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Effects of flywheel training on strength-related variables in female populations. A systematic review

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ABSTRACT

This study aimed to evaluate the effect of flywheel training on female populations, report practical recommendations for practitioners based on the currently available evidence, underline the limitations of current literature, and establish future research directions. Studies were searched through the electronic databases (PubMed, SPORTDiscus, and Web of Science) following the preferred reporting items for systematic reviews and meta-analysis statement guidelines. The methodological quality of the 7 studies included in this review ranged from 10 to 19 points (*good* to *excellent*), with an average score of 14-points (*good*). These studies were carried out between 2004 and 2019 and comprised a total of 100 female participants. The training duration ranged from 5 weeks to 24 weeks, with volume ranging from 1 to 4 sets and 7 to 12 repetitions, and frequency ranged from 1 to 3 times a week. The contemporary literature suggests that flywheel training is a safe and time-effective strategy to enhance physical outcomes with young and elderly females. With this information, practitioners may be inclined to prescribe flywheel training as an effective countermeasure for injuries or falls and as potent stimulus for physical enhancement.

KEYWORDS: isoinertial, women, eccentric, performance, health

INTRODUCTION

The importance of strength training is widely recognized as being a key staple in training programmes for the enhancement of athletic performance (Suchomel et al., 2016, 2018), with the relationship between strength and jump (Comfort et al., 2014; Nuzzo et al., 2008), linear speed (Comfort et al., 2014; Silva et al., 2015), and change of direction (COD) speed (Beato, Bianchi, et al., 2019; Hammami et al., 2017; Suchomel et al., 2016) evident throughout the literature. In addition, strength training has also been shown to mitigate the potential risk of non-contact injuries (Case et al., 2020; Lauersen et al., 2014) in athlete populations as well as to improve physical parameters and promote beneficial muscle adaptations in healthy sedentary and physically active individuals (Tesch et al., 2017). Thus, its inclusion in athlete (performance), sedentary and physically active individuals training programmes is undeniable. Numerous methods have been proven to be effective for the development of strength in various populations, such as: bilateral lower limb movements (*e.g.* back squats and deadlifts) (Appleby et al., 2019; Bazyler et al., 2014), unilateral lower body training (*e.g.* step ups and rear foot elevated split squats (Appleby et al., 2019; Newton et al., 2006) and more recently, flywheel (isoinertial) training (Beato, De Keijzer, et al., 2019; Beato, McErlain-Naylor, et al., 2020; de Hoyo et al., 2015; Gonzalo-Skok et al., 2017; Madruga-parera et al., 2020), where a wide variety of exercises can be performed. Several studies have described the advantages of flywheel training and attempted to explain its physiological mechanisms, and outcomes for performance and health (Beato & Dello Iacono, 2020; Sañudo et al., 2019; Tesch et al., 2017).

Flywheel exercise has been reported to be a valid strategy for obtaining both acute performance enhancement and chronic adaptations (Beato, McErlain-Naylor, et al., 2020; Maroto-Izquierdo et al., 2017). Flywheel training typically involves similar movement patterns to traditional resistance training (squats or lunges), although this depends upon the desired goal of the programme (Beato, Bigby, et al., 2019; Beato, Madruga-Parera, et al., 2019; de Hoyo et al., 2015; Stevens et al., 2014; Tous-Fajardo et al., 2006). The morphological and strength benefits of flywheel training likely derive from the combination of both concentric-eccentric contractions (Beato & Dello Iacono, 2020); however, the main peculiarity of this training method is the overload generated during the eccentric portion of the exercise (Maroto-Izquierdo et al., 2017; Nuñez Sanchez & Sáez de Villarreal, 2017). The benefits deriving from eccentric exercise have been largely reported in the literature, including preferential recruitment of high threshold motor units, higher force output production and lower energy expenditure compared with both isometric and concentric muscle contractions (Douglas et al., 2017; Hody et al., 2019). For the aforementioned reasons, flywheel training may be particularly effective for improving physical adaptations. From a performance prospective, Nunez et al.

(Núñez et al., 2018) compared the effects of a 6-week flywheel training programme consisting of either squats or lunges on countermovement jump (CMJ) and COD speed, in 27 young active male subjects. Both programmes showed *small* improvements in CMJ height (effect size [Cohen's *d*] = 0.28-0.42) and moderate improvements in COD time (*d* = 0.70-0.75). Similar results in jump and COD speed were noted by Gonzalo-Skok et al. (Gonzalo-Skok et al., 2017) who used bilateral squats and multidirectional COD movements (in the form of flywheel training), on 48 team-sport athletes. *Small* to *moderate* improvements were shown in COD performance (*d* = 0.35-0.61), *small* improvements in bilateral and unilateral CMJ (*d* = 0.27-0.42) and *small* to *large* improvements in lateral and horizontal jumping (*d* = 0.43-0.87). Finally, Madruga-Parera et al. (Madruga-parera et al., 2020) compared the effects of an 8-week flywheel training vs. cable resistance training programmes, using 34 male youth handball athletes. Both training interventions showed significant ($p < 0.001$) improvements in COD and repeated COD performance; however, the flywheel training intervention was superior for repeated COD improvements (*d* = -1.35 vs. -0.22). Additionally, Norrbrand et al. (Norrbrand et al., 2008) reported muscular and strength adaptations such as cross-sectional area (CSA) and maximal voluntary contractions following a 5-week flywheel training programme (2-3 times a week) in healthy men. Bruseghini et al. (Bruseghini et al., 2015) reported significant increments in CSA (4%) and isokinetic strength (10%) following an 8-week flywheel 4 x 7 maximal bilateral knee extension/flexion training protocol. As such, Tesch et al., (Tesch et al., 2017) reported that flywheel training is a valid method of treating age-induced skeletal muscle atrophy, and in particular that this resistance training appears to be more effective than traditional weight training.

