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1 **VALIDITY AND RELIABILITY OF A FLYWHEEL SQUAT TEST IN SPORT**

2

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16 **ABSTRACT**

17 The aims of this study were to examine the test-retest reliability and construct validity of the
18 flywheel (FW)-squat test. Twenty male amateur team sports athletes (mean±SD: age 23±3
19 years) completed one familiarization session and two similar testing sessions including: FW-
20 squat test with an inertial load of 0.061 kg·m², standing long jump (SLJ), countermovement
21 jump (CMJ) and 5-m change of direction (COD-5m) tests, and isokinetic strength assessments
22 of the knee extensor and flexor muscles. Test-retest reliability was assessed with intraclass
23 correlation coefficient (ICC) and coefficient of variation (CV) of data collected. Construct
24 validity was determined as the degree of relationships between the FW-squat test outputs and
25 both athletic tests and isokinetic assessments scores computed with Pearson's correlation
26 coefficients. Excellent relative (ICC=0.94-0.95) and acceptable absolute (CV=5.9%-6.8%)
27 reliability scores were found for both concentric and eccentric power outputs collected during
28 the FW-squat test. The same outputs showed *moderate to large* positive correlations with
29 concentric and eccentric knee extensor and flexor muscle peak force values (r range: 0.465-
30 0.566) measured during the isokinetic test. The FW-squat test is a valid and reliable test to
31 assess lower limb performance given its correlation with isokinetic test, as well as its *excellent*
32 relative and *acceptable* absolute reliability.

33 **Key words:** iso-inertial, eccentric-overload, performance, sports, strength

34

35

36 **Introduction**

37 Since the '90s, flywheel devices have been used as training tools in resistance training
38 programs designed to improve muscular strength capabilities in both healthy active and sport
39 populations (Colliander & Tesch, 1990; Dudley, Tesch, Miller, & Buchanan, 1991). A growing
40 body of scientific evidence supports the use of this resistance training modality to induce acute
41 performance enhancements and chronic adaptations (Beato, McErlain-Naylor, Halperin, &
42 Dello Iacono, 2020; Madruga-Parera et al., 2019; Tesch, Fernandez-Gonzalo, & Lundberg,
43 2017). In fact, flywheel training was found to induce beneficial morphological changes of the
44 musculoskeletal system (*e.g.*, hypertrophy) and to improve muscular strength levels, which in
45 turn may translate into sport-specific performance (*e.g.*, jump, sprint, and agility) enhancement
46 (de Hoyo et al., 2015; Maroto-Izquierdo et al., 2017; Tesch et al., 2017). The rationale for using
47 flywheel devices in resistance training settings stems from the mechanical advantages
48 associated with this training method. Flywheel devices operate as *isoinertial* machines as
49 opposed to the common strength training methods implementing isotonic movements (Beato,
50 De Keijzer, et al., 2019; Beato, Stiff, & Coratella, 2019; Maroto-Izquierdo et al., 2017; Vicens-
51 Bordas, Esteve, Fort-Vanmeerhaeghe, Bandholm, & Thorborg, 2018). This means that
52 flywheel exercises are executed in a non-gravitatory condition, allowing the generation of
53 mechanical overload throughout the negative (eccentric) phase of the exercise by returning the
54 inertia accumulated by the rotating wheel during the precedent positive (concentric) phase
55 (Beato, De Keijzer, et al., 2019; Franchi & Maffiuletti, 2019). Inherently, this eccentric
56 mechanical load cannot be easily attained during traditional resistance exercises (Beato, Bigby,
57 et al., 2019). Augmented mechanical loads and the associated eccentric contractions are
58 advantageous for enhancing athletic performance (Beato, De Keijzer, et al., 2019; Beato,
59 Madruga-Parera, Piqueras-Sanchiz, Moreno-Pérez, & Romero-Rodriguez, 2019; Maroto-
60 Izquierdo et al., 2017). Firstly, eccentric contractions exploit greater muscular mechanical
61 efficiency in comparison to concentric contractions (Hody, Croisier, Bury, Rogister, &
62 Leprince, 2019; Zamparo, Bolomini, Nardello, & Beato, 2015) because greater levels of force
63 can be produced with less energy. Secondly, accentuated eccentric muscle contractions can
64 elicit a few beneficial neuromuscular adaptations: improved motor unit synchronization,
65 selective recruitment of higher-order motor units, and greater motor unit discharge rate (Hody
66 et al., 2019). These responses represent key aspects for muscular strength and power
67 development (Douglas, Pearson, Ross, & McGuigan, 2017).

