2025, Retos, 62, 910-917
 ISSN: Edición impresa: 1579-1726. Edición Web: 1988-2041 (https://recyt.fecyt.es/index.php/retos/index)

The maximum flywheel load for assessing flywheel performance: validation and reproducibility in the squat exercise

La máxima carga en flywheel para evaluar el rendimiento: validación y reproducibilidad en la sentadilla

*Alejandro Muñoz-López, *Diego Marmol, **Alberto Sanchez-Sixto, ***Marco Pozzo, ****Pablo Floría
*Universidad de Sevilla (España), **Universidad CEU Fernando III, CEU Universities (España), ***SmartCoach Technologies, CA (Estados Unidos), ****Universidad Pablo de Olavide

Abstract. This work studied the concept of the maximum flywheel load (MFL) as a measure of maximum dynamic performance in the flywheel half-squat exercise. Twenty physically active participants were recruited for the study. The MFL load was calculated using an exponential mean concentric angular acceleration-moment of inertia relationship, at the point where its' first derivative was lower to 1 unit. Construct validity was analysed by studying the association between MFL and sprint (peak velocity) and jump (countermovement jump, drop jump, and repeated jump in 30" heights, vertical stiffness, and reactive strength index) performance. The reliability of the test-retest was analysed after four and eight sessions. MFL showed moderate to very large significant associations with sprint velocity, jump height, drop jump stiffness, and reactive strength index. Test-retest analysis revealed excellent relative (intraclass correlation coefficient = 0.91) and good absolute reliability (coefficient of variation, after four (4.2%), and after eight (3.9%) familiarization sessions).
Keywords: programming; strength; eccentric overload; force-velocity profile; strength level

Resumen. Este trabajo analizó el concepto de la máxima carga en flywheel (MLF) como un valor de máximo rendimiento dinámico en el ejercicio de media sentadilla en flywheel. Veinte personas físicamente activas participaron en este estudio. La carga de MLF fue calculada utilizando la relación exponencial de la aceleración-momento media de inercia angular concéntrica en el punto en el que la primera derivada era inferior a 1 unidad. La validez fue analizada estudiando la asociación entre el MLF y el rendimiento en sprint (velocidad máxima) y el salto (salto con contramovimiento, drop jump, saltos repetidos en 30", stiffness vertical y el índice reactivo de fuerza). La fiabilidad del test-retest fue analizada después de la cuarta y octava sesión. El MFL mostró una asociación significativa de moderada a muy larga con la velocidad de sprint, altura de salto, el stiffness del drop jump, y el índice reactivo de fuerza. El análisis de test-retest reveló una excelente fiabilidad (coeficiente de correlación intraclase = 0,91) y buena fiabilidad absoluta (coeficiente de variación, tras cuatro (4,2%) y tras ocho (3,9%) sesiones de familiarización).
Palabras clave: programación; fuerza; sobrecarga excéntrica; perfil fuerza-velocidad; nivel de fuerza.

Fecha recepción: 02-05-24. Fecha de aceptación: 20-10-24
Alberto Sanchez-Sixto
asanchezsixto@ceu.es

Introduction

Resistance training (RT) is a commonly used method to improve athletic performance and fitness. The effect of RT depends on the relative external load used during exercise, which can target the neural (i.e., motor unit recruitment) or peripheral (i.e., muscle mass) components of strength (Kraemer et al., 2017). In traditional RT (such as weightlifting), the maximum dynamic performance for a given exercise is characterised by the one maximum repetition (1RM), which also allows to create different relative training zones (Schoenfeld et al., 2021). However, the 1RM is only applicable to resistance training equipment significantly influenced by gravity, and not all training options are affected in this way.

In recent years, the use of flywheel resistance training devices (FRTD) in RT programmes has become increasingly popular (Muñoz-López, et al., 2021; Raya-González et al., 2021). FRTDs consist of a spinning flywheel connected to a rope or strap that the athletes pull with maximum voluntary force in the concentric phase, which is returned in the eccentric phase (Berg & Tesch, 1998). Understanding the mechanical loading of a flywheel exercise is crucial to comprise the potential training effects using different external loads (Beato, et al., 2021). Many studies have focused on establishing the association between different absolute external loads and several mechanical outputs such as power (Muñoz-López, et al., 2021; Sabido et al., 2018), velocity (McErlain-Naylor & Beato, 2021; Muñoz-López, et al., 2021), force (Martinez-Aranda & Fernandez-Gonzalo, 2017; Muñoz-López et al., 2022) or muscle activation (Carroll et al., 2019). However, to date, no study has analysed the use of different relative loads in FRTDs to elicit different training adaptations.

Research showed that including FRTD in RT programs can help improving strength, power, and hypertrophy in some sports activities (de Keijzer et al., 2022). Furthermore, it has been shown that using FRTD can also improve performance in specific athletic skills, such as jumping and sprinting (Raya-González et al., 2021). Practitioners may use different workload intensities to enhance performance in these activities. Studies have analysed variables related to sprinting and jumping performance to identify crucial points of these actions (Wisløff et al., 2004). Sprinting and jumping share a common feature in their use of the stretch-shortening cycle (SCC). The primary neuromuscular determinants of jump and sprint skills are similar to FRTD due to their reliance on the SSC (Martinez-Aranda & Fernandez-Gonzalo, 2017). During a sprint, the peak velocity allows coaches to know the ability of the athlete to generate horizontal acceleration during fast moments of a sprint (Samozino et al., 2012). In addition, jump performance is highly associated with reducing muscle slack and build-up of