Collectively, these studies highlight that training with flywheel technology may elicit *small* to *large* improvements in measures of athletic performance and promote both CSA and strength increments in sedentary and healthy men (Bruseghini et al., 2015; Maroto-Izquierdo et al., 2017; Naczk et al., 2016; Norrbrand et al., 2008). However, it must be acknowledged that the samples used in the aforementioned studies were, and typically are, male. Conversely, the volume of literature pertaining to flywheel training studies using female populations is scarce, with a significant amount of research necessary to understand the benefits of this training methodology with females. Therefore, the aims of the present systematic review were to: 1) evaluate and summarize the effect of flywheel training on females, 2) report practical recommendations for practitioners based on the current available evidence on how flywheel training can offer clinical and sport advantages in applied settings, 3) underline the current limitations of the literature and establish future research directions.

2. MATERIALS AND METHODS

The present review was carried out following the recommendations and criteria established in the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) statement guidelines (Liberati et al., 2009).

2.1. Search Strategy

For this systematic review, potential studies were identified in PubMed/MEDLINE, SPORTDiscus, and Web of Science (including all Web of Science Core Collection: Citation Indexes) databases. The search syntax included the following keywords coupled with Boolean operators: ("flywheel" AND "female") OR ("isoinertial" AND "female"). A year restriction was applied for this search (i.e., studies published between 1990 and 2020). In addition, a secondary search was performed based on the screening of the reference lists of these studies and the studies that cited the included studies through Google Scholar. Two authors (KDK and MB) independently screened the title and abstract of each reference to locate potentially relevant studies and reviewed them in detail to identify articles that met the inclusion criteria. Following both searches, studies were uploaded to reference manager software (Zotero, version 5.0.85, Corporation for Digital Scholarship, Vienna, USA). All articles were reviewed and screened for duplicates. Based on the study title, author, year of publication, DOI, ISBN fields, duplicates were identified and merged using the "Duplicate Items" function.

2.2. Inclusion Criteria

The studies included in the present review had to fulfil the following inclusion criteria: (a) the sample must be composed of female participants, (b) studies that analysed the effect of flywheel or isoinertial training of different groups (*e.g.* flywheel vs. control) were reported in a differentiated way (*i.e.* specific data for each group), (c) studies needed to report flywheel or isoinertial training or provide sufficient data to calculate it through standardized equations, and (d) studies had to be the full-text published in a peer-reviewed journal. In addition, conference abstracts, letters to the editor, errata, narrative reviews, systematic reviews, meta-analyses or invited commentaries and studies that were not written in English were excluded.

2.3. Study Coding and Data extraction

The following moderator variables were extracted from the included studies: (a) authors, year of publication and study design, (b) sample characteristics (including sample size, age, and status), (c) follow-up duration, (d) trial data (duration, volume and inertia (intensity) utilised), and (e) participants did not use supplements or ergogenic aids during the intervention period.

2.4. Methodological Quality Assessment

While the methodological quality analysis of studies is often conducted using either: (i) the PEDro scale; (ii) the Delphi scale; or (iii) the Cochrane scale, previous research has illustrated that non-healthcare studies (*e.g.* strength and conditioning) typically score low using these methodological scales. Subsequently, using methods reported by Brughelli et al. (Brughelli et al., 2008), the 7 remaining studies were assessed using an evaluation derived from the three aforementioned scales. The aim of this analysis was to evaluate study quality and identify areas of methodological weakness. The scale utilises 10-item criteria ranging from 0-20 points with the score for each criterion reported as follows: 0 = clearly no; 1 = maybe; and 2 = clearly yes. Based on this procedure, the studies were classified as follows: low methodological quality (≤ 50% of total points); good methodological quality (51–75% of total points); and excellent methodological quality (> 75% of total points) (Brughelli et al., 2008). All of the criteria included are reported in Table 1.

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

Data extraction and methodological quality assessment were performed independently by two authors (KDK and MB) and discrepancies between the authors were resolved in consultation with a third reviewer (JRG).

3. RESULTS

3.1. Search Results

The initial search identified 179 studies, while 3 additional studies were found through the secondary search. Subsequently, 153 search results were excluded based on their titles and/or abstracts. The full text of the remaining 20 studies were examined in more detail, with 13 studies being excluded because they did not meet the inclusion criteria. After the final screening, 7 studies were included in the review (as reported in Figure 1) (Fernandez-Gonzalo et al., 2014; Gual et al., 2016; Lundberg et al., 2019; Onambélé et al., 2008; Sañudo et al., 2019; Seynnes et al., 2007; Tesch et al., 2004).

*****Please, add here Figure 1*****

In the selected studies, changes in performance following flywheel protocols were calculated as percentage differences (%) using the following formula:

$$(\text{post} - \text{baseline}) / \text{baseline} \times 100$$

Hedges *g* were calculated from the original investigation to examine the extent of the training outcomes. Specifically, effect sizes (ES) were determined for each flywheel protocol as for within-group analyses and calculated relative to baseline or control conditions absent of any intervention. This approach enabled the estimation of unbiased effects and standardized comparisons between protocols (Lakens, 2013). Hedges *g* was interpreted as: *trivial* < 0.2, *small* ≥ 0.2, *moderate* ≥ 0.6, *large* ≥ 1.2, and *very large* > 2.0 (Hopkins et al., 2009).

