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VALIDITY AND RELIABILITY OF A FLYWHEEL SQUAT TEST IN SPORT

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ABSTRACT

The aims of this study were to examine the test-retest reliability and construct validity of the flywheel (FW)-squat test. Twenty male amateur team sports athletes (mean±SD: age 23±3 years) completed one familiarization session and two similar testing sessions including: FW-squat test with an inertial load of 0.061 $kg \cdot m^2$, standing long jump (SLJ), countermovement jump (CMJ) and 5-m change of direction (COD-5m) tests, and isokinetic strength assessments of the knee extensor and flexor muscles. Test-retest reliability was assessed with intraclass correlation coefficient (ICC) and coefficient of variation (CV) of data collected. Construct validity was determined as the degree of relationships between the FW-squat test outputs and both athletic tests and isokinetic assessments scores computed with Pearson's correlation coefficients. Excellent relative (ICC=0.94-0.95) and acceptable absolute (CV=5.9%-6.8%) reliability scores were found for both concentric and eccentric power outputs collected during the FW-squat test. The same outputs showed *moderate* to *large* positive correlations with concentric and eccentric knee extensor and flexor muscle peak force values (r range: 0.465-0.566) measured during the isokinetic test. The FW-squat test is a valid and reliable test to assess lower limb performance given its correlation with isokinetic test, as well as its *excellent* relative and *acceptable* absolute reliability.

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

Introduction

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

Load monitoring is a critical component of training periodization strategies that coaches and practitioners adopt to enhance performance and concurrently mitigate risk of overtraining and injuries (Issurin, 2010; Sabido, Hernández-Davó, & Pereyra-Gerber, 2018). Acute responses and long-term adaptations to traditional resistance training are routinely assessed by monitoring the mechanical outputs associated to machine-based or free-lifting exercises through the use of tracking technologies (*e.g.*, linear positioning transducers, accelerometers and optical sensors) (Issurin, 2010). In particular, force, power and derivatives (rate of force and rate of power) parameters are the most common and reliable measures collected for this purpose. While this approach is well established and widely implemented in traditional resistance training routines, an equivalent method applicable to flywheel exercises is yet to be developed (Beato et al., 2020). In this regard, two main issues emerge from previous studies and require further consideration. Firstly, a broad range of inertial loads (0.03–0.11 kg·m^2) induces similar adaptations (Beato et al., 2020; A. G. Coratella, Beato, Cè, Scurati, & Milanese, 2019). Secondly, the same inertial loads can result in different mechanical demands between subjects. This is due to the fact that the mechanical outputs of flywheel exercises are dependent on both the resistance – *inertial force* – generated by the rotating wheel and the speed of the concentric and eccentric actions, which are self-paced by each subject (Sabido et al., 2018; Worcester, Baker, & Bollinger, 2020). As a consequence, absolute inertial intensities (i.e., inertial loads) cannot be considered to compare flywheel training outputs between subjects (Maroto-Izquierdo et al., 2017; Tesch et al., 2017). A valid approach overcoming these limitations is to use the individual power outputs. In fact, mechanical power accounts for both the inertial force and speed components, thus representing a parameter suitable for a more accurate load monitoring procedure in flywheel training. Evidence about power output reliability during flywheel exercises is very limited in the literature (Sabido et al., 2018), and a systematic testing procedure necessary to evaluate chronic adaptations (Beato et al., 2020) has not been validated yet.

In view of the growing implementation of flywheel training in sport and clinical settings, and more precisely the potential of the flywheel squat (FW-squat) in serving as a performance test apart from being solely a conditioning tool, an important first step is to establish the reliability of the FW-squat test and to investigate whether or not it is correlated with other common type of muscular strength assessments (Impellizzeri & Marcora, 2009) and athletic performances (Tesch et al., 2017). Establishing the test-retest reliability of a FW-squat test will allow coaches and exercise scientists to calculate the precision of the test results and the associated confidence interval limits, which are necessary to further detect real changes in performances, and to develop an appreciation for day-to-day performance variability in training and testing. By investigating the extent to which the FW-squat correlates with performances in tests considered as gold standard methods in a particular field of research, it a necessary step to corroborate its construct validity. In this regard, isokinetic assessment of concentric and eccentric torques of the knee extensors and flexors muscles are considered as the gold standard method of strength assessment and routinely included in athletic testing (Impellizzeri, Bizzini, Rampinini, Cereda, & Maffiuletti, 2008). Both knee extensors and flexion peak torques are positively correlated with athletic performance such as sprinting speed, jumping, and change of direction performance (G. Coratella, Beato, & Schena, 2018). However, isokinetic machines are very expensive and of limited availability. For financial and logistical reasons, many athletes have limited access to this device. Therefore, tests that incorporate similar muscle groups and that correlate with performances of both the isokinetic test and athletic tasks could serve as an affordable and accessible alternative.