2025, Retos, 62, 910-917

stimulation when SSC occurs (van Hooren & Zolotarjova, 2017). Performance of FRTD is similar to vertical jump, thus also taking advantage of the SSC within repetitions (van Hooren & Zolotarjova, 2017). Furthermore, vertical stiffness is a variable that reflects the body's ability to resist length changes and is related to the ability to utilise the SSC (Maloney et al., 2019). Therefore, improvements in performance in FRTD may be translated into improvements in jumping and sprinting skills. To assess this, it is essential to establish an index that reflects maximum dynamic performance in FRTD, similar to 1RM in traditional RT. Beato et al. (Beato, et al., 2021) recently analyzed the construct validity of using an absolute external load in the flywheel squat exercise, finding moderate to large positive correlations with concentric and eccentric knee muscles isokinetic torque. However, they did not observe a significant association with jumps or change-of-direction activities.

The flywheel performance for a given exercise can be evaluated by measuring the flywheel angular velocity with an encoder and calculating the power (Muñoz-López, et al., 2021). The use of progressive loading tests in RT helps measure key components of strength development (Samozino et al., 2012). These tests are commonly used in traditional weightlifting to determine the optimal load that produces the highest power output (Kawamori, 2004), or to measure the maximum dynamic performance by calculating 1RM (Loturco et al., 2019). However, the concept of 1RM cannot be applied to FRTD because an individual can always accelerate the flywheel moment of inertia, as a result torque will be always generated, which increases proportionally with load (Muñoz-López, et al., 2021). Researchers have used maximum power load (Maroto-Izquierdo et al., 2020; Nuñez et al., 2019; Sagelv et al., 2020) or variables such as velocity, force, or power (Muñoz-López, et al., 2021) against different external loads to determine an athlete's flywheel dynamic performance for a particular exercise. However, the assessment of the athlete's performance in flywheel training is only a characterisation of a load's mechanical output, making it challenging to establish relative training zones. The determination of workload intensity training zones for flywheel resistance training devices (FRTDs) has been an understudied area. Muñoz-López et al. (2021) recently introduced the novel index of maximal flywheel load (MFL) to provide an index to program relative workloads in FRTD. In this research, authors proposed the index as the cut-off point from a logarithmic relationship between the concentric mean angular acceleration and the moment of inertia during a progressive test in the flywheel half-squat exercise. Authors only explored the calculation methods in this paper, comparing different options to calculate the index. To date, this is the only study that has calculated the MFL index, and more research is needed to understand its validity.

This research aimed to analyse the construct validity and test-retest reliability of the MFL index to assess the maximum dynamic performance of the flywheel in the squat exercise. More concretely, the study 1) investigated the association between MFL and performance in sprint and jump activities, and 2) determined the test-retest reliability of the MFL calculation method, in relation to the experience using FRTD. Our main hypothesis is that MFL will be positively associated with jump and sprint performance due to the implication of the SSC on these sport activities and flywheel exercises. In addition, we hypothesize that MFL will be enough reliable to detect changes in flywheel dynamic performance across different days of the same week.

Materials and Methods

Design

This study follows an observational crossover design. Participants took part in the study for a total of seven weeks (Figure 1). The first two weeks were used to familiarise participants with the flywheel half-squat exercise, during two training sessions per week (session one to session four). The third week was used to perform a randomised loading test using a flywheel half squat exercise (MFL test). The participants completed the test twice during this week (MFL test one and retest one). Weeks four to five were used to continue the familiarization of the exercise, but also to familiarise with the sprints and vertical jumps (session five to eight). During the sixth week, the participants again executed the loading test twice (MFL test two and retest two). The last week consisted of a test session for testing sprints and vertical jumps. All sessions and tests were interspersed at 48-72 h.

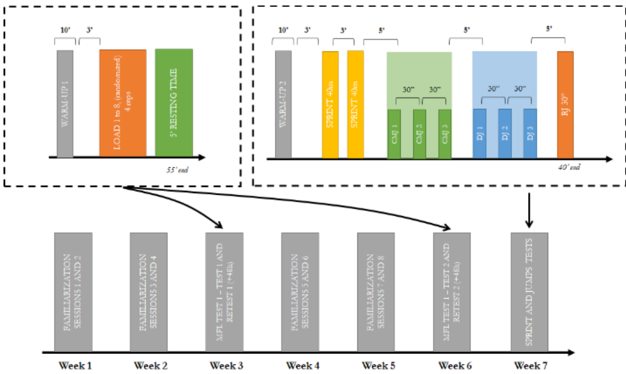

Figure 1. Schematic representation of the study design. CMJ= countermovement jump. DJ= drop jump. RJ= repeated jumps.

Participants

A total of 15 men (19.4 ± 1.8 years, height = 1.78 ± 0.77 m, weight = 78.6 ± 14.7 kg, 7.8 ± 5.1 years of physical activity) and 5 women (20.6 ± 2.5 years, height = 1.63 ± 0.88 m, weight = 61.7 ± 6.3 kg, 6.4 ± 6 years of physical activity) physically healthy and active participants (total number of participants = 20) were involved in this study. The main inclusion criteria were to be over 18 years old and to have been involved without interruption during the last six months in sports or physical activities that require the use of the lower limb muscle preferably.