The equation $d = M_{diff}/S_{av}$ (M_{diff}, mean difference; S_{av}, average standard deviation [SD]) was used for this purpose with the adjustment factor of

$$g = (1 - 3/d_{df} - 1) \times d$$

3.2 Descriptive Characteristics of the Studies

The included studies are summarized in Table 2. The 7 selected studies resulted in 11 cohorts as 4 studies had more than one group. Two studies were carried out with an elderly female population and 5 with young adults. These studies were carried out between 2004 and 2019 and comprised a total of 100 participants, divided as follows: 36 older adult females and 64 young adults. In addition, 3 studies utilised a single group study, 2 utilised a parallel group design, while 2 utilised a randomized controlled trial (RCT) design. The training duration ranged from 5 weeks to 24 weeks, and the intervention protocols were clearly described in all 7 studies, however the inertial load utilised was reported only in 5 studies. Training volume ranged from 1 to 4 sets, number of repetitions ranged from 7 to 12 per set, training frequency ranged from 1 to 3 times a week. The key outcomes of the studies selected in this systematic review included only lower limb performance tests such as: 1 repetition-maximum (1RM), jump and squat tests (power output), as well as changes in muscle morphological adaptations such as anatomical CSA. Variations in key findings were reported by summarizing the percentage variation and the Hedges *g* standardised effect size.

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

3.3 Methodological Quality Assessment

Table 3 shows the individual scores for the quality assessment. Values ranged from 10 to 19 points (*good* to *excellent*), with an average score of 14 points (*good*). Regarding the individual quality assessment, two studies were categorized as *excellent*, while the five remaining studies were categorized as being of *good* quality.

*****Please, add here Table 3*****

4. DISCUSSION

This systematic review aimed to evaluate and summarize practical, clinical and sporting applications of flywheel training with female populations while also underlining the current limitations of the literature and establish future research directions. Despite the growing interest on flywheel training (Beato & Dello Iacono, 2020; Maroto-Izquierdo et al., 2017; Raya-González et al., 2020; Vicens-Bordas et al., 2018), this is the first systematic review to exclusively focus on female populations. This knowledge can provide valuable information for the implementation of flywheel-based exercises with females of different ages and facilitate the launch of comprehensive future research related to this topic.

4.1 Flywheel training and elderly females

Resistance training is a key factor related to improvement or maintenance of quality of life because it can mitigate progressive age-related impairments (*e.g.* muscle atrophy and strength decreases) (Fragala et al., 2019; Hortobagyi et al., 2001). In this regard, regular resistance training improves neuromuscular function, strength, power, movement capacity and balance (Gillespie et al., 2012; Howe et al., 2011). Although eccentric training appears to be more effective than concentric modalities (in isolation) for increasing muscle mass and strength in healthy adults (Roig et al., 2009), resistance training that requires both concentric and eccentric training seems to exhibit a greater potential for strength improvements in older adults (Tesch et al., 2017). Flywheel training benefits are associated with the combination of high-intensity concentric contractions and the presence of an eccentric-overload (Beato & Dello Iacono, 2020), so, this modality may therefore be an interesting alternative for improvement of health-related capacities in elderly populations. Despite this, only two studies have analysed the effects of flywheel programs in elderly females (Onambélé et al., 2008; Sañudo et al., 2019). Firstly, Onambélé et al. (Onambélé et al., 2008) applied a 12-week progressive flywheel knee extension training program, obtaining improvements in isometric quadriceps strength (8%; g = 0.63, *moderate*), knee-extension power (28%; g = 1.57, *large*), and tendon stiffness (136%;

g = 7.1, *very large*). Recently, Sañudo et al. (Sañudo et al., 2019) observed that 6-weeks of 2-3 weekly flywheel squat training (inertia = 0.025 - 0.05 kg·m^2) sessions increased power performance (63%), velocity (48%) and mobility/balance (13%). Both studies analysed males and females together, only included lower limb exercises and one of them failed to report the inertia used (Onambélé et al., 2008). Information about the inertia used is critical for the ecological validity of the protocol and for its replication in future research. Despite this, the promising results highlight that flywheel programs can improve quality of life measures, movement capacity, and reduce the risk of falls in elderly females. Future research may wish to follow a comprehensive methodology (*e.g.* diary tracking, information on hormone therapy, etc.) to further understand how to implement flywheel programs with elderly females (Blagrove et al., 2020). Tracking aging-related hormonal changes (*e.g.* follicle stimulating hormone and Estradiol) and activity levels (via self-reported questionnaires or hip-worn accelerometers) may also add valuable insight into the response of elderly females (Juppi et al., 2020).

