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Review

Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis

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ABSTRACT

Objectives: The purpose of this meta-analysis was to examine the effect of flywheel (FW) resistance training with Eccentric Overload (FW-EOT) on muscle size and functional capacities (i.e. strength and power) in athletes and healthy subjects, and to compare FW-induced adaptations with those triggered by traditional resistance exercise interventions.
Design: A systematic review and meta-analysis of randomised controlled trials.
Methods: A search of electronic databases [PubMed, MEDLINE (SportDiscus), Web of Science, Scopus and PEDro] was conducted to identify all publications employing FW-EOT up to April 30, 2016. Outcomes were analyzed as continuous outcomes using a random effects model to calculate a standardized mean difference (SMD) and 95% CI. A total of 9 studies with 276 subjects and 92 effect sizes met the inclusion criteria and were included in the statistical analyses.
Results: The overall pooled estimate from the main effects analysis was 0.63 (95% CI 0.49–0.76) with a significant ($p < 0.001$) Z overall effect of 9.17. No significant heterogeneity (p value = 0.78) was found. The meta-analysis showed significant differences between FW-EOT vs. conventional resistance training in concentric and eccentric strength, muscle power, muscle hypertrophy, vertical jump height and running speed, favoring FW-EOT.
Conclusions: This meta-analysis provides evidence supporting the superiority of FW-EOT, compared with traditional weight-stack exercise, to promote skeletal muscle adaptations in terms of strength, power and size in healthy subjects and athletes.

1. Introduction

Eccentric (ECC) training has been extensively studied in the scientific literature.[1] In comparison with concentric (CON) exercise, isolated ECC actions are characterized by producing higher peaks of force[2] with lower muscle activation[3,4] and metabolic cost,[5] as well as higher solicitation of Type IIx fibers,[6] increased cross-education effect[7] and greater cortical activity.[8] Furthermore, despite producing high levels of muscle damage and soreness after the initial bout,[9] ECC-based resistance exercise training has been associated with effective muscle damage prevention mechanisms,[10–12] earlier increments in muscle mass when compared with CON[13,14] and improved jumping performance.[10,15] Thereby, ECC actions seem to optimize the efficacy of training.[16,17]

The ability to produce force in the CON phase limits the load/weight to be used during training. As a result, and given the higher force production capacity of skeletal muscle during ECC actions, the loads used during traditional free weights or weight-stack exercise are sub-optimal during the ECC phase of the movement.[2,18] However, optimization of resistance training using a strictly ECC regime is rather complex and technically difficult to apply.[19] In addition, ECC actions are rarely isolated in real-life situations, and usually appear during the stretch-shortening cycle, inducing a greater contribution of the elastic components in the muscle-tendon unit; the stretch-shortening cycle increases the potential to produce force in the subsequent CON action due

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to increased storage and use of elastic energy.[17] Several methods have been designed and proposed to offer an eccentric overload (EO) during resistance training, such as (1) controlling and adjusting the time/velocity of CON and ECC movement during resistance training[20,21]; (2) using third-party assistance or devices for moving/rising the load during the CON phase[10–12]; and (3) employing isokinetic dynamometers.[22]

Devices created to isolate or overload the ECC phase of the muscle action have emerged as an alternative method that may produce greater muscle adaptations, and therefore have been developed and/or tested for rehabilitation and performance purposes. The iso-inertial devices were originally designed by Berg & Tesch[23] in 1994 to counteract the deleterious effect of microgravity on skeletal muscle. Such technology presents one of the most-used exercise paradigms