2025, Retos, 62, 910-917

Participants were excluded from the study in the event of presenting any kind of medical contraindication against performing vigorous and maximal physical exercises, or any kind of pathology, injury, or disease. The total statistical power for 20 participants was 0.79 (considering a large effect size for a point biserial correlation model (0.5) and an alpha error of probability of 0.05). We informed the participants about the research purpose, and they gave their consent to participate prior to any execution. All protocols followed the Declaration of Helsinki guidelines. This study was approved by the Ethics Committee of the University of Seville (protocol number 0864-N-22).

Procedures

Participants were familiarized using the half-squat flywheel exercise, using six sets of four repetitions during each training session, with the loads (i.e., *moments of inertia*) used during the loading test. For vertical jumps or sprints, participants executed five jumps for each type or three sprints in each training session. The loading test consisted of eight sets of two submaximal repetitions plus four maximal repetitions with different randomised loads (0.025 to 0.200 $kg \cdot m^2$, with loads increments of 0.025 $kg \cdot m^2$). Loads represents the FRTD moment of inertia. Resting time between sets was five minutes. The flywheel device used in this study was a cylindrical shaft device (Kbox 3, Exxentrix, Sweden), with a load range ranging from 0.005 to 0.300 $kg \cdot m^2$ and an axis radius width of 0.025 m. The minimum possible increment in the moment of inertia for the device was 0.005 $kg \cdot m^2$. Before each test, the participants performed a standard warm-up: five minutes of cycling at 50 *W* and 75 *rpm*, three minutes of joint mobilisation, three CMJ jumps and six submaximal repetitions of the flywheel half-squat exercise with the lower load used (i.e., 0.025 $kg \cdot m^2$). During the execution of the exercise, we verbally encouraged the participants to accelerate the flywheel disk as fast as possible towards the concentric phase while braking as hard as possible at the last third of the eccentric phase. We monitored the angular speed of the flywheel disk using a rotary encoder (SmartCoach Lite, SmartCoach Tech, USA) and the corresponding software (SmartCoach Desktop, v. 5.8.0.61, SmartCoach Tech, USA). We calculated the mean concentric angular acceleration as the increment in concentric velocity during the concentric phase divided by the concentric phase time. Those variables were calculated by the manufacturer's software. We took the highest mean concentric angular acceleration for each load to calculate MFL.

We used a battery of tests to measure participants' sprint and jump skills. The same standard warm-up was used before any test. The participants performed sprint, CMJ, DJ, and RJ tests. First, the participants ran two maximal 40 *m* sprints, with three minutes of recovery between sprints. The best of the two trials was considered for further analyses. Sprints were carried out from a split stance position. Athletes were instructed to remain still before starting the sprint and allowed to start their sprint when they felt ready. A Stalker ATS II radar device was positioned 5 m directly behind the starting line at a height of 1 m. The STATS software (version 5.0.2.1, Stalker ATS II Applied Concepts, Dallas TX, USA) was used to collect radar data at 46.875 Hz. Peak speed was calculated using a least-squares approach between raw speed-time data and modelled speed-time data similar to previous investigations (Samozino, 2018). All calculations were performed using a custom-made MATLAB script (MATLAB R2121b, The MathWorks, Inc. Natick, Massachusetts, USA).

To assess vertical jump performance, the participants performed three CMJ and, after five minutes of rest, three DJs of 30 *cm* (Peng et al. 2011) height with 30 seconds of rest between trials. The average of the three trials was considered for further analyses. Finally, after five minutes of rest, participants completed a 60 second continuous self-paced double leg jump (RJ) trial. In all jumps, participants retained the arms akimbo and were instructed to "jump as high as possible". All jumps were performed on a contact map connected to a computer (Chronojump-Boscosystem, Barcelona, Spain) for measuring ground contact and flight times. From the flight times, the flight height (m) in CMJ, DJ and RJ was calculated. From flight and contact times, leg stiffness ($kN \cdot m^{-1} \cdot kg^{-1}$) and RSI in DJ and RJ were estimated (Caderby & Dalleau, 2018).

Maximum Flywheel Load Calculation

MFL concept was computed following previous indications (Muñoz-López, et al., 2021). The previous study employed a logarithmic model to calculate the MFL. However, an exponential model is suggested in this study because any moment of inertia can always be accelerated by an individual. The quasi-horizontal asymptote observed in the exponential model (Figure 2) is not present in a logarithmic model. Conversely, a logarithmic model predicts a point on the x-axis where y (mean concentric angular acceleration in this case) equals zero, which is unreal. Hence, the MFL was determined as the load where the subject could no longer maintain the continuity of the previous relationship between the mean angular acceleration and the moment of inertia with lower loads. We used the mean angular acceleration's first partial derivative to find the MFL. The MFL was the moment of inertia that caused a 1-point decrease in this derivative. The reason for choosing a threshold of less than 1 is that, in general, a slope less than 1 indicates a slow change, in this case, of mean angular acceleration (*Y*) in relation to the external load (*X*). In practical terms, from this point, an individual will apply almost the same acceleration, regardless the moment of inertia. An Excel spreadsheet is provided as supplementary material to better illustrate the calculation and obtain the MFL during a progressive loading test.