4.2 Flywheel training and young female adults

In contrast to research with elderly females, the effects of flywheel exercises on young and healthy females have been studied to a greater extent (Fernandez-Gonzalo et al., 2014; Gual et al., 2016; Seynnes et al., 2007; Tesch et al., 2004). Significant benefits have been reported after applying flywheel training with males in both skeletal muscle adaptations (*e.g.* strength, power and hypertrophy) (Fernandez-Gonzalo et al., 2014; Naczk et al., 2016; Norrbrand et al., 2010) and sports-related actions (*e.g.* jump, sprint and COD) (Coratella et al., 2019; de Hoyo et al., 2015; Tous-Fajardo et al., 2016). However, observed differences across genders in response to resistance training highlight why it is essential to specifically study the effects of flywheel exercise on females (Kraemer et al., 1998). Tesch et al. (Tesch et al., 2004) observed increases in knee extensor CSA (>6%) and isometric strength (10-12%) with a mixed male and female cohort after 5 weeks of flywheel training (4 x 7 flywheel knee extension, 2-3 sessions per week). Seynnes et al. (Seynnes et al., 2007) applied a similar protocol [*i.e.* 4 x 7 flywheel knee extensions, 3 x week], finding *small* to *moderate* improvements in CSA (6.5-7.4%, *g* = 0.21-0.81) and isometric strength (39%), while also reporting important changes in architecture of the knee extensors, including changes in fascicle length (9.9%) and pennation angle (7.7%). The two studies reported similar improvements in CSA following very similar short duration flywheel protocols, which underline the validity of flywheel training to generate hypertrophic and isometric strength improvements in short periods of time. However, both studies had a limited number of female participants that were not analysed separately from their male counterparts, which makes it difficult to draw definitive conclusions on the effects of flywheel training on females. Additionally, neither of these studies reported the inertia utilised, which is a key factor for the success of the training protocol. Future studies should clearly report the range of inertias utilised to facilitate the comparison of their findings with other studies. Lundberg et al. (Lundberg et al., 2019) analysed the effects of 12-weeks flywheel knee extensions (*i.e.* 4 x 7, inertia range 0.05-0.075 kg·m^2, 2-3 x week) on females and males separately. The authors reported *moderate* improvements in 1RM (17%, g = 0.78), *moderate* improvements in knee-extension power (26%; g = 1.00) and *small* changes in CSA (5-8%, g = 0.21-0.31), supporting the aforementioned findings (Seynnes et al., 2007; Tesch et al., 2004). Furthermore, Lundberg et al. (Lundberg et al., 2019) also postulated that flywheel training may be a more time-efficient training method than regular weight-stack methodologies since fewer repetitions were required to achieve similar outcomes. Regarding sport-related actions, Fernández-Gonzalo et al. (Fernandez-Gonzalo et al., 2014) obtained *large* improvements in vertical jump height during the SJ (8%, g = 1.42) and CMJ (6%, g = 1.75)] through a 6-week flywheel supine squat training program (4 x 7, with an inertia of 0.14 kg·m^2), which also improved 1RM by 20% (g = 2.49, *very large*). Similarly, Gual et al. (Gual et al., 2016) implemented a 24-week protocol involving weekly flywheel half squat training with a mixed group of male and female basketball and volleyball players. However, a lower improvement was reported in jumping performance such as CMJ (3%; g = 0.19, *trivial*) in comparison to the investigation by Fernández-Gonzalo et al. (Fernandez-Gonzalo et al., 2014). Several factors could explain these differences in outcomes. Firstly, the differences in inertial load and training frequency per week (1 vs. 3 times a week) could have impacted outcomes. Secondly, differences between physical level of the two samples enrolled (volleyball and basketball athletes (Gual et al., 2016) vs. physically active subjects (Fernandez-Gonzalo et al., 2014) may have affected response to the protocol. Differences in response to flywheel training can be attributable to differences in participant physical level and this should be taken into consideration when applying flywheel technology. Thirdly, Fernández-Gonzalo et al. (Fernandez-Gonzalo et al., 2014) separated their male and female cohort prior to data analysis while Gual et al. (Gual et al., 2016) did not. Nonetheless, the 3% improvement of jumping performance reported in-season by Gual et al. (Gual et al., 2016) should not be neglected since it highlights that a reduced training frequency and inertial load may still be beneficial for athletes. However, it is necessary to highlight that elite athletes generally require a higher training volume and frequency than other populations (Beato & Dello Iacono, 2020; Maroto-Izquierdo et al., 2017). Nonetheless, the elite athletes recruited in this study reported substantial improvements in squat power (57-61%; g = 2.90-3.40, *very large*) and did not suffer from any patellar tendinopathy issues. Therefore, this study highlights that a single weekly session of flywheel squat training enhances lower limb muscle performance without triggering patellar tendon complaints in basketball and volleyball players.

Despite the fact that flywheel training programmes involving young and healthy females have been studied to a greater extent than elderly females, the present section enrolled only five studies. Therefore, future research is needed to better understand the training modalities more suitable for active and sporting female populations. It should be noted that no study analysed the effects of flywheel exercises on the upper limbs, therefore future studies could verify the applicability of flywheel exercises to improve upper limb strength and sport-related performance. Additionally, several studies reported in this review combined male and female participants without differentiating them for analysis (via gender). Future studies analysing females only are required. However, the results obtained in the included studies indicate that flywheel-based resistance training is an effective method for improving physical performance such as jumping, 1-RM, isometric strength, and concentric and eccentric squat outputs in healthy young females, so it would be advisable to introduce these exercises in training periodization with these populations.

4.3 Informed implementation of flywheel exercises in research settings and applied contexts

Multiple factors, including training intensity, volume, and exercise type, affect flywheel training outcomes. Variety in such factors can influence physical capacity and performance and must therefore be controlled for.

Training intensity

A large variety of inertias were employed – ranging from 0.025-0.14 kg·m^2, with all of them achieving their desired goals. A similar range of inertial intensities (0.05-0.11 kg·m^2) have previously been recommended for inducing chronic adaptations and performance improvements in athletic populations (Beato & Dello Iacono, 2020). A lack of information still exists regarding optimal inertial load with elderly females, with only one investigation highlighting that a range of 0.025 – 0.05 kg·m^2 can improve power and mobility (Sañudo et al., 2019). A variety of inertial loads can be employed with younger females (0.025-0.075 kg·m^2; 0.11 kg·m^2; 0.14 kg·m^2) to achieve desired strength, power, and hypertrophy objectives (Fernandez-Gonzalo et al., 2014; Gual et al., 2016; Lundberg et al., 2019).

Training Volume

As evidenced by the majority of protocols in this review, a program utilising multiple sets and repetitions (4 x 7-8, respectively) can effectively achieve chronic adaptations with elderly and younger females. Onambele et al. (Onambélé et al., 2008) reported a progressive loading strategy (1 x 8 to 4 x 12) may be attractive for frail, diseased, and/or elderly participants because it may reduce the negative effects of novel intense eccentric exercise (Hody et al., 2019). Nonetheless, the only other investigation with elderly female participants utilised a 4 x 7 loading scheme (Sañudo et al., 2019) – hence it is still unclear whether it is of greater benefit to utilise progressive (with increasing repetitions and sets) or consistent loading strategies for chronic adaptations in elderly females.