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

Methods

Participants

An *a priori* power analysis using G-power indicated that a total sample of 20 subjects would be required to detect a *large* correlation (r=0.60) with 80% power and an alpha of 5%. Twenty male amateur university athletes (mean ± SD: age 23 ± 3 years; body mass 75.5 ± 15.7 kg; height 1.80 ± 0.07 m) participated in this study. The subjects were 12 soccer players, 2 rugby players, and 6 resistance trained athletes. Inclusive criteria for participation were the absence of any injury or illness and regular participation in training activities (a minimum of 2 training sessions per week), as well as, subjects should have at least 1 year of experience in both traditional resistance training and flywheel exercises. All subjects were informed about the potential risks and benefits associated to the procedures of this study before giving written consent. The Ethics Committee of the School of Health and Sports Sciences at the University of Suffolk (UK) approved this study (SREC011/RT). All procedures were conducted according to the Declaration of Helsinki for studies involving human subjects.

Procedure

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

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

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

Standing long jump (SLJ)

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

Countermovement jump (CMJ)

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

Change of direction (COD)

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

Isokinetic strength test

An isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) was used to measure the knee extensor and flexors muscles torques of the dominant limb. The procedures followed previous recommendations (G. Coratella et al., 2018): briefly, the device was calibrated according to the manufacturer’s guidelines and the center of rotation was aligned with the tested knee. Subjects were seated on the dynamometer chair, with their trunks slightly reclined backwards and a hip angle of 95 degrees. Two seatbelts secured the trunk, and one strap secured the tested limb, while the untested limb was secured by an additional lever. Each testing modality consisted of 3 maximal repetitions and was separated by 2 min of passive recovery. The knee extensor muscles peak torque was measured in concentric ($60^{\cdot}s^{-1}$), and the knee flexor muscles peak torque was measured in concentric ($60^{\cdot}s^{-1}$) and eccentric ($60^{\cdot}s^{-1}$) modality (Beato, Stiff, et al., 2019). Verbal encouragements were provided to the participants to maximize performance.

Flywheel half squat test

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

Statistical Analyses

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

Results

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

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

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

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

*****Please, Table 2 here*****

Discussion

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

In view of the growing research interest and broad implementation of the FW-squat exercise in applied settings (Tesch et al., 2017), examining its day-to-day performance variability is of key value allows scientists and practitioners to assess performance outcomes and training effects in a more sensitive and accurate manner. The test-retest reliability scores of the FW-squat test observed in this study are very encouraging and comparable to other very common field and isokinetic strength tests, with ICC and CV% ranging from 0.92 to 0.97 and from 2.0% to 5.5%, respectively (Table 1). The familiarization completed before the actual FW-squat testing sessions and the specific experience with flywheel training of the participants of this study may have contributed to ensure consistency of the performance scores across the test-retest sessions thus reducing the error in the test. However, this finding should be interpreted with caution. In fact, the SWC scores of both the concentric (55 W) and eccentric (61 W) power outputs were smaller than the TEEs of the same measures (67 W and 68 W for concentric and eccentric power outputs, respectively). TEE is defined as the noise or uncertainty of the test, which should be preferably lower than the correspondent SWC (Impellizzeri & Marcora, 2009), which represents the minimum variation interpretable as meaningful with an acceptable probability (Hopkins, Marshall, Batterham, & Hanin, 2009). Therefore, the results of this study (TEE > SWC) question the sensitivity of the FW-squat related scores in detecting small but important variations. This finding aligns to what is generally reported in the sport science literature (Dugdale, Arthur, Sanders, & Hunter, 2019; Silva, Nassis, & Rebelo, 2015) whereby intra-individual inconsistency in athletic performance is commonly observed and explained by the daily fluctuations of biological and physiological mechanisms underpinning athletic tasks. Nevertheless, the reliability scores of FW-squat test were found acceptable, with concentric and eccentric power outputs CVs% equal to 5.9% and 6.8%, respectively. This is a finding of practical value considering that the similar relative reliability (ICC > 0.90) and absolute reliability (CV ranging from 4.3% to 7.7%) of isokinetic tests reported in the literature (Impellizzeri et al., 2008), which are in agreement with the isokinetic reliability reported in this study (Table 1). Therefore, this study supports the reliability of the FW-squat test but suggest considering changes in scores greater than 5.9% and 6.8% for concentric and eccentric power, respectively, as to infer real changes in performance.