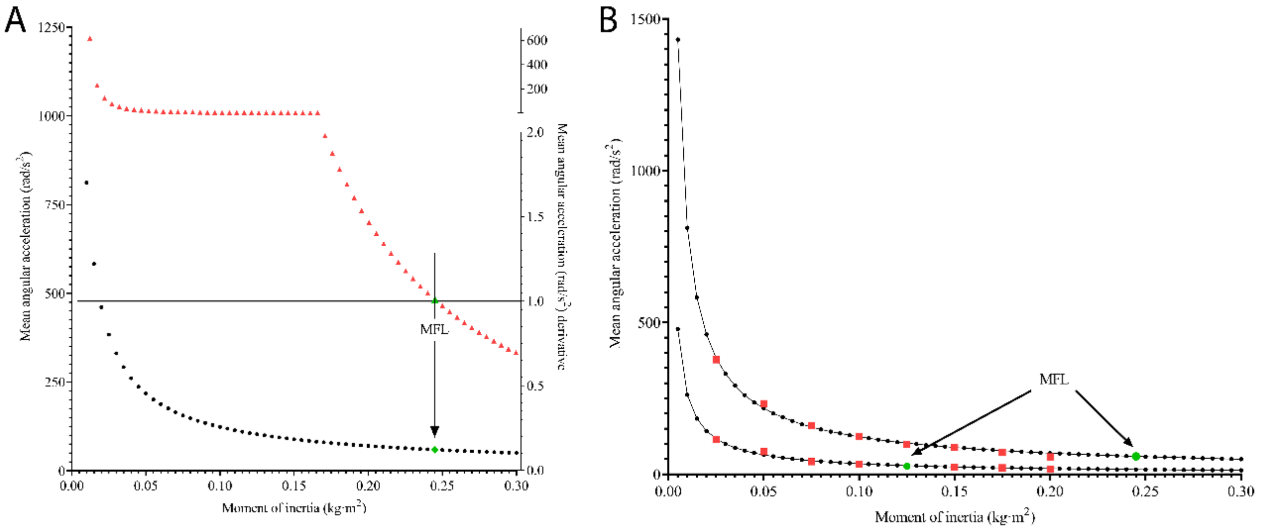

Figure 2. Acceleration-load profile. A) The left *y* axis represents with black dots the acceleration-load profile for an individual; the right *y* axis with red triangles represents the first derivative of the mean angular acceleration. The horizontal line corresponds to the value where mean angular acceleration derivative is equal to 1 (cut-off point suggested to calculate the Maximum Flywheel Load – MFL). B) Representative example of two individuals with a clear visible difference in the whole mean angular acceleration-moment of inertia curve. The black dots represent the acceleration-load profile. The green dots represent the maximum flywheel load. The red squares represent the real mean angular acceleration measured during the maximum flywheel load test.

Statistical analyses

Descriptive data are shown as mean ± standard deviation. Before any analysis, pairwise associations were tested using the Shapiro-Wilk test. We used correlation analyses to assess the MFL construct validity, with the performance outcomes derived from the sprint and jump tests. For that, we tested the associations between MFL calculated with different cut-off points and each performance variable tested. In the case of a normal pairwise distribution, we tested the associations using the Pearson's correlation coefficient. In contrast, we used the Spearman rank coefficient. Both coefficients are represented with *r*. Additionally, 95% confidence intervals (CI) were calculated for each association. We used the following qualitative interpretation for the associations: <0.1 *trivial*, 0.1-0.3 *small*, 0.3-0.5 *moderate*, 0.5-0.7 *large*, 0.7-0.9 *very large* (Beato, Fleming, et al., 2021) For test-retest reliability analyses, we calculated the intraclass correlation coefficient (ICC) and the typical error expressed as coefficient of variation (CV), with their corresponding confidence limits calculated at 95%. For the ICC (relative reliability) we qualitatively interpreted the results as: ICC < 0.5, *unacceptable*; 0.6 > ICC ≥ 0.5, *poor*; 0.7 > ICC ≥ 0.6, *questionable*; 0.8 > ICC ≥ 0.7, *acceptable*; 0.9 > ICC ≥ 0.8, *good*; ICC ≥ 0.9, *excellent* (Atkinson & Nevill, 1998). For the CV (absolute reliability) we qualitatively interpreted the results as: CV < 5%, *good*; 10% > CV ≥ 5; *acceptable*; CV ≥ 10%; *unacceptable* (Cormack et al., 2008). To understand the index capacity to detect a minimum meaningful change, we also calculated the smallest worthwhile change (SWC) by multiplying the average change in individual standard deviation times 0.2 (corresponding to a low effect size to obtain a possible small SWC) (Beato, Fleming, et al., 2021). We used JASP software (Windows v. 0.16.2, University of Amsterdam, The Netherlands) to execute the descriptive and association analyses. For the reliability analyses, we used a customised spreadsheet (Hopkins, 2015). We considered a significant association when the p-value was less than 0.05.

Results

Construct validity

MFL showed significant moderate to very large associations with sprint and vertical jumps performance outcomes. The lowest associations were observed with Sprint Vpeak, while the largest associations were observed with CMJ Height and DJ Stiffness. The correlations plots and specific *r* values are shown in Figure 3.