Training Frequency and Duration

Tesch, et al. (Tesch et al., 2004) highlight that the flywheel may induce significant changes in performance with a reduced time requirement in comparison to traditional methods. However, further research is needed to verify if differences between flywheel and traditional methods exist (Vicens-Bordas et al., 2018). The current review also reports that significant power capability improvements were seen over a 24-week in-season period with a weekly flywheel squat session (Gual et al., 2016), which underlines that a low dosage of flywheel training can effectively enhance athletic capabilities. Importantly for this population, no aggravation of patellar tendinopathies was reported - which is of significant importance for player performance and availability in team sports. Nonetheless, within this investigation - injury, pain, and/or dysfunction were only reported if players missed matches, missing out on possible subtle patellar tendon issues arising throughout the training week (Gual et al., 2016). Such subtle differences may have impacted training quality or quantity throughout the season. Overall, it appears that 2-3 sessions of flywheel training are effective for inducing adaptions in elderly and young female populations (Fernandez-Gonzalo et al., 2014; Lundberg et al., 2019; Onambélé et al., 2008; Sañudo et al., 2019; Seynnes et al., 2007; Tesch et al., 2004). Athletic populations may benefit either from one or multiple sessions per week depending on other training and competition demands (Gonzalo-Skok et al., 2019) – although further investigation into the effects dosage of flywheel training dosage is necessary.

Exercise type

Although it has been evidenced that multiple modalities of flywheel training can exhibit eccentric overload (Gual et al., 2016), key differences in physical requirements exist between different exercises (Fernandez-Gonzalo et al., 2014; Gual et al., 2016; Lundberg et al., 2019).

Differences in modalities are associated with a wide array of benefits and pitfalls: muscle synergist activation, dynamic correspondence, sustainability/comfort of the protocol and whether or not they affect availability for participation in competitive sports (Lundberg et al., 2019; Onambélé et al., 2008; Sañudo et al., 2019). As alluded to by Gual et al. (Gual et al., 2016), the relevance of the training stimulus to sport specific movements may be a key determining factor for improvements with athletic populations. Similarly, Sañudo et al (Sañudo et al., 2019). argue for the importance of specificity, justifying the use of a supine squat rather than a leg extension. Specifically, the hip abductors, adductors, and ankle plantar/dorsi-flexors have a great influence on balance performance, and may not be sufficiently targeted with a single joint protocol, such as the leg extension (Gual et al., 2016; Sañudo et al., 2019). Nonetheless, further research is necessary to determine whether differences exist between single- and multi-joint exercises for strength and power adaptations with young and elderly females.

4.4 Limitations and directions for future research

From the existing literature a few questions emerge which should be acknowledged and discussed in view of future research directions:

1. *Reduced sample of females:* In the 7 studies chosen for this systematic review, a total of 100 females took part in an experimental group. Furthermore, the sample was heterogeneous, so factors such as age, gender, strength levels or training history could have influenced the response to flywheel training programs.

2. *Females and males analysed together in some studies:* Given the proven differences between male and female endocrine, neuromuscular, and cellular response to high intensity exercise (Kraemer et al., 1998), future research only with females would ensure training prescription and outcomes are optimized for females. The present review was limited to reporting findings where both sexes were included and not separated in the analysis, hence those results should be interpreted with caution.

3. *Study design:* None of 7 studies were classified as low methodological value and five studies were categorized as being of *good* quality, while two studies were categorized as *excellent*. Values ranged from 10 to 19 points (*good* to *excellent*), with an average score of 14 points (*good*). Nonetheless, further high-quality investigations based on a comprehensive methodology (items criteria reported in Table 1) must be implemented with female populations

to better understand the applicability and the advantages of flywheel training in female populations. Specifically, well designed RCT are required (Beato & Dello Iacono, 2020).

4. *The effect of the menstrual cycle on resistance training investigations:* As clearly stated in a recent systematic review (Blagrove et al., 2020), time-of-day of training and testing should be taken in account as day hormonal fluctuation can alter response. Furthermore, investigations should also aim to accurately determine optimal strength testing days and inter-individual variability within the menstrual cycle for each participant. Establishing whether participants utilize oral contraceptives may be another key factor related to creating well-designed studies.

5. *Monitoring training sessions and testing:* the knowledge of inertial load utilised, and the power outputs produced during flywheel exercises are key components to consider for the designing of protocols. Physiological and performance adaptations could be analysed according to the concentric and eccentric power achieved by each participant during flywheel tests (Beato, Fleming, et al., 2020). Practitioners should consider the number of repetitions and sets, the inertia used, and the weekly training frequency adopted as key factors for the success of their training protocols. Future studies using and comparing different flywheel protocols should aim to highlight the necessary dose utilised to achieve improvements in the female population. Additionally, as recently reported (Beato & Dello Iacono, 2020), the load quantification with rotatory encoders may help to efficiently manage exercise prescription and monitoring – particularly in the frameworks of injury prevention and rehabilitation, where the applications of flywheel training are not currently well-explored.

6. *Exercises:* Research involving males studied the effect of several exercises on physical parameters (Beato, de Keijzer, et al., 2020; Maroto-Izquierdo et al., 2017), while only a limited number of lower limb exercises such as leg extension and squat have been used in studies enrolling female populations. Future research may wish to investigate the effects of deadlifts, lunges, or other functional movements with elderly or younger female populations, as well as the combination of several exercises into the same flywheel training program. Additionally, the effectiveness of different flywheel exercises on strength parameters (*e.g.* concentric and eccentric hamstring strength) could be particularly important considering that female athletes frequently suffer from hamstring and knee injuries.

CONCLUSIONS

The contemporary literature suggests that flywheel training is a safe and time-effective strategy to enhance physical outcomes with young and elderly females. With this information, practitioners may be inclined to prescribe flywheel training as an effective countermeasure for injuries or falls and as potent stimulus for physical enhancement in young and elderly female populations. Nonetheless, a lack of clarity still exists on appropriate flywheel training dosage, frequency, and intensity with females. Therefore, further high-quality investigations into this topic are warranted to establish clear guidelines and construct a thorough consensus about the use of flywheel training methodologies with female populations.