68

69 Load monitoring is a critical component of training periodization strategies that coaches and
70 practitioners adopt to enhance performance and concurrently mitigate risk of overtraining and
71 injuries (Issurin, 2010; Sabido, Hernández-Davó, & Pereyra-Gerber, 2018). Acute responses
72 and long-term adaptations to traditional resistance training are routinely assessed by
73 monitoring the mechanical outputs associated to machine-based or free-lifting exercises
74 through the use of tracking technologies (*e.g.*, linear positioning transducers, accelerometers
75 and optical sensors) (Issurin, 2010). In particular, force, power and derivatives (rate of force
76 and rate of power) parameters are the most common and reliable measures collected for this
77 purpose. While this approach is well established and widely implemented in traditional
78 resistance training routines, an equivalent method applicable to flywheel exercises is yet to be
79 developed (Beato et al., 2020). In this regard, two main issues emerge from previous studies
80 and require further consideration. Firstly, a broad range of inertial loads (0.03–0.11 kg·m²)
81 induces similar adaptations (Beato et al., 2020; A. G. Coratella, Beato, Cè, Scurati, & Milanese,
82 2019). Secondly, the same inertial loads can result in different mechanical demands between
83 subjects. This is due to the fact that the mechanical outputs of flywheel exercises are dependent
84 on both the resistance – *inertial force* – generated by the rotating wheel and the speed of the
85 concentric and eccentric actions, which are self-paced by each subject (Sabido et al., 2018;
86 Worcester, Baker, & Bollinger, 2020). As a consequence, absolute inertial intensities (*i.e.*,
87 inertial loads) cannot be considered to compare flywheel training outputs between subjects
88 (Maroto-Izquierdo et al., 2017; Tesch et al., 2017). A valid approach overcoming these
89 limitations is to use the individual power outputs. In fact, mechanical power accounts for both
90 the inertial force and speed components, thus representing a parameter suitable for a more
91 accurate load monitoring procedure in flywheel training. Evidence about power output
92 reliability during flywheel exercises is very limited in the literature (Sabido et al., 2018), and a
93 systematic testing procedure necessary to evaluate chronic adaptations (Beato et al., 2020) has
94 not been validated yet.

95

96 In view of the growing implementation of flywheel training in sport and clinical settings, and
97 more precisely the potential of the flywheel squat (FW-squat) in serving as a performance test
98 apart from being solely a conditioning tool, an important first step is to establish the reliability
99 of the FW-squat test and to investigate whether or not it is correlated with other common type
100 of muscular strength assessments (Impellizzeri & Marcora, 2009) and athletic performances
101 (Tesch et al., 2017). Establishing the test-retest reliability of a FW-squat test will allow coaches
102 and exercise scientists to calculate the precision of the test results and the associated confidence

103 interval limits, which are necessary to further detect real changes in performances, and to
104 develop an appreciation for day-to-day performance variability in training and testing. By
105 investigating the extent to which the FW-squat correlates with performances in tests considered
106 as gold standard methods in a particular field of research, it a necessary step to corroborate its
107 construct validity. In this regard, isokinetic assessment of concentric and eccentric torques of
108 the knee extensors and flexors muscles are considered as the gold standard method of strength
109 assessment and routinely included in athletic testing (Impellizzeri, Bizzini, Rampinini, Cereda,
110 & Maffiuletti, 2008). Both knee extensors and flexion peak torques are positively correlated
111 with athletic performance such as sprinting speed, jumping, and change of direction
112 performance (G. Coratella, Beato, & Schena, 2018). However, isokinetic machines are very
113 expensive and of limited availability. For financial and logistical reasons, many athletes have
114 limited access to this device. Therefore, tests that incorporate similar muscle groups and that
115 correlate with performances of both the isokinetic test and athletic tasks could serve as an
116 affordable and accessible alternative.