2025, Retos, 62, 910-917

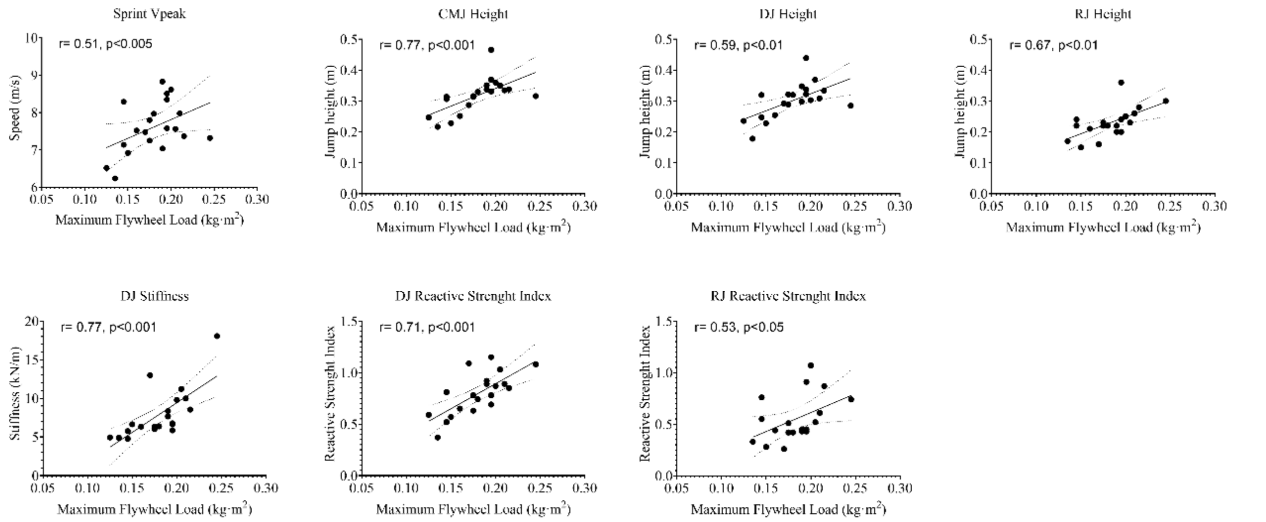

Figure 3. Significant correlation plots between MFL and each performance outcome. The error bands show the 95% confidence limits for each association. *r*= correlation coefficient. Vpeak = maximum speed. CMJ= countermovement jump. DJ= drop jump. RJ= repeated jump.

Reliability

Absolute and relative test-retest reliability remained excellent and good, regardless of the individual's experience (4 vs. 8 sessions using the technology). The SWC was less than the minimum possible increase in the moment of inertia for the flywheel device used.

Table 1.
Maximum flywheel load test-retest reproducibility results

Familiarization sessions	Weekday	MFL (kg·m²)	ICC (95% CL)	CV% (95% CL)	SWC (kg·m²)
After 4 sessions	Day 1	0.157 ± 0.02	0.91 (0.80 – 0.96)	4.2 (3.2 – 6.0)	0.004
	Day 2	0.158 ± 0.02	excellent	good	
After 8 sessions	Day 1	0.177 ± 0.03	0.96 (0.90 – 0.98)	3.9 (2.9 – 5.6)	0.004
	Day 2	0.180 ± 0.03	excellent	good	

Sprint and jump test

For the sprint test, the average Vpeak was 7.61 ± 0.69 m/s. The average jump heights for the different jump tests were: CMJh= 0.31 ± 0.06 m, DJh= 0.30 ± 0.06 m, and RJh= 0.23 ± 0.05 m. For the rest of the jump performance parameters, the average values were: DJ-rsi= 0.80 ± 0.21, RJ-rsi= 0.55 ± 0.22, DJ-stiff= 7.89 ± 3.46 kN/m, and RJ-stiff= 9.98 ± 9.88 kN/m.

Discussion

This study aimed to evaluate the construct validity and reliability of the MFL index to measure the maximum dynamic performance of the flywheel in the squat exercise. We confirmed our two hypotheses because 1) MFL showed a strong correlation with sport activities that involve the SSC, such as sprinting and jumping, and 2) the test-retest reliability of the MFL was found to be good when tested during the same week, with the same score after four or eight familiarization sessions. The results also indicated that the minimum detectable change in the MFL was lower than the minimum possible external load used in the flywheel device. Hence, MFL can be defined as the moment of inertia where a sudden change in the rate of change of acceleration with respect to load drops from 1 point.

Sprinting and jumping are common sports activities that are typically evaluated during daily training programmes. The present study found *moderate* to very *large* associations between the MFL index and the performance outcomes of both activities. This indicates that MFL is a valid index for assessing the performance of SSC that occurs during the flywheel half-squat exercise. The MFL is the point where the mean angular acceleration begins to be almost horizontally related to the moment of inertia. This relationship is exponential (Figure 2, A), so a higher MFL results in greater differences at lower moments of inertia (Figure 2, B). This could explain the association between MFL and Vpeak, as athletes who can express high speeds during sprinting may also be able to express high values of angular acceleration against low moments of inertia. Further studies may support this assumption.

Regarding jump performance, the results showed that MFL was significantly and very largely associated with the height of CMJ, DJ, and RJ. The principle of specificity states that the closer a training exercise is to the competition movement, the greater the transfer of gains (Kasper, 2019). Although previous studies did not observe improvements in specific movements within the same plane of motion when compared to performance on the flywheel device (de Hoyo et al., 2015; Pecci et al., 2023). Therefore, improvements in MFL may lead to improvements in vertical jump height,

2025, Retos, 62, 910-917

which represented almost 50% of the variance (Figure 3). Thus, previous studies, which did not find improvements in specific movements, but did on strength levels (de Hoyo et al., 2015; Pecci et al., 2023), probably have not significantly improved MFL. In addition, significant associations were found between *moderate* to *very large* between MFL and vertical stiffness and RSI (reactive strength index) for DJ and RJ, respectively. A previous investigation showed that SSC during a jump is affected by stiffness (Maloney et al. 2019). When executing half-squats with FRTD, athletes emphasise an SSC half-squat with FRTD and a jump show similarity between them, so the specificity of the actions might explain this association. The RSI is a measure of jump height and execution time. A previous study showed that fast movements increase RSI, while maintaining jump height (Sánchez-Sixto et al., 2021). Performing a half squat with FRTD encourages participants to reach high speeds, resulting in fast and high force application. The ability to brake with high velocity during a jump is crucial to reduce execution time and achieve high force values (Sánchez-Sixto et al., 2021). FRTD highlights this mechanism and provides insights into participants' ability to apply high and fast forces during jump-breaking actions. Together, these findings suggest that practitioners can use MFL to assess the peak dynamic flywheel performance in the flywheel half-squat exercise.