REFERENCES

Appleby, B. B., Cormack, S. J., & Newton, R. U. (2019). Specificity and transfer of lower-body strength. *Journal of Strength and Conditioning Research*, *33*(2), 318–326. https://doi.org/10.1519/JSC.0000000000002923

Bazyler, C. D., Sato, K., Wassinger, C. A., Lamont, H. S., & Stone, M. H. (2014). The efficacy of incorporating partial squats in maximal strength training. *Journal of Strength and Conditioning Research*, *28*(11), 3024–3032. https://doi.org/10.1519/JSC.0000000000000465

Beato, M., Bianchi, M., Coratella, G., Merlini, M., & Drust, B. (2019). A single session of straight line and change-of-direction sprinting per week does not lead to different fitness improvements in elite young soccer players. *Journal of Strength and Conditioning Research*, Ahead of print. https://doi.org/10.1519/JSC.0000000000003369

Beato, M., Bigby, A. E. J., De Keijzer, K. L., Nakamura, F. Y., Coratella, G., & McErlain-Naylor, S. A. (2019). Post-activation potentiation effect of eccentric overload and traditional weightlifting exercise on jumping and sprinting performance in male athletes. *PLOS ONE*, *14*(9), e0222466. https://doi.org/10.1371/journal.pone.0222466

Beato, M., de Keijzer, K. L., Fleming, A., Coates, A., La Spina, O., Coratella, G., & McErlain-Naylor, S. A. (2020). Post flywheel squat vs. flywheel deadlift potentiation of lower limb isokinetic peak torques in male athletes. *Sports Biomechanics*, 1–14. https://doi.org/10.1080/14763141.2020.1810750

Beato, M., De Keijzer, K. L., Leskauskas, Z., Allen, W. J., Dello Iacono, A., & McErlain-Naylor, S. A. (2019). Effect of postactivation potentiation after medium vs. high inertia eccentric overload exercise on standing long jump, countermovement jump, and change of direction performance. *Journal of Strength and Conditioning Research*, Ahead of print. https://doi.org/10.1519/JSC.0000000000003214

Beato, M., & Dello Iacono, A. (2020). Implementing flywheel (isoinertial) exercise in strength training: Current evidence, practical recommendations, and future directions. *Frontiers in Physiology*, *11*. https://doi.org/10.3389/fphys.2020.00569

Beato, M., Fleming, A., Coates, A., & Dello Iacono, A. (2020). Validity and reliability of a flywheel squat test in sport. *Journal of Sports Sciences*, *00*(00), 1–7. https://doi.org/10.1080/02640414.2020.1827530

Beato, M., Madruga-Parera, M., Piqueras-Sanchiz, F., Moreno-Pérez, V., & Romero-Rodriguez, D. (2019). Acute effect of eccentric overload exercises on change of direction performance and lower-limb muscle contractile function. *Journal of Strength and Conditioning Research*, Ahead of print. https://doi.org/10.1519/JSC.0000000000003359

Beato, M., McErlain-Naylor, S. A., Halperin, I., & Dello Iacono, A. (2020). Current evidence and practical applications of flywheel eccentric overload exercises as postactivation potentiation protocols: A brief review. *International Journal of Sports Physiology and Performance*, *15*(2), 154–161. https://doi.org/10.1123/ijspp.2019-0476

Blagrove, R. C., Bruinvels, G., & Pedlar, C. R. (2020). Variations in strength-related measures during the menstrual cycle in eumenorrheic women: A systematic review and meta-analysis. *Journal of Science and Medicine in Sport*. https://doi.org/10.1016/j.jsams.2020.04.022

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport. *Sports Medicine*, *38*(12), 1045–1063. https://doi.org/10.2165/00007256-200838120-00007

Bruseghini, P., Calabria, E., Tam, E., Milanese, C., Oliboni, E., Pezzato, A., Pogliaghi, S., Salvagno, G. L., Schena, F., Mucelli, R. P., & Capelli, C. (2015). Effects of eight weeks of aerobic interval training and of isoinertial resistance training on risk factors of cardiometabolic diseases and exercise capacity in healthy elderly subjects. *Oncotarget*, *6*(19), 16998–17015. https://doi.org/10.18632/oncotarget.4031

Case, M. J., Knudson, D. V., & Downey, D. L. (2020). Barbell squat relative strength as an identifier for lower extremity injury in collegiate athletes. *Journal of Strength and Conditioning Research*, *34*(5), 1249–1253. https://doi.org/10.1519/JSC.0000000000003554

Comfort, P., Stewart, A., Bloom, L., & Clarkson, B. (2014). Relationships between strength, sprint, and jump performance in well-trained youth soccer players. *Journal of Strength and Conditioning Research*, *28*(1), 173–177. https://doi.org/10.1519/JSC.0b013e318291b8c7

Coratella, A. G., Beato, M., Cè, E., Scurati, R., & Milanese, C. (2019). Effects of in-season enhanced negative work-based vs traditional weight training on change of direction and hamstrings-to-quadriceps ratio in soccer players. *Biology of Sport*, 241–248.

de Hoyo, M., Pozzo, M., Sañudo, B., Carrasco, L., Gonzalo-Skok, O., Domínguez-Cobo, S., & Morán-Camacho, E. (2015). Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *International Journal of Sports Physiology and Performance*, *10*(1), 46–52. https://doi.org/10.1123/ijspp.2013-0547

Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2017). Eccentric exercise: physiological characteristics and acute Responses. *Sports Medicine*, *47*(4), 663–675. https://doi.org/10.1007/s40279-016-0624-8