117

118 To the best of our knowledge, the reliability of flywheel related mechanical outputs has been
119 previously investigated only in two studies (Sabido et al., 2018; Weakley, Fernández-Valdés,
120 Thomas, Ramirez-Lopez, & Jones, 2019), while the relationships of these measures with gold-
121 standard parameters for strength assessment (*i.e.*, isokinetic torques) and athletic tasks
122 performances are not reported in the literature. Accordingly, the aims of this study were
123 twofold. The first was to establish the test-retest reliability of the power outputs of the FW-
124 squat test across two separate days. The second was to establish the correlations between the
125 FW-squat test power outputs with the isokinetic peak concentric and eccentric torques of the
126 knee extensors and flexors, and performances in athletic tasks such as standing long jump
127 (SLJ), countermovement jump (CMJ), and 5-m change of direction (COD-5m).

128

129 **Methods**

130

131 **Participants**

132 An *a priori* power analysis using G-power indicated that a total sample of 20 subjects would
133 be required to detect a *large* correlation ($r=0.60$) with 80% power and an alpha of 5%. Twenty
134 male amateur university athletes (mean \pm SD: age 23 ± 3 years; body mass 75.5 ± 15.7 kg;
135 height 1.80 ± 0.07 m) participated in this study. The subjects were 12 soccer players, 2 rugby
136 players, and 6 resistance trained athletes. Inclusive criteria for participation were the absence

137 of any injury or illness and regular participation in training activities (a minimum of 2 training
138 sessions per week), as well as, subjects should have at least 1 year of experience in both
139 traditional resistance training and flywheel exercises. All subjects were informed about the
140 potential risks and benefits associated to the procedures of this study before giving written
141 consent. The Ethics Committee of the School of Health and Sports Sciences at the University
142 of Suffolk (UK) approved this study (SREC011/RT). All procedures were conducted according
143 to the Declaration of Helsinki for studies involving human subjects.

144

145 **Procedure**

146 This study evaluated the test-retest reliability of a FW-squat test as well as the correlations with
147 athletic performances and isokinetic test scores using a correlation design. The study was
148 conducted over a 2-week period during which the participants attended the laboratory on three
149 separate occasions (study design reported in Figure 1).

150

151 *****Figure 1 here, please*****

152

153 The first visit served to familiarize the subjects with the flywheel device (Hody et al., 2019;
154 Sabido et al., 2018) and the testing protocols used in this study. During the second occasion,
155 body mass and height were recorded through a standard stadiometer (Seca 286dp; Seca,
156 Hamburg, Germany). Then, baseline measures for SLJ, CMJ, COD-5m, isokinetic test, and
157 FW-squat test were collected. This specific testing order and a passive recovery interval of 5
158 min were maintained between the tests in order to ensure adequate recovery and limit the likely
159 negative effect due to fatigue on the following task. One week later, on the third occasion
160 participants repeated the same standardized procedures. During each session, subjects
161 performed a standardized warm-up including 10 min of cycling at a constant power (1·W per
162 kg of body mass) on an ergometer (Sport Excalibur lode, Groningen, Netherlands) followed by
163 dynamic mobilization exercises (Beato, Bigby, et al., 2019; Beato, Stiff, et al., 2019; de
164 Keijzer, McErlain-Naylor, Dello Iacono, & Beato, 2020). Each testing session was performed
165 at the same time of day (9 am to 12.00 pm) in order to reduce the effect of circadian rhythms
166 on performance. Moreover, participants were instructed to avoid intense training 24 hours
167 before each day of testing, prohibited from consuming any known stimulant (*e.g.*, caffeine) or
168 depressant (*e.g.*, alcohol) substances for 24 hours before testing, and instructed to rehydrate *ad*
169 *libitum*.

170

171 *Standing long jump (SLJ)*

172 A SLJ test was used to assess the horizontal non-rebounding jumping capability (de Keijzer et
173 al., 2020). Subjects stood just behind a line marked on the floor, and then jumped as far as
174 possible with the use of arm swing. Jump distance was measured from the starting line to the
175 point at which the heel contacted the ground on landing (Beato, Bianchi, Coratella, Merlini, &
176 Drust, 2018). The validity and reliability of this test were previously reported in literature
177 (Markovic, Dizdar, Jukic, & Cardinale, 2004). Three SLJ tests were performed and the best
178 result was recorded. The recovery between the trials was 1 min.