The flywheel half-squat exercise is more complicated compared to barbell or smith half-squats because it includes a forced downward movement at the beginning of the eccentric phase, which is a defining characteristic of flywheel training (Berg & Tesch, 1994). As a result, incorporating FRTD into training programmes requires a period of familiarisation (Tous-Fajardo et al., 2006). Sabido et al. (2018) suggest a minimum of two familiarisation sessions, but a more stable peak power was achieved after four sessions. Our study found that MFL values were reliable after four familiarisation sessions for practitioners without prior experience using FRTD, using loads from 0.025 kg·m^2 to 0.200 kg·m^2 in random order (Table 1). Using absolute loads, power outputs have been proven to have excellent relative and acceptable absolute reliability for the flywheel squat exercise (Beato, et al., 2021). However, it remains unknown whether the MFL calculation is reproducible on multiple days within the same training week. Given the difficulties in executing the flywheel technique (Tous-Fajardo et al., 2006), it is important to study the reliability of the index, particularly in relation to the experience using FRTD. Therefore, an index to monitor the flywheel's peak dynamic performance, which could be used in the future to establish different relative training zones, must show good construct validity with other performance outcomes that focus on the development of the SCC component, and have a minimum level of reproducibility between days, even with limited experience using flywheel technology. No changes in the reliability scores were observed after 8 familiarization sessions. A recent review showed that the ICC of 1RM for lower body exercises was between 0.64 and 0.99, with CV ranging from 0.5 to 12% (Grgic et al., 2020). Experienced strength training men showed similar reliability of the 1RM test-retest in barbell back squats (ICC = 0.82), which was lower than the one achieved in our study after only four familiarisation sessions (Çetin et al., 2022). The authors also found an SWC of 4.72 kg for barbell back squats (Çetin et al., 2022), indicating slight improvements in peak dynamic strength. Our study found that the SWC was lower than the minimum moment of inertia (i.e., external load) that can be increased in the flywheel device used (SWC = 0.004 vs. possible minimum inertia increase = 0.005 kg·m2), which is important for determining the sensitivity of the MFL. Therefore, MFL is a reliable and sensitive index to detect changes in flywheel half-squat exercise performance.

In RT, the intensity of the workload is often prescribed as a percentage of 1RM (Kraemer & Ratamess, 2004). However, this approach cannot be applied to the flywheel resistance training device (FRTD) as the individual can move the load at will (Muñoz-López, Floria, et al., 2021). Instead, in FRTD, MFL can be considered as a future option to measure performance. Our study of the flywheel acceleration-load relationship found that there is a clear point at which an individual can no longer increase the acceleration of the flywheel disk, regardless of the moment of inertia used (Figure 2). This suggests that using higher loads than MFL does not improve acceleration and, therefore, velocity. Hence, MFL can serve as a measure of maximum dynamic performance for flywheel half-squat exercise, much like 1RM in barbell training.

This study has several limitations. It has a small sample size of individuals without prior experience, a pooling of data from men and women without considering potential gender differences, and limited applicability to other populations such as elderly or high-performance athletes. Further research is needed to examine the validity and test-retest reliability of the concept in different populations, for various types of exercise, and with different types of flywheel devices. Furthermore, research should also explore the relationship between MFL and vertical jump biomechanics, and the effects of using different relative MFL loads in sports. Finally, for a more practical application, we recommend studying the relationship between MFL changes and sport-performance tests in several sports.

Conclusion

This study found that the MFL index is a valid and reliable measure of performance in the flywheel half-squat exercise. It is associated with sprint and jump performance variables and can be used by practitioners and coaches to monitor strength gains and transfer of skills in jumping height, reactive strength index, vertical stiffness, and linear sprinting. Four training sessions are enough to obtain good levels of reliability. It may be possible that the MFL calculation in FRTD could have the same use as 1RM in traditional 1RM, even for inexperienced practitioners, and that relative loads based on percent MFL could be used in the future to program training routines. However, this assumption must be further researched.

Declaration of interest

The authors report there are no competing interests to declare.

References

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports medicine (Auckland, N.Z.)*, *26*(4), 217–238.

Beato, M., Fleming, A., Coates, A., & Dello Iacono, A. (2021). Validity and reliability of a flywheel squat test in sport. *Journal of Sports Sciences*, *39*(5), 482–488. https://doi.org/10.1080/02640414.2020.1827530

Beato, M., Maroto-Izquierdo, S., Hernández-Davó, J. L., & Raya-González, J. (2021). Flywheel Training Periodization in Team Sports. *Frontiers in Physiology*, *12*(November), 1–6. https://doi.org/10.3389/fphys.2021.732802

Berg, H. E., & Tesch, P. A. (1994). A gravity-independent ergometer to be used for resistance training in space. *Aviation Space and Environmental Medicine*, *65*(8), 752–756.