The *moderate to large* correlations between the FW-squat test power outputs and the isokinetic peak torque values are also a finding with relevant and practical value (Table 2). This association likely arises from the similar muscle action and neuromuscular responses associated with the FW-squat and both the isokinetic knee extensors and flexors muscles. In fact, while the FW-squat requires a nearly maximal activation of the knee extensors during both the concentric and eccentric phases, the recruitment of the antagonist knee flexors primarily occurs during the downward phase of the squat when attempting to counteract the inertial momentum and to break the movement into a stop. Indeed, the likely lower recruitment and contribution of the knee flexors in terms of force production necessary to complete the FW-squat test can assist explaining the weaker (*moderate*) correlations compared with the torques produced by the extensor muscles (*large*). Interestingly, the correlation between FW-squat test and isokinetic eccentric hamstring torques were greater than the concentric torques produced by the same muscles. This finding is not completely surprising and appears in line with the role of force absorbers the knee flexor muscles have during the downward phase of the squat. In particular, the hamstring muscles are of bi-articular nature, occupy the posterior compartment of the thigh crossing both the hip and the knee joints. During the downward phase of the FW-squat, the trunk segment progressively leans forward and rotates around the hip horizontal axis thus requiring the hamstring muscles to forcefully act in an eccentric mode so to provide an adequate force absorption and contribute to control the augmented negative body momentum (Aspe & Swinton, 2014; Dello Iacono, Ayalon, & Wang, 2019; Maddigan, Button, & Behm, 2014). Finally, *small* to *moderate* non-significant relationships were found between the power outputs of the FW-squat test and SLJ, CMJ, and COD-5m performances. These findings are not unexpected when considering the biomechanical dissimilarities in force production demands between the FW-squat test, which is a non-gravitatory based exercise and the common field assessments. Moreover, both the SLJ and the COD-5m are horizontal in nature, with predominant antero-posterior and medio-lateral forces production demands, which likely explain the *small* relationship with the FW-squat test (Dello Iacono, Martone, Milic, & Padulo, 2017; Dello Iacono, Martone, & Padulo, 2016). Despite the *small* to *moderate* correlations between FW-squat test and field-based assessments, the *excellent* relative and *acceptable* absolute reliability of the FW-squat test and *moderate* to *large* positive correlations with isokinetic peak torque values, supports its use as an alternative or additional test alongside other assessment tools regularly implemented in sport science domains.

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

In conclusion, this is the first study reporting the reliability and construct validity of a FW-squat test. The FW squat test resulted in *excellent* (ICC) and *acceptable* (CV) reliability scores for both the concentric and eccentric power outputs. These values provide initial guidelines allowing practitioners to understand what variability can be considered a real change in comparison with random performance fluctuations. This study also reported *moderate* to *large* relationships between the FW-squat test performance scores and isokinetic lower limb strength parameters. Therefore, FW-squat test can be a valid and reliable alternative test to assess lower limbs performance following training intervention which mainly targets the knee extensor and flexor muscles. Since the large utilization of flywheel devices in sport and research settings, the validation of this test is the first step for a more accurate and sensitive evaluation of flywheel training adaptations and associated transfer effects on performance. However, practitioners are strongly advised to familiarize their athletes with the testing procedure to ensure reliable results. In conclusion, sports scientists can use the FW-squat test loaded with an inertia of 0.061 $kg \cdot m^2$ as a valid monitoring tool informing performance assessment and training periodization practices.