179

180 *Countermovement jump (CMJ)*

181 Vertical jump performance was assessed with the CMJ (de Keijzer et al., 2020; Rodriguez-
182 Rosell, Mora-Custodio, Franco-Márquez, Yáñez-García, & González-Badillo, 2016). Subjects
183 were instructed to keep their hands on their hips to prevent the influence of arm movements.
184 Starting position was stationary, erect, with knees fully extended. The subjects then squatted
185 down to a self-selected depth before starting a powerful upward motion. They were instructed
186 to jump as high as possible, and verbal encouragement was provided to each subject before
187 each trial. Each subject performed three trials with passive recovery of 1 min between jumps,
188 and the best result was recorded. The height of each jump (cm) was assessed with the Optojump
189 apparatus (Optojump Next, Microgate, Bolzano, Italy).

190

191 *Change of direction (COD)*

192 COD was tested via the 5 m shuttle run (COD-5m) consisting of 2 x 5 m sprints separated by
193 a dominant leg unilateral 180° turn (Chaouachi et al., 2012). The dominant leg was defined as
194 the preferred limb used to kick the ball. One pair of infrared timing gates (Microgate, Bolzano,
195 Italy) were positioned at the start and end line position of the COD test set up. Tests started on
196 the “Go” command from a standing position, with the front foot 0.2 m from the photocell beam
197 (Beato et al., 2018). Three COD-5m tests were performed and the best result was recorded.
198 The recovery between the trials was 1 min.

199

200 *Isokinetic strength test*

201 An isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) was used to
202 measure the knee extensor and flexors muscles torques of the dominant limb. The procedures
203 followed previous recommendations (G. Coratella et al., 2018): briefly, the device was
204 calibrated according to the manufacturer’s guidelines and the center of rotation was aligned

205 with the tested knee. Subjects were seated on the dynamometer chair, with their trunks slightly
206 reclined backwards and a hip angle of 95 degrees. Two seatbelts secured the trunk, and one
207 strap secured the tested limb, while the untested limb was secured by an additional lever. Each
208 testing modality consisted of 3 maximal repetitions and was separated by 2 min of passive
209 recovery. The knee extensor muscles peak torque was measured in concentric (60 s^{-1}), and the
210 knee flexor muscles peak torque was measured in concentric (60 s^{-1}) and eccentric (60 s^{-1})
211 modality (Beato, Stiff, et al., 2019). Verbal encouragements were provided to the participants
212 to maximize performance.

213

214 *Flywheel half squat test*

215 FW-squat test was performed using a standardized ergometer (D11 Full, Desmotec, Biella,
216 Italy). The protocol consisted of 3 sets of 6 repetitions (2 initial repetitions were performed to
217 attain the initial momentum) each at maximal intended velocity, interspersed by 2 min of
218 passive recovery. This protocol, consisting of 6 squat repetitions, was selected in order to avoid
219 a power decrement due to transient fatigue as previously reported (Sabido et al., 2018) and to
220 obtain power optimization (Beato, Bigby, et al., 2019). The following load was used for each
221 participant: one pro disc (diameter = 0.285 m; mass = 6.0 kg; inertia = 0.060 kg m^2). The inertia
222 of the ergometer was estimated as 0.0011 kg m^2 , therefore the total inertia load was 0.061
223 kg m^2 . This inertia load was selected based on the power outputs and inertia load used by
224 Sabido et al. (Sabido et al., 2018) and Beato et al. (Beato, Bigby, et al., 2019). Previous research
225 reported that an inertia range from 0.03 to 0.09 kg m^2 may optimize power outputs during a
226 squat exercise (Sabido et al., 2018), while, higher inertial loads (*e.g.*, 0.1 kg m^2) may
227 significantly reduce power outputs during flywheel squats primarily by decreasing movement
228 velocity (Worcester et al., 2020). Power was monitored for each repetition using an integrated
229 rotatory position transducer (Beato, Bigby, et al., 2019). The FW-squat test reported two power
230 outputs (concentric and eccentric power in watts). In this study, the average of the peak power
231 outputs of the 6 repetitions of the second and third sets were recorded, while the first set was
232 excluded from the average calculation (because the power output in the first set was generally
233 lower than the following two sets). The subjects were instructed to perform the concentric
234 phase with maximal velocity and to achieve approximately 90° of knee flexion during the
235 eccentric phase, which was controlled. Each movement was evaluated qualitatively by an
236 investigator, offering kinematic feedback to the athletes as well as strong standardized
237 encouragements to maximally perform each repetition (Beato, Stiff, et al., 2019). The flywheel

238 procedure reported in this study was previously utilized with this ergometer and its full
239 description has been recently published (Beato, Bigby, et al., 2019; Beato, Stiff, et al., 2019).