Berg, H. E., & Tesch, P. A. (1998). Force and power characteristics of a resistive exercise device for use in space. *Acta Astronautica*, *42*(1), 219–230. https://doi.org/10.1016/S0094-5765(98)00119-2

Caderby, T., & Dalleau, G. (2018). A simple method for measuring lower limb stiffness in hopping. In *Biomechanics of Training and Testing: Innovative Concepts and Simple Field Methods*. https://doi.org/10.1007/978-3-319-05633-3_6

Carroll, K. M., Wagle, J. P., Sato, K., Taber, C. B., Yoshida, N., Bingham, G. E., & Stone, M. H. (2019). Characterising overload in inertial flywheel devices for use in exercise training. *Sports Biomechanics*, *18*(4), 390–401. https://doi.org/10.1080/14763141.2018.1433715

Çetin, O., Akyildiz, Z., Demirtaş, B., Sungur, Y., Clemente, F. M., Cazan, F., & Ardigò, L. P. (2022). Reliability and validity of the multi-point method and the 2-point method's variations of estimating the one-repetition maximum for deadlift and back squat exercises. *PeerJ*, *10*. https://doi.org/10.7717/peerj.13013

Cormack, S. J., Newton, R. U., McGulgan, M. R., & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International journal of sports physiology and performance*, *3*(2), 131–144. https://doi.org/10.1123/IJSPP.3.2.131

de Hoyo, M., Sañudo, B., Carrasco, L., Domínguez-Cobo, S., Mateo-Cortes, J., Cadenas-Sánchez, M. M., & Nimphius, S. (2015). Effects of traditional versus horizontal inertial flywheel power training on common sport-related tasks. *Journal of human kinetics*, *47*(1), 155-167. https://doi.org/10.1515/hukin-2015-0071.

de Keijzer, K. L., Gonzalez, J. R., & Beato, M. (2022). The effect of flywheel training on strength and physical capacities in sporting and healthy populations: An umbrella review. In *PLoS ONE* (Bd. 17, Nummer 2 February). Public Library of Science. https://doi.org/10.1371/journal.pone.0264375

Grgic, J., Lazinica, B., Schoenfeld, B. J., & Pedisic, Z. (2020). Test–Retest Reliability of the One-Repetition Maximum (1RM) Strength Assessment: a Systematic Review. In *Sports Medicine - Open* (Bd. 6, Nummer 1). Springer. https://doi.org/10.1186/s40798-020-00260-z

Hopkins, W. G. (2015). Spreadsheets for Analysis of Validity and Reliability. *Sportscience*, *39*, 16–42.

Kasper, K. (2019). Sports Training Principles. *Current Sports Medicine Reports*, *18*(4), 95–96. https://doi.org/10.1249/JSR.0000000000000576

Kawamori N, H. G. (2004). The optimal training load for the development of muscular power. *J Strength Cond Res*, *18(3)*, 675-84. https://doi.org/10.1519/1533-4287(2004)18<675:TOTLFT>2.0.CO;2.

Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of Resistance Training: Progression and Exercise Prescription. *Medicine and Science in Sports and Exercise*, *36*(4), 674–688. https://doi.org/10.1249/01.MSS.0000121945.36635.61

Kraemer, W. J., Ratamess, N. A., Flanagan, S. D., Shurley, J. P., Todd, J. S., & Todd, T. C. (2017). Understanding the Science of Resistance Training: An Evolutionary Perspective. *Sports Medicine*, *47*(12), 2415–2435. https://doi.org/10.1007/s40279-017-0779-y

Loturco, I., Suchomel, T., Bishop, C., Kobal, R., Pereira, L. A., & McGuigan, M. (2019). One-repetition-maximum measures or maximum bar-power output: Which is more related to sport performance? *International Journal of Sports Physiology and Performance*, *14*(1), 33–37. https://doi.org/10.1123/ijspp.2018-0255

Maloney, S. J., Richards, J., Jelly, L., & Fletcher, I. M. (2019). Unilateral stiffness interventions augment vertical stiffness and change of direction speed. *Journal of Strength and Conditioning Research*, *33*(2), 372–379. https://doi.org/10.1519/JSC.0000000000002006

Maroto-Izquierdo, S., Bautista, I., & Rivera, F. (2020). Post-activation performance enhancement (PAPE) after a single-bout of high-intensity flywheel resistance training. *Biology of Sport*, 343–350. https://doi.org/10.5114/biolsport.2020.96318

Martinez-Aranda, L. M. M., & Fernandez-Gonzalo, R. (2017). Effects of inertial setting on power, force, work, and eccentric overload during flywheel resistance exercise in women and men. *Journal of Strength and Conditioning Research*, *31*(6), 1653–1661. https://doi.org/10.1519/JSC.0000000000001635

McErlain-Naylor, S. A., & Beato, M. (2021). Concentric and eccentric inertia–velocity and inertia–power relationships in the flywheel squat. *Journal of Sports Sciences*, *39*(10), 1136–1143. https://doi.org/10.1080/02640414.2020.1860472.

Maloney, S. J., Richards, J., Jelly, L., & Fletcher, I. M. (2019). Unilateral stiffness interventions augment vertical stiffness and change of direction speed. *Journal of Strength and Conditioning Research*, *33*(2), 372-379. https://doi.org/10.1519/JSC.0000000000002006.

