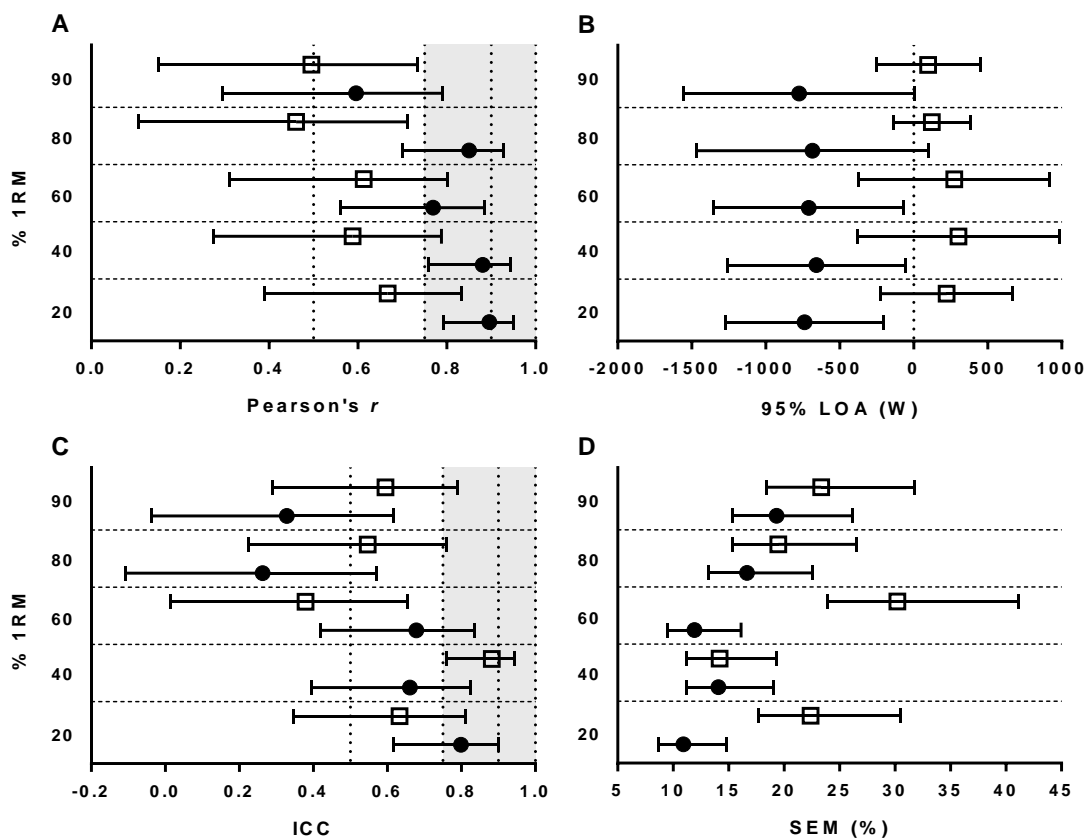
Mean power

● Back Squat □ Bench Press



Peak power

● Back Squat □ Bench Press



Supplemental Digital Content 1. Standardised mean bias between PUSH™ and GYM methods

| | Back Squat | | | | | Bench Press | | | | |
|-----------------------------------|------------|------|------|------|------|-------------|------|------|------|------|
| | 20% | 40% | 60% | 80% | 90% | 20% | 40% | 60% | 80% | 90% |
| MV (m·s ⁻¹) | 0.61 | 1.17 | 1.41 | 2.23 | 2.61 | 1.06 | 0.68 | 0.55 | 1.03 | 1.12 |
| PV (m·s ⁻¹) | 0.53 | 1.20 | 1.58 | 2.23 | 2.74 | 0.55 | 0.37 | 0.18 | 0.00 | 0.10 |
| MP (W) | 0.51 | 1.10 | 1.73 | 2.24 | 2.08 | 0.35 | 0.31 | 0.00 | 0.64 | 0.60 |
| PP (W) | 1.20 | 1.01 | 1.39 | 1.43 | 1.59 | 0.74 | 0.73 | 0.70 | 0.88 | 0.48 |

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.