240

241 *Statistical Analyses*

242 Data were analyzed by using JASP software (version 0.9.2; JASP, Amsterdam, The
243 Netherlands). Data are presented as mean \pm standard deviation (SD). The Shapiro-Wilk test
244 was used to determine whether data were normally distributed. The test-retest (session 2 vs.
245 session 3) relative reliability was assessed using the intraclass correlation coefficient (ICC) test
246 and interpreted as follows: $ICC > 0.9 = excellent$; $0.9 > ICC > 0.8 = good$; $0.8 > ICC > 0.7 =$
247 *acceptable*; $0.7 > ICC > 0.6 = questionable$; $0.6 > ICC > 0.5 = poor$; $ICC < 0.5 = unacceptable$
248 (Atkinson & Nevill, 1998). Technical error of estimate (TEE) was calculated using the
249 following formula: $TEE = SD \cdot \sqrt{1 - ICC}$. TE was reported in association with the smallest
250 worthwhile change (SWC) calculated as 0.2 multiplied by the between-subject SD. Coefficient
251 of variation (CV), which represent absolute reliability, was reported and considered *good* and
252 *acceptable* with values $< 5\%$ and between 5% and 10%, respectively (Cormack, Newton,
253 McGuigan, & Doyle, 2008). 95% confidence intervals (CI) were also reported for all the
254 reliability and correlation scores. Pearson's correlation coefficient (r) were computed to assess
255 the relationship between FW-squat test power outputs and performance for all tests. The
256 strength of the relationship was assessed as $< 0.1 = trivial$; $0.1 - 0.3 = small$; $0.3 - 0.5 = moderate$;
257 $0.5 - 0.7 = large$; $0.7 - 0.9 = very large$; and $0.9 - 1.0 = almost perfect$. Statistical significance was
258 set at $p < 0.05$.

259

260 **Results**

261 FW-squat test concentric ($w = 0.924$, $p = 0.117$) and eccentric ($w = 0.937$, $p = 0.207$) power
262 outputs were both normally distributed. Test-retest reliability for SLJ, CMJ, COD-5m,
263 isokinetic test parameters and FW-squat test are reported in Table 1.

264

265 *****Please, Table 1 here*****

266

267 Test-retest reliability analysis revealed no significant differences for the FW-squat test
268 concentric ($t = 0.277$, $p = 0.785$) and eccentric power outputs ($t = 0.179$, $p = 0.860$). Test-retest
269 differences (Δ) were -8W (95% CI -68, 52W) and -5W (95% CI -61, 52W) for concentric and
270 eccentric output, respectively. Δ differences for concentric and eccentric FW-squat test were
271 smaller than the SWC (55 vs 61 W, respectively, Table 1).

272

273 Relationships between FW-squat test relative and absolute power outputs and performance in
274 SLJ, CMJ, COD-5m and isokinetic tests are reported in Table 2.

275

276

Please, Table 2 here

277

278 **Discussion**

279 The aims of this study were to examine the test-rest reliability of the power outputs collected
280 during the FW-squat test and to establish their relationships both with lower limbs strength
281 measured with an isokinetic device and dynamic performances assessed through athletic tests.
282 *Excellent* relative reliability (ICC) and *acceptable* absolute (CV) scores were detected between
283 days for the FW-squat test power outputs (Table 1). Both concentric and eccentric power
284 outputs of the FW-squat test showed *moderate to large* positive correlations with peak
285 concentric knee extensor torques, and both concentric and eccentric knee flexor torques (Table
286 2). The FW-squat test can be considered as reliable, associated with performance in commonly
287 used isokinetic lower limb assessments, and as such implementable as monitoring and testing
288 procedure in flywheel training. Finally, FW-squat test cannot be considered as a substitute of
289 commonly used field test such as SLJ, CMJ and COD-5m, but as a valid and reliable addition.