Fernandez-Gonzalo, R., Lundberg, T. R., Alvarez-Alvarez, L., & de Paz, J. A. (2014). Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. *European Journal of Applied Physiology*, *114*(5), 1075–1084. https://doi.org/10.1007/s00421-014-2836-7

Fragala, M. S., Cadore, E. L., Dorgo, S., Izquierdo, M., Kraemer, W. J., Peterson, M. D., & Ryan, E. D. (2019). Resistance training for older adults. *Journal of Strength and Conditioning Research*, *33*(8), 2019–2052. https://doi.org/10.1519/JSC.0000000000003230

Gillespie, L. D., Robertson, M. C., Gillespie, W. J., Sherrington, C., Gates, S., Clemson, L. M., & Lamb, S. E. (2012). Interventions for preventing falls in older people living in the community. *Cochrane Database of Systematic Reviews*, *9*, CD007146. https://doi.org/10.1002/14651858.CD007146.pub3

Gonzalo-Skok, O., Moreno-Azze, A., Arjol-Serrano, J. L., Tous-Fajardo, J., & Bishop, C. (2019). A comparison of 3 different unilateral strength training strategies to enhance jumping performance and decrease interlimb asymmetries in soccer players. *International Journal of Sports Physiology and Performance*, *14*(9), 1256–1264. https://doi.org/10.1123/ijspp.2018-0920

Gonzalo-Skok, O., Tous-Fajardo, J., Valero-Campo, C., Berzosa, C., Bataller, A. V., Arjol-Serrano, J. L., Moras, G., & Mendez-Villanueva, A. (2017). Eccentric-overload training in team-sport functional performance: constant bilateral vertical versus variable unilateral multidirectional movements. *International Journal of Sports Physiology and Performance*, *12*(7), 951–958. https://doi.org/10.1123/ijspp.2016-0251

Gual, G., Fort-Vanmeerhaeghe, A., Romero-Rodríguez, D., & Tesch, P. A. (2016). Effects of In-Season Inertial Resistance Training With Eccentric Overload in a Sports Population at Risk for Patellar Tendinopathy. *Journal of Strength and Conditioning Research*, *30*(7), 1834–1842. https://doi.org/10.1519/JSC.0000000000001286

Hammami, M., Negra, Y., Shephard, R. J., & Chelly, M. S. (2017). The Effect of Standard Strength vs. Contrast Strength Training on the Development of Sprint, Agility, Repeated Change of Direction, and Jump in Junior Male Soccer Players. *Journal of Strength and Conditioning Research*, *31*(4), 901–912. https://doi.org/10.1519/JSC.0000000000001815

Hody, S., Croisier, J.-L., Bury, T., Rogister, B., & Leprince, P. (2019). Eccentric muscle contractions: risks and benefits. *Frontiers in Physiology*, *10*, 536. https://doi.org/10.3389/fphys.2019.00536

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278

Hortobagyi, T., Tunnel, D., Moody, J., Beam, S., & DeVita, P. (2001). Low- or high-intensity strength training partially restores impaired quadriceps force accuracy and steadiness in aged adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *56*(1), B38–B47. https://doi.org/10.1093/gerona/56.1.B38

Howe, T. E., Rochester, L., Neil, F., Skelton, D. A., & Ballinger, C. (2011). Exercise for improving balance in older people. *Cochrane Database of Systematic Reviews*. https://doi.org/10.1002/14651858.CD004963.pub3

Juppi, H.-K., Sipilä, S., Cronin, N. J., Karvinen, S., Karppinen, J. E., Tammelin, T. H., Aukee, P., Kovanen, V., Kujala, U. M., & Laakkonen, E. K. (2020). Role of menopausal transition and physical activity in loss of lean and muscle mass: a follow-up study in middle-aged finnish women. *Journal of Clinical Medicine*, *9*(5), 1588. https://doi.org/10.3390/jcm9051588

Kraemer, W. J., Staron, R. S., Hagerman, F. C., Hikida, R. S., Fry, A. C., Gordon, S. E., Nindl, B. C., Gothshalk, L. A., Volek, J. S., Marx, J. O., Newton, R. U., & Häkkinen, K. (1998). The effects of short-term resistance training on endocrine function in men and women. *European Journal of Applied Physiology and Occupational Physiology*, *78*(1), 69–76. https://doi.org/10.1007/s004210050389

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*(November), 1–12. https://doi.org/10.3389/fpsyg.2013.00863

Lauersen, J. B., Bertelsen, D. M., & Andersen, L. B. (2014). The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *British Journal of Sports Medicine*, *48*(11), 871–877.

https://doi.org/10.1136/bjsports-2013-092538

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gotzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ*, *339*(jul21 1), b2700–b2700. https://doi.org/10.1136/bmj.b2700

Lundberg, T. R., García-Gutiérrez, M. T., Mandić, M., Lilja, M., & Fernandez-Gonzalo, R. (2019). Regional and muscle-specific adaptations in knee extensor hypertrophy using flywheel versus conventional weight-stack resistance exercise. *Applied Physiology, Nutrition, and Metabolism*, *44*(8), 827–833. https://doi.org/10.1139/apnm-2018-0774

Madruga-parera, M., Bishop, C., Fort-vanmeerhaeghe, A., Beato, M., Gonzalo-skok, O., & Romero-rodr, D. (2020). Effects of 8 weeks of isoinertial vs. cable- resistance training on motor skills performance and interlimb asymmetries. *Journal of Strength & Conditioning Research*, [Epub ahead of print]. https://doi.org/10.1519/JSC.0000000000003594

Maroto-Izquierdo, S., García-López, D., Fernandez-Gonzalo, R., Moreira, O. C., González-Gallego, J., & de Paz, J. A. (2017). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *Journal of Science and Medicine in Sport*, *20*(10), 943–951. https://doi.org/10.1016/j.jsams.2017.03.004