Muñoz-López, A., Floria, P., Sañudo, B., Pecci, J., Carmona, J., & Pozzo, M. (2021). The Maximum Flywheel Load : A Novel Index to Monitor Loading Intensity of Flywheel Devices. *Sensors*, *23*, 8124–16. https://doi.org/10.3390/s21238124

Muñoz-López, A., Fonseca, F., Ramirez-Campillo, R., Gantois, P., Nuñez, F. J., & Nakamura, F. Y. (2021). The use of real-time monitoring during flywheel resistance training programs: how can we measure the eccentric overload? A systematic review and meta-analysis. *Biology of Sport*, 639–652.

Muñoz-López, A., Galiano, C., Nuñez, F. J., & Floría, P. (2022). The flywheel device shaft shape determines force and velocity profiles in the half squat exercise. *Journal of Human Kinetics*, *81*(January), 15–25. https://doi.org/10.2478/hukin-2022-0002

Muñoz-López, A., Pozzo, M., & Floria, P. (2021). Real-time mechanical responses to overload and fatigue using a flywheel training device. *Journal of Biomechanics*, *121*, 110429. https://doi.org/10.1016/j.jbiomech.2021.110429

Nuñez, F. J., De Hoyo, M., López, A. M., Sañudo, B., Otero-Esquina, C., Sanchez, H., & Gonzalo-Skok, O. (2019). Eccentric-concentric ratio: a key factor for defining strength training in soccer. *International Journal of Sports Medicine*, *40*(12), 796-802. https://doi.org/10.1055/a-0977-5478.

Pecci Barea, F. J., Muñoz López, A., Jones, P. A., & Sañudo Corrales, F. D. B. (2023). Effects of 6 weeks in-season flywheel squat resistance training on strength, vertical jump, change of direction and sprint performance in professional female soccer players. *Biology of Sport, 40 (2),* 521-529. https://doi.org/10.5114/biolsport.2023.118022.

Peng, H. T., Kernozek, T. W., & Song, C. Y. (2011). Quadricep and hamstring activation during drop jumps with changes in drop height. *Physical Therapy in Sport*, *12*(3), 127-132. https://doi.org/10.1016/j.ptsp.2010.10.001

Raya-González, J., Prat-Luri, A., López-Valenciano, A., Sabido, R., & Hernández-Davó, J. L. (2021). Effects of Flywheel Resistance Training on Sport Actions. A Systematic Review and Meta-Analysis. *Journal of Human Kinetics*, 77(1), 191–204. https://doi.org/10.2478/hukin-2021-0020

Sabido, R., Hernández-Davó, J. L., & Pereyra-Gerber, G. T. (2018). Influence of different inertial loads on basic training variables during the flywheel squat exercise. *International Journal of Sports Physiology and Performance*, *13*(4), 482–489. https://doi.org/10.1123/ijspp.2017-0282

Sagelv, E. H., Pedersen, S., Nilsen, L. P. R., Casolo, A., Welde, B., Randers, M. B., & Pettersen, S. A. (2020). Flywheel squats versus free weight high load squats for improving high velocity movements in football. A randomized controlled trial. *BMC Sports Science, Medicine and Rehabilitation*, *12*, 1-13. https://doi.org/10.1186/s13102-020-00210.

Samozino, P. (2018). A simple method for measuring force, velocity and power capabilities and mechanical effectiveness during sprint running. In *Biomechanics of Training and Testing: Innovative Concepts and Simple Field Methods*. https://doi.org/10.1007/978-3-319-05633-3_11

Samozino, P., Rejc, E., di Prampero, P. E., Belli, A., & Morin, J. B. (2012). Optimal force-velocity profile in ballistic movements-Altius: Citius or Fortius? *Medicine and Science in Sports and Exercise*, *44*(2), 313–322. https://doi.org/10.1249/MSS.0b013e31822d757a

Sánchez-Sixto, A., McMahon, J. J., & Floría, P. (2021). Verbal instructions affect reactive strength index modified and time-series waveforms in basketball players. *Sports Biomechanics*. https://doi.org/10.1080/14763141.2020.1836252

Schoenfeld, B. J., Grgic, J., Every, D. W. van, & Plotkin, D. L. (2021). *Loading Recommendations for Muscle Strength, Hypertrophy, and Local Endurance: A Re-Examination of the Repetition Continuum*.

Tous-Fajardo, J., Maldonado, R. A., Quintana, J. M., Pozzo, M., & Tesch, P. A. (2006). The flywheel leg-curl machine: offering eccentric overload for hamstring development. *International Journal of Sports Physiology and Performance*, *1*(3), 293–298. https://doi.org/10.1123/ijspp.1.3.293

van Hooren, B., & Zolotarjova, J. (2017). The Difference between Countermovement and Squat Jump Performances: A Review of Underlying Mechanisms with Practical Applications. In *Journal of Strength and Conditioning Research* (Bd. 31, Nummer 7, S. 2011–2020). https://doi.org/10.1519/JSC.0000000000001913

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine*, *38*(3), 285–288. https://doi.org/10.1136/bjsm.2002.002071

Datos de los/as autores/as y traductor/a:

Alejandro Muñoz-López	amunoz26@us.es	Autor/a
Diego Marmol	diego.marmol99@gmail.com	Autor/a
Alberto Sanchez-Sixto	asanchezsixto@ceu.es	Autor/a
Marco Pozzo	marco.pozzo@smartcoach.tech	Autor/a – Traductor/a
Pablo Floría	pfloriam@upo.es	Autor/a