290

291 In view of the growing research interest and broad implementation of the FW-squat exercise
292 in applied settings (Tesch et al., 2017), examining its day-to-day performance variability is of
293 key value allows scientists and practitioners to assess performance outcomes and training
294 effects in a more sensitive and accurate manner. The test-retest reliability scores of the FW-
295 squat test observed in this study are very encouraging and comparable to other very common
296 field and isokinetic strength tests, with ICC and CV% ranging from 0.92 to 0.97 and from 2.0%
297 to 5.5%, respectively (Table 1). The familiarization completed before the actual FW-squat
298 testing sessions and the specific experience with flywheel training of the participants of this
299 study may have contributed to ensure consistency of the performance scores across the test-
300 retest sessions thus reducing the error in the test. However, this finding should be interpreted
301 with caution. In fact, the SWC scores of both the concentric (55 W) and eccentric (61 W) power
302 outputs were smaller than the TEEs of the same measures (67 W and 68 W for concentric and
303 eccentric power outputs, respectively). TEE is defined as the noise or uncertainty of the test,
304 which should be preferably lower than the correspondent SWC (Impellizzeri & Marcora,
305 2009), which represents the minimum variation interpretable as meaningful with an acceptable

306 probability (Hopkins, Marshall, Batterham, & Hanin, 2009). Therefore, the results of this study
307 (TEE > SWC) question the sensitivity of the FW-squat related scores in detecting small but
308 important variations. This finding aligns to what is generally reported in the sport science
309 literature (Dugdale, Arthur, Sanders, & Hunter, 2019; Silva, Nassis, & Rebelo, 2015) whereby
310 intra-individual inconsistency in athletic performance is commonly observed and explained by
311 the daily fluctuations of biological and physiological mechanisms underpinning athletic tasks.
312 Nevertheless, the reliability scores of FW-squat test were found acceptable, with concentric
313 and eccentric power outputs CVs% equal to 5.9% and 6.8%, respectively. This is a finding of
314 practical value considering that the similar relative reliability (ICC > 0.90) and absolute
315 reliability (CV ranging from 4.3% to 7.7%) of isokinetic tests reported in the literature
316 (Impellizzeri et al., 2008), which are in agreement with the isokinetic reliability reported in this
317 study (Table 1). Therefore, this study supports the reliability of the FW-squat test but suggest
318 considering changes in scores greater than 5.9% and 6.8% for concentric and eccentric power,
319 respectively, as to infer real changes in performance.

320

321 The *moderate to large* correlations between the FW-squat test power outputs and the isokinetic
322 peak torque values are also a finding with relevant and practical value (Table 2). This
323 association likely arises from the similar muscle action and neuromuscular responses
324 associated with the FW-squat and both the isokinetic knee extensors and flexors muscles. In
325 fact, while the FW-squat requires a nearly maximal activation of the knee extensors during
326 both the concentric and eccentric phases, the recruitment of the antagonist knee flexors
327 primarily occurs during the downward phase of the squat when attempting to counteract the
328 inertial momentum and to break the movement into a stop. Indeed, the likely lower recruitment
329 and contribution of the knee flexors in terms of force production necessary to complete the
330 FW-squat test can assist explaining the weaker (*moderate*) correlations compared with the
331 torques produced by the extensor muscles (*large*). Interestingly, the correlation between FW-
332 squat test and isokinetic eccentric hamstring torques were greater than the concentric torques
333 produced by the same muscles. This finding is not completely surprising and appears in line
334 with the role of force absorbers the knee flexor muscles have during the downward phase of
335 the squat. In particular, the hamstring muscles are of bi-articular nature, occupy the posterior
336 compartment of the thigh crossing both the hip and the knee joints. During the downward phase
337 of the FW-squat, the trunk segment progressively leans forward and rotates around the hip
338 horizontal axis thus requiring the hamstring muscles to forcefully act in an eccentric mode so
339 to provide an adequate force absorption and contribute to control the augmented negative body

340 momentum (Aspe & Swinton, 2014; Dello Iacono, Ayalon, & Wang, 2019; Maddigan, Button,
341 & Behm, 2014). Finally, *small* to *moderate* non-significant relationships were found between
342 the power outputs of the FW-squat test and SLJ, CMJ, and COD-5m performances. These
343 findings are not unexpected when considering the biomechanical dissimilarities in force
344 production demands between the FW-squat test, which is a non-gravitatory based exercise and
345 the common field assessments. Moreover, both the SLJ and the COD-5m are horizontal in
346 nature, with predominant antero-posterior and medio-lateral forces production demands, which
347 likely explain the *small* relationship with the FW-squat test (Dello Iacono, Martone, Milic, &
348 Padulo, 2017; Dello Iacono, Martone, & Padulo, 2016). Despite the *small* to *moderate*
349 correlations between FW-squat test and field-based assessments, the *excellent* relative and
350 *acceptable* absolute reliability of the FW-squat test and *moderate* to *large* positive correlations
351 with isokinetic peak torque values, supports its use as an alternative or additional test alongside
352 other assessment tools regularly implemented in sport science domains.

