Considerations to optimize strength and muscle mass gains through flywheel resistance devices. A narrative review.

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ABSTRACT

Flywheel (FW) resistance training is considered a valid and time-efficient method to improve force production and muscular hypertrophy. However, no definitive consensus exists regarding FW parameters for optimizing chronic training responses. This review therefore aims to examine the FW training literature and provides evidence-based conclusions and practical applications for practitioners. This review reports that FW resistance training is a valid strategy to improve force, power, and hypertrophy responses, however, differences with traditional training programs have not been clearly established and currently it is not possible to state that FW training is superior compared to traditional resistance training methodologies. Moreover, the differences between populations and sex should be studied in further depth to be able to establish robust conclusions. Finally, this review reports variables (duration, volume, and intensity) that should be adopted to improve force, power and hypertrophy responses – even though future research is needed to establish the appropriate training dose for specific populations.

Keywords: strength; eccentric-overload; hypertrophy; force; gender

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INTRODUCTION

In the early 90's, the National Aeronautics Space and Administration and the international space medicine community were alerted to the neuromuscular dysfunctions and concurrent muscle atrophy of the musculoskeletal system experienced by astronauts due to the absence of gravity during prolonged space travel (6). To alleviate this problem, flywheel resistance devices were conceived to facilitate resistance training in a gravity-independent scenario (25). The application of flywheel training as a resistance training method has since gained popularity in athletic and non-athletic populations, obtaining promising results in both sports performance and health realms (18,41).

Flywheel devices are characterized by producing unlimited resistance during the entire range of motion (32). In order to initiate the concentric phase of the movement, the participant must pull, push or curl a cord/strap connected to a fixed shaft which holds the flywheel disc(s) (34). The force applied during this phase allows for the unwinding of the cord/strap, causing rotation of the flywheel disc(s) and energy storage. Once the concentric action is completed, the cord/strap rewinds and the participant must resist the pull of the device by braking (eccentric movement phase), and absorb the energy stored in the flywheel (22). In addition, following a series of indications (e.g., to delay the braking action to the last third of the eccentric phase) favors the presence of greater load during the eccentric phase than the concentric one - considered eccentric overload (EO) (40). There are several devices that follow this methodology, which present several mechanical differences (35). Firstly, YoYo® Technology (Stockholm, Sweden) which was introduced by Berg and Tesch (6) and is based in the use of flywheel disc(s) to regulate the moment of inertia during training. Secondly, Versapulley (VP, Costa Mesa, CA, USA) devices provide resistance by adding weights on the flywheel cone where the cord is wound and rewound (9). Finally, the Inertial Training and Measurement System (ITMS) comprises of a steel frame attached to the ground, encompassing an inertial wheel (with a 506-mm radius) on whose circumference a cord is mounted; in this case, the moment of inertia on the ITMS is increased by adding weights to the system (31). It is important to highlight that the inertial load configuration of these devices varies because their different characteristics modify their mechanical responses. For example, Sabido et al. (44) reported that lower moments of inertia (0.025 kg·m^2) elicit higher concentric peak power output values than higher moments of inertia. Meanwhile, medium-to-high moments of inertia (0.050-0.100 kg·m^2) allow for greater eccentric demands and are frequently used to achieve an EO with team sport players (25). However, generalization is not possible because moment of inertia selection and the related mechanical outputs change depending on the exercise selected. Since mechanical outputs (*i.e.*, force, power, and speed) obtained may differ due to different flywheel device configurations and influence training outcomes differently – greater attention should be paid to the flywheel device utilized (25).