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Figure 1. Testing procedure

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

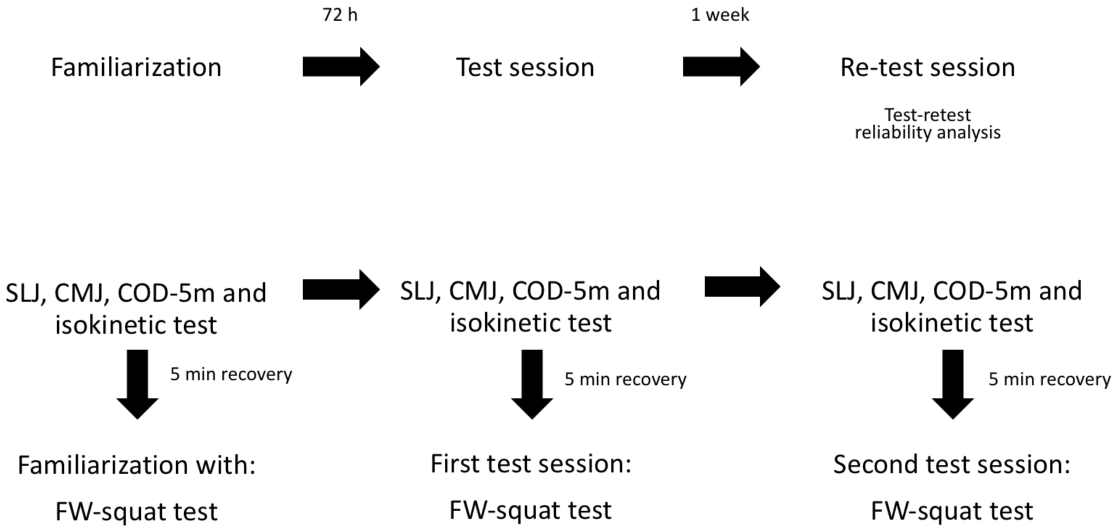

Table 1. Reliability data recorded during test-retest procedure (20 subjects).

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)	*Excellent*	5.14 (2.0%)	*Acceptable*	4.2
CMJ (cm)	40.1±6.9	41.2±7.3	0.97 (0.94, 0.99)	*Excellent*	1.3 (3.0%)	*Good*	1.5
COD-5m (sec)	2.81±0.20	2.80±0.18	0.92 (0.82, 0.97)	*Excellent*	0.06 (2.0%)	*Good*	0.04
Isokinetic quad con (Nm)	214±52	221±54	0.95 (0.93, 0.97)	*Excellent*	12 (5.5%)	*Acceptable*	11
Isokinetic ham con (Nm)	142±31	144±25	0.93 (0.89, 0.97)	*Excellent*	7 (4.6%)	*Good*	5
Isokinetic ham ecc (Nm)	180±35	187±30	0.93 (0.85, 0.96)	*Excellent*	8 (4.2%)	*Good*	6
FW-squat test con (W)	1012±297	1120±274	0.94 (0.86, 0.97)	*Excellent*	67 (5.9%)	*Acceptable*	55
FW-squat test ecc (W)	988±301	993±302	0.95 (0.89, 0.93)	*Excellent*	68 (6.8%)	*Acceptable*	61

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

Table 2. Relationship between FW squat test power outputs and performance for SLJ, CMJ, COD-5m and Isokinetic test parameters (20 subjects). Data are reported with r (strength of the relationship) and 95% CI.

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) *small*	.312 (-.151, .663) *moderate*	.225 (-.242, .607) *small*	**.534*** **(.120, .790)** ***large***	**.472*** **(.038, .757)** ***moderate***	**.516*** **(.096, .780)** ***large***	-	**.940*** ***(.851, .976)*** ***almost perfect***
FW-squat test eccentric (W)	.243 (-.224, .619) *small*	.430 (-.016, .733) *moderate*	.130 (-.332, .541) *small*	**.556*** **(.151, .801)** ***large***	**.465*** **(.028, 0.75)** ***moderate***	**.502*** **(.077, .773)** ***large***	**.940*** ***(.851, .976)*** ***almost perfect***	-

CI = Confidence Intervals, r =Pearson correlation coefficient, SLJ = Standing long jump, CMJ = Countermovement jump, COD-5m = 5-m change of direction, FW = Flywheel, cm = centimetres, s = seconds, * = $p < 0.05$.