353

354 This study is not without limitations. Firstly, these results can only be generalized to (a) male
355 athletes, (b) who are experienced with the FW-squat exercise (1 year), (c) who completed at
356 least one familiarization session before the actual test-retest procedures and (d) who are highly
357 motivated (Hody et al., 2019; Sabido et al., 2018). Future studies should investigate the number
358 of familiarization sessions necessary to obtain comparable reliable data also in female
359 participants, not necessarily athletes and with limited or null resistance training and flywheel
360 training experience. Secondly, the choice of the inertia utilized in this test is another limiting
361 factor. We have selected an intermediate inertial load of $0.06 \text{ kg}\cdot\text{m}^2$ based on available
362 literature recommending a broad range of inertias (0.03 to $0.11 \text{ kg}\cdot\text{m}^2$) to induce acute and
363 chronic adaptations from (Beato et al., 2020; Maroto-Izquierdo et al., 2017). However, the
364 choice of an absolute inertial load cannot be generalized across subjects and athletes from
365 different sport disciplines and with heterogeneous fitness levels and strength characteristics.
366 Lastly, building on the findings of this study that investigated only the construct validity of the
367 FW-squat test, future investigation are warranted to examine its longitudinal validity or ability
368 to measure changes in the reference performance measure (responsiveness) (Husted, Cook,
369 Farewell, & Gladman, 2000).

370

371 In conclusion, this is the first study reporting the reliability and construct validity of a FW-
372 squat test. The FW squat test resulted in *excellent* (ICC) and *acceptable* (CV) reliability scores
373 for both the concentric and eccentric power outputs. These values provide initial guidelines

374 allowing practitioners to understand what variability can be considered a real change in
375 comparison with random performance fluctuations. This study also reported *moderate to large*
376 relationships between the FW-squat test performance scores and isokinetic lower limb strength
377 parameters. Therefore, FW-squat test can be a valid and reliable alternative test to assess lower
378 limbs performance following training intervention which mainly targets the knee extensor and
379 flexor muscles. Since the large utilization of flywheel devices in sport and research settings,
380 the validation of this test is the first step for a more accurate and sensitive evaluation of
381 flywheel training adaptations and associated transfer effects on performance. However,
382 practitioners are strongly advised to familiarize their athletes with the testing procedure to
383 ensure reliable results. In conclusion, sports scientists can use the FW-squat test loaded with
384 an inertia of 0.061 kg·m² as a valid monitoring tool informing performance assessment and
385 training periodization practices.

386

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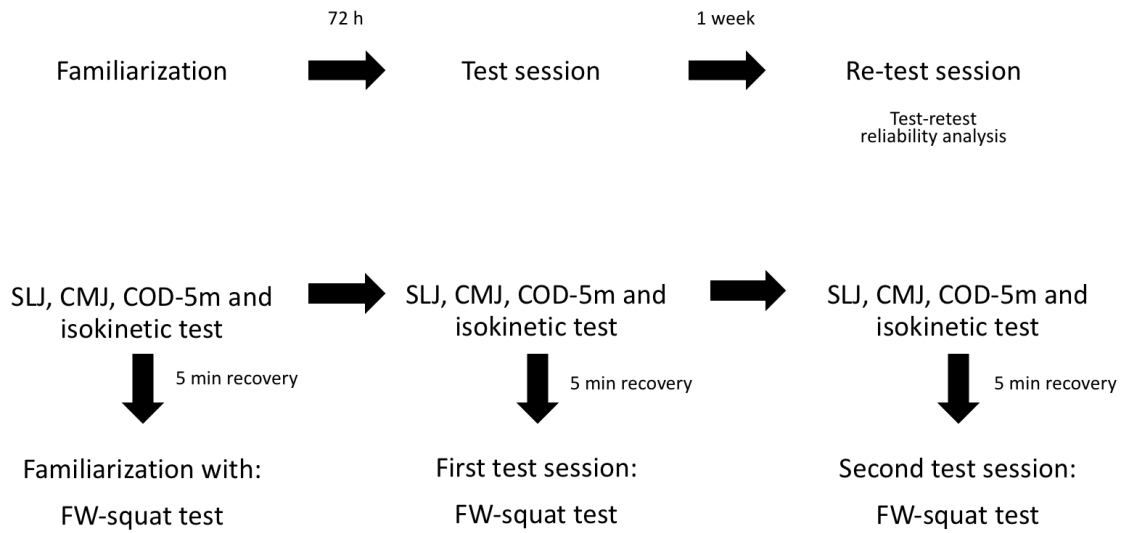
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544 **Figure 1. Testing procedure**