Naczk, M., Naczk, A., Brzenczek-Owczarzak, W., Arlet, J., & Adach, Z. (2016). Impact of inertial training on strength and power performance in young active men. *Journal of Strength and Conditioning Research*, *30*(8), 2107–2113. https://doi.org/10.1097/JSC.0000000000000217

Newton, R. U., Gerber, A., Nimphius, S., Shim, J. K., Doan, B. K., Robertson, M., Pearson, D. R., Craig, B. W., Häkkinen, K., & Kraemer, W. J. (2006). Determination of functional strength imbalance of the lower extremities. *Journal of Strength and Conditioning Research*, *20*(4), 971–977. https://doi.org/10.1519/R-5050501x.1

Norrbrand, L., Fluckey, J. D., Pozzo, M., & Tesch, P. A. (2008). Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *European Journal of Applied Physiology*, *102*(3), 271–281. https://doi.org/10.1007/s00421-007-0583-8

Norrbrand, L., Pozzo, M., & Tesch, P. A. (2010). Flywheel resistance training calls for greater eccentric muscle activation than weight training. *European Journal of Applied Physiology*, *110*(5), 997–1005. https://doi.org/10.1007/s00421-010-1575-7

Núñez, F. J., Santalla, A., Carrasquila, I., Asian, J. A., Reina, J. I., & Suarez-Arrones, L. J.

(2018). The effects of unilateral and bilateral eccentric overload training on hypertrophy, muscle power and COD performance, and its determinants, in team sport players. *PLOS ONE*, *13*(3), e0193841. https://doi.org/10.1371/journal.pone.0193841

Nuñez Sanchez, F. J., & Sáez de Villarreal, E. (2017). Does flywheel paradigm training improve muscle volume and force? A Meta-Analysis. *Journal of Strength and Conditioning Research*, *31*(11), 3177–3186. https://doi.org/10.1519/JSC.0000000000002095

Nuzzo, J. L., McBride, J. M., Cormie, P., & McCaulley, G. O. (2008). Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *Journal of Strength and Conditioning Research*, *22*(3), 699–707. https://doi.org/10.1519/JSC.0b013e31816d5eda

Onambélé, G. L., Maganaris, C. N., Mian, O. S., Tam, E., Rejc, E., McEwan, I. M., & Narici, M. V. (2008). Neuromuscular and balance responses to flywheel inertial versus weight training in older persons. *Journal of Biomechanics*, *41*(15), 3133–3138. https://doi.org/10.1016/j.jbiomech.2008.09.004

Raya-González, J., Castillo, D., & Beato, M. (2020). The flywheel paradigm in team sports. *Strength and Conditioning Journal*, [Epub ahead of print]. https://doi.org/10.1519/SSC.0000000000000561

Roig, M., O'Brien, K., Kirk, G., Murray, R., McKinnon, P., Shadgan, B., & Reid, W. D. (2009). The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *British Journal of Sports Medicine*, *43*(8), 556–568. https://doi.org/10.1136/bjsm.2008.051417

Sañudo, B., González-Navarrete, Á., Álvarez-Barbosa, F., de Hoyo, M., Del Pozo, J., & Rogers, M. E. (2019). Effect of flywheel resistance training on balance performance in older adults. A randomized controlled trial. *Journal of Sports Science & Medicine*, *18*(2), 344–350.

Seynnes, O. R., de Boer, M., & Narici, M. V. (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *Journal of Applied Physiology*, *102*(1), 368–373. https://doi.org/10.1152/japplphysiol.00789.2006

Silva, J. R., Nassis, G. P., & Rebelo, A. (2015). Strength training in soccer with a specific focus on highly trained players. *Sports Medicine - Open*, *1*(1), 17. https://doi.org/10.1186/s40798-015-0006-z

Stevens, T. G. A., De Ruiter, C. J., van Niel, C., van de Rhee, R., Beek, P. J., Geert, J. P., & Savelsbergh, G. J. P. (2014). Measuring acceleration and deceleration in soccer-specific movements using a local position measurement (LPM) system. *International Journal of*

Sports Physiology and Performance, *9*(FEBRUARY), 446–456. https://doi.org/10.1123/ijspp.2013-0340

Suchomel, T. J., Nimphius, S., Bellon, C. R., & Stone, M. H. (2018). The importance of muscular strength: training considerations. *Sports Medicine*, *48*(4), 765–785. https://doi.org/10.1007/s40279-018-0862-z

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Medicine (Auckland, N.Z.)*, *46*(10), 1419–1449. https://doi.org/10.1007/s40279-016-0486-0

Tesch, P. A., Ekberg, A., Lindquist, D. M., & Trieschmann, J. T. (2004). Muscle hypertrophy following 5-week resistance training using a non-gravity-dependent exercise system. *Acta Physiologica Scandinavica*, *180*(1), 89–98. https://doi.org/10.1046/j.0001-6772.2003.01225.x

Tesch, P. A., Fernandez-Gonzalo, R., & Lundberg, T. R. (2017). Clinical applications of iso-inertial, eccentric-overload (YoYo™) resistance exercise. *Frontiers in Physiology*, *8*, 241. https://doi.org/10.3389/fphys.2017.00241

Tous-Fajardo, J., Gonzalo-Skok, O., Arjol-Serrano, J. L., & Tesch, P. (2016). Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *International Journal of Sports Physiology and Performance*, *11*(1), 66–73. https://doi.org/10.1123/ijspp.2015-0010

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.2013-0547

Vicens-Bordas, J., Esteve, E., Fort-Vanmeerhaeghe, A., Bandholm, T., & Thorborg, K. (2018). Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses. *Journal of Science and Medicine in Sport*, *21*(1), 75–83. https://doi.org/10.1016/j.jsams.2017.10.006