The benefits derived from flywheel resistance devices are supported by the capacity of these devices to produce an eccentric load that is greater than what is usually achieved with traditional resistance devices such as free weights and stack machines (3). Training under eccentric contractions induces a preferential upregulation of satellite cell activity and transcriptional pathways in fast-twitch muscle fibers and increases the protein synthesis (8,28). In addition, not only do eccentric contractions allow for greater work efficiency (higher force outputs and lower energy expenditure compared to isometric and concentric muscle contractions), eccentric contractions require fewer motor units to generate the same amount of force during a submaximal exercise (11). The simultaneous exposure to force generation and musculotendinous stretch experienced during flywheel training benefits from the aforementioned physiological and mechanical peculiarities of eccentric training and optimizes chronic adaptations related to force and hypertrophy (20,34). Previously, Illera et al. (17) observed a significant increase in quadriceps muscle mass (pre: 1959.8 ± 358.2 cm^3 vs. 2127.7 ± 399.2 cm^3; $p < 0.001$) after only 4 weeks of flywheel training (10 flywheel half-squat sessions). Similarly, De Hoyo et al. (16) applied a 6-week (18 sessions of flywheel front step) training program in healthy and physically active males and obtained a significant increase ($p < 0.05$) in maximal voluntary isometric contraction force in the leg extension exercise (pre: 106.56 vs. 121.63 N, $p = 0.011$) after the intervention period. However, there is currently a lack of consensus on the load settings that flywheel programs should meet to optimize force and hypertrophy variables (e.g., peak torque or cross-sectional area). Additionally, the superior effects of flywheel devices compared to traditional resistance training methods, or the differentiated effects between male and female populations need to be evaluated. Therefore, a summary of the literature on the benefits and current limitations of this training methodology on force and hypertrophy variables is needed.

Specifically, the aims of the present narrative review were to: (1) evaluate and summarize the current literature surrounding the effect of flywheel resistance training on force and hypertrophy variables, considering differences with traditional resistance training methods and differences between male and female populations, (2) report practical recommendations for practitioners based on the currently available evidence on how flywheel training can be used in applied settings, (3) underline the current limitations of the literature and establish future research directions.

Force and power adaptations

Force production is considered as a relevant value for sport performance and injury prevention (5,47). Although the term force is used in a rather general way by many practitioners, it would be more appropriate if a more precise terminology considering its many characteristics be utilized. For instance, practitioners should refer to specific parts of the force-velocity and force-time curves (15) and the specific type of resistance modality (isokinetic, isometric, iso-weight and flywheel) when referring to force (13). All of the flywheel studies (Table 1) reported significant improvements in specific variables such as isokinetic peak torque, ranging from 12.3-27.4% for upper limbs and 3.5-17.0% for lower limbs. Upper body flywheel training programs have been effective when performed over durations of 4-6 weeks with a training frequency of 2-3 weekly sessions and volume ranging from 4 sets of 7 repetitions to as little as 3 sets of 15-20 s (24,29,30). Only high-level handball athletes and swimmers were investigated at a unique joint (elbow) - largely limiting conclusions. Further studies into the effects of upper limb flywheel training with various populations should be conducted. Previous studies investigating the effect of flywheel training on the lower limbs were carried out with soccer players and swimmers (1,10,27,31). Specifically, 3 sets of 15 s or 2-4 sets of 7-10 repetitions has shown to be a valid flywheel training program to improve isokinetic torque with swimmers and soccer players (1,10,27,31). The current literature reports that improvements in peak torque are seen in both the concentric and eccentric phases – although application of flywheel training should be based according to the practitioners' aims.

The one repetition maximum (1RM) is one of the key variables assessed in strength and conditioning programs (2). Several studies have therefore used 1RM testing to measure improvements in lower limbs after flywheel training (10,12,21,23,43,45). Changes in 1RM between 7 and 20.4% were observed in the aforementioned studies, with only one of them, conducted in professional handball players, showing no significant differences (23). It is probable that since the players investigated were professional athletes, the effectiveness of training was limited - as frequently seen with strength training programs applied to high training volumes (15). Therefore, practitioners working with high level athletes should use tailored flywheel programs to obtain strength improvements. The majority of the studies included in this review used a half-squat flywheel exercise, although 2 of them used full-squat or leg extension exercises (21,43). Flywheel training programs lasted between 6-8 weeks in duration and commonly consisted of 4 sets of 7 repetitions. Alternatively, one study used a lower volume of 2-4 sets of 8 repetitions (43), while Sagelv et al. (45) implemented a progressive change in volume utilized. Moments of inertia that were effectively used varied between 0.050 and 0.11 $kg \cdot m^2$. It is the authors' opinion that the selection of volume and intensity depend on the exercise selected and the athletes' level and a generalization is not possible. Based on the current evidence, further studies comparing the different effects of moments of inertia on 1RM are necessary.

Several studies have considered maximal voluntary isometric contraction (MVIC) to assess force level after a flywheel training programs (16,17,32,46,48). Although these studies have only focused on the lower limbs, improvements ranged from 11-38.9% in MVIC values. Flywheel programs reported in this review had a duration of 4-5 weeks with a weekly frequency of 2-3 sessions per week. The most common exercise used in those studies was a flywheel leg extension. High moments of inertia were usually selected (> 0.090 $kg \cdot m^2$), although some studies did not report the moment of inertia used (16,46,48). Future studies investigating the benefits of flywheel training on isometric contractions are also required.

Due to the relevance of power outputs in sport performance (e.g., team sports), a large number of studies have analyzed the effects of flywheel training programs on this variable (14,19,21,23,24,29–32,36,38), which has been measured usually as peak power or mean power. Regarding the upper limbs (i.e., elbow joint), only 3 studies investigated the effectiveness of flywheel training programs (24,29,30). Specifically, 4-6 weeks of upper body flywheel training improved handball players and swimmers power outputs by 10 and 34%. In these studies, weekly frequencies of 2-3 sessions were applied, combining repetition number (24) and repetitions performed during a certain time period (29,30). Unfortunately, only Maroto-Izquierdo et al. (24) reported the moments of inertia used (0.025 and 0.074 kg·m^2), which is a limitation of the current literature. The majority of the studies have focused on developing power in the lower limbs and report improvements of 8.3-37.9% after flywheel training programs (14,19,20,23,31,32,36,38). The main configuration used in these studies was 4 sets of 7 repetitions over a duration of 5-6 weeks. These studies reported a weekly frequency ranging between 2-3 sessions per week. Interestingly, Gual et al. (14) observed enhancements in power after a flywheel training program applying only a weekly training session but over a longer (24 week) period with team-sport athletes. The moments of inertia that were effectively used in these studies ranged between 0.050-0.110 kg·m^2.

*****Include Table 1 near here, please*****

Hypertrophy effects

Due to the strong positive relationship observed between the muscles' capacity to generate force and their cross-sectional area (CSA) (26), hypertrophy should be considered a main goal to be pursued by both professional and recreational athletes. To obtain hypertrophy adaptations, practitioners have used stack machines and free weights. However, the emphasis during these exercises is placed on the concentric phase, while the eccentric phase is typically underloaded. The exposure to higher eccentric training loads may be particularly effective for generating hypertrophy adaptations and should be considered an interesting alternative to traditional resistance training (39). This review reports in Table 2 the studies that have investigated the effect of flywheel resistance training on hypertrophic adaptations.

*****Include Table 2 near here, please*****

A large number of investigations conducted on this topic have focused on the lower limbs, while only one evaluated hypertrophy improvements in the upper limbs (24). These studies have analyzed several variables such as volume, muscle mass (MM), or lean mass (LM), although the most common variable was the cross-sectional area (CSA). Regarding this, changes in CSA have been analyzed mainly in thigh muscle (7,19,20,36,46,48), although some studies have included gastrocnemius and adductor CSA (7,36). The flywheel resistance training programs were applied for 5-6 weeks, with a frequency of 2-3 sessions per week. Most of the aforementioned studies utilized a training configuration of 4 sets of 7 repetitions using high moments of inertia (i.e., 0.110 kg·m^2) and obtained improvements ranging from 3-8% in CSA. These improvements are lower compared to those seen in force and power parameters - suggesting that to optimize hypertrophy responses, flywheel programs may need to be applied over longer time periods (e.g., at least 10 weeks). Moreover, these findings show that the initial strength and power adaptations are largely due to neuromuscular adaptations. Although 3 sets of 10 repetitions of flywheel training is generally considered adequate for obtaining hypertrophy adaptations, one study did not report such outcomes with healthy college-age participants (7). Practitioners should consider using higher training volume to achieve muscular hypertrophy adaptations. With regards to muscle volume, improvements of 3.5-67.9% were observed when 4 sets of 7 repetitions or 5 sets of 10 repetitions with high moments of inertia (0.075 - 0.110 kg·m^2) were used (17,21,33). Such findings highlight the effectiveness of multi-set programs for obtaining hypertrophic adaptations with flywheel devices. Likewise, increments of 4.4-23.1% in MM and LM were found following similar training configurations (4 sets of 7 repetitions with moments of inertia of 0.075 - 0.110 kg·m^2) (10,12,23). Instead, only one investigation analyzed the effects of a flywheel-based program on muscle mass in the upper limbs (24). Specifically, a flywheel program was applied for 6 weeks (2 sessions per week of 4 sets of 7 repetitions) with professional handball players involving lateral raises, internal and external rotations (using moments of inertia of 0.025 and 0.074 kg·m^2) exercises. The study reported an increase in the muscle thickness (MT) of 14.5–45.9% ($p < 0.05$) and although the preliminary results are promising (24), more studies focusing on the upper limbs and on different lower limb muscles are still necessary.

Differences between flywheel and traditional resistance training devices

Despite the promising effects related to flywheel devices on force and hypertrophy, it is necessary to compare these effects with those obtained using traditional resistance training devices. Focusing on force/power variables, de Hoyo et al. (16) compared a flywheel front step exercise (5-7 sets of 8 repetitions) with a traditional half squat with a stack machine (7 sets of 8 repetitions) over 6 weeks (3 sessions per week) in healthy and physically active males. The study reported no significant differences between groups in

MVIC, although a greater magnitude of effect was observed for flywheel participants. Likewise, Monajati et al. (27) reported increases in peak torque (quadriceps and hamstring) after a 6-week multi-exercise flywheel intervention (2 sets of 8 repetitions and moments of inertia ranging from 0.13-0.22 kg·m^2) performed twice a week with recreational volleyball players. However, no significant differences were observed when compared to a traditional resistance training group (body weight-based training program). Conversely, Sagelv et al. (45) observed a greater increase in the squat 1RM in the traditional group (4 sets of 4 repetitions of 1RM) compared to the flywheel group (flywheel half squat; 3-4 sets of 4-6 repetitions; inertial load from 0.025-0.100 kg·m^2) after 6 weeks (2 sessions per week). On the other hand, Norrbrand et al. (32) applied 2 different resistance programs (traditional vs. flywheel) for 5 weeks (2-3 sessions per week) and observed no differences in training response between flywheel group (knee extension; 4 sets of 7 repetitions; 0.11 and 0.22 kg·m^2) compared with the traditional group (4 sets of 7 repetitions) related to power variables (concentric and eccentric peak power). Regarding hypertrophy variables, the 3 studies that compared the effects of flywheel with traditional devices observed similar increases in variables such as CSA and LM after both training interventions (7,10,21). Due to these findings, it seems that it is not possible to state if a difference between these training modalities exist, therefore future studies are necessary to address this gap in knowledge. The authors of this review suggest combining both methods, flywheel and traditional resistance exercises within resistance training programs and periodization in order to optimize their effects on force, power and hypertrophy parameters.

Differences between male and female participants

The studies reported in this review have mainly involved male participants, while the volume of literature pertaining to flywheel training studies using female populations is scarce (18,42). Due to the differences between males and females in terms of physical fitness and responses to resistance training programs exist (e.g., due to different hormonal levels), further analysis to differentiate response to flywheel and traditional resistance programs between sexes is necessary. In this sense, Fernández-Gonzalo et al. (12) compared the effects of a flywheel program (supine squat [i.e., squat performed from a fully flat supine position]: 4 sets of 7 repetitions; 0.070 kg·m^2; 6 weeks; 2-3 sessions per week) on males and females in force parameters, observing higher increases in leg press 1RM in favor of the male group. Similarly, Lundberg et al. (21) observed greater improvements in leg extension 1RM in active males compared to females after the application of an 8-week (2-3 sessions per week) flywheel program (knee extensions; 4 sets of 7 repetitions; 0.075 kg·m^2 for males and 0.050 kg·m^2 for females). However, these authors reported no between sex (males vs. females) differences in hypertrophy parameters after the intervention. Since prior studies on this topic are scarce, is not possible to establish robust conclusions, so future studies are necessary to increase knowledge on the topic. Moreover, further research is needed to establish the right dose-response according to sex differences. Finally, the current evidence about upper limb muscle groups is not available and warrants further research.

Informed implementation of flywheel resistance exercises

Training intensity

Different intensities (moments of inertia) can be used according to the adaptations that practitioners want to achieve. In this regard, moments of inertia of 0.050 kg·m^2 or higher may be preferential for improving strength (*i.e.*, 1RM), while to enhance MVIC values, even higher moments of inertia (> 0.090 kg·m^2) are recommended. For power increases, moments of inertia ranging from 0.050-0.100 kg·m^2 should be implemented. Ideally, loads should be individualized based on athletes' strength level to maximize power production, but these rough guidelines may be useful. Finally, for hypertrophy, moments of inertia greater than 0.075 kg·m^2 are generally recommended, although greater results have also been obtained using moments of inertia closer to 0.100 kg·m^2.

Training volume

This review reports that 4 sets of 7 repetitions is the volume configuration most commonly applied in flywheel training programs, which is suitable to obtain improvements in force and power parameters. For these variables, configurations of 2 sets of 8 or 10 repetitions are also suitable, although if optimizing training for hypertrophy responses, at least 4 sets are recommended.

Training frequency and duration

Different training frequencies and duration depend largely on the target or objective of training. In this sense, protocols lasting 4-6 weeks with 2-3 weekly sessions are recommended for improving force parameters. Based on the current studies, this is similar for power variables, although preferably > 5 weeks would be prescribed. Meanwhile, improvements in maximal strength (1RM) and hypertrophy may require a longer training duration of at least 6 weeks with a training frequency of 2 sessions per week - although hypertrophic adaptations may benefit from even longer training protocols.

Limitations and directions for future research

The main limitations on this topic are 1) the scarce inclusion of female samples in previous studies (42) and 2) the lower use of upper limb exercises in flywheel training programs. In this regard, further studies should be performed in these topics. Studies that compare the same flywheel training protocol using different inertial loads are also of interest. Likewise, future studies using progressions in training volume or comparing different periodization models must be implemented to increase knowledge on the topic (4). Finally, it would be recommended to compare the effects of the same flywheel programs over different durations.

CONCLUSIONS

Flywheel resistance training is a valid strategy to improve force and power levels and to obtain hypertrophy responses in healthy and active populations (18). However, differences between flywheel and traditional resistance training programs have not been clearly established. It is not currently possible to state that flywheel training is superior to traditional resistance training methodologies. Moreover, the differences between populations and sex should be studied in further depth to be able to establish robust conclusions. Finally, this review provides guidance on the duration, volume and intensity of training when aiming to improve force, power and hypertrophy outcomes with healthy and active populations. Nonetheless, future research is needed to establish the appropriate training dose for specific populations.

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Table and figure captions

Table 1. Summary of research investigating flywheel (FW) training programs effects on strength/power performances.

Table 2. Summary of research investigating flywheel (FW) training programs effects on hypertrophy.