545 Standing long jump (SLJ), countermovement jump (CMJ), 5-m change of direction (COD-
546 5m), FW = flywheel.



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573 Table 1. Reliability data recorded during test-retest procedure (20 subjects).

Variables	Test 1 (mean ± SD)	Test 2 (mean ± SD)	Test-retest reliability ICC (95% CI)	Reliability qualitative interpretation	Test-retest reliability TE (CV%)	Reliability qualitative interpretation	SWC
SLJ (cm)	261±21	266±24	0.94 (0.85, 0.97)	<i>Excellent</i>	5.14 (2.0%)	<i>Acceptable</i>	4.2
CMJ (cm)	40.1±6.9	41.2±7.3	0.97 (0.94, 0.99)	<i>Excellent</i>	1.3 (3.0%)	<i>Good</i>	1.5
COD-5m (sec)	2.81±0.20	2.80±0.18	0.92 (0.82, 0.97)	<i>Excellent</i>	0.06 (2.0%)	<i>Good</i>	0.04
Isokinetic quad con (Nm)	214±52	221±54	0.95 (0.93, 0.97)	<i>Excellent</i>	12 (5.5%)	<i>Acceptable</i>	11
Isokinetic ham con (Nm)	142±31	144±25	0.93 (0.89, 0.97)	<i>Excellent</i>	7 (4.6%)	<i>Good</i>	5
Isokinetic ham ecc (Nm)	180±35	187±30	0.93 (0.85, 0.96)	<i>Excellent</i>	8 (4.2%)	<i>Good</i>	6
FW-squat test con (W)	1012±297	1120±274	0.94 (0.86, 0.97)	<i>Excellent</i>	67 (5.9%)	<i>Acceptable</i>	55
FW-squat test ecc (W)	988±301	993±302	0.95 (0.89, 0.93)	<i>Excellent</i>	68 (6.8%)	<i>Acceptable</i>	61

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575 ICC = intra-class correlation coefficient, TE = Technical error of measurement, CV = coefficient of variation, SWC = smallest worthwhile change, CI =
 576 Confidence Intervals, standing long jump (SLJ), countermovement jump (CMJ), 5-m change of direction (COD-5m), FW = flywheel, cm = centimetres,
 577 s = seconds.

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579 Table 2. Relationship between FW squat test power outputs and performance for SLJ, CMJ, COD-5m and Isokinetic test parameters (20 subjects).

580 Data are reported with r (strength of the relationship) and 95% CI.

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Variables	SLJ (cm)	CMJ (cm)	COD-5m (sec)	Isokinetic quad concentric (Nm)	Isokinetic ham concentric (Nm)	Isokinetic ham eccentric (Nm)	FW-squat test concentric (W)	FW-squat test eccentric (W)
FW-squat test concentric (W)	.123 (-.338, .536) <i>small</i>	.312 (-.151, .663) <i>moderate</i>	.225 (-.242, .607) <i>small</i>	.534* (.120, .790) <i>large</i>	.472* (.038, .757) <i>moderate</i>	.516* (.096, .780) <i>large</i>	-	.940* (.851, .976) <i>almost perfect</i>
FW-squat test eccentric (W)	.243 (-.224, .619) <i>small</i>	.430 (-.016, .733) <i>moderate</i>	.130 (-.332, .541) <i>small</i>	.556* (.151, .801) <i>large</i>	.465* (.028, 0.75) <i>moderate</i>	.502* (.077, .773) <i>large</i>	.940* (.851, .976) <i>almost perfect</i>	-

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583 CI = Confidence Intervals, r = Pearson correlation coefficient, SLJ = Standing long jump, CMJ = Countermovement jump, COD-5m = 5-m change of direction,

584 FW = Flywheel, cm = centimetres, s = seconds, * = p < 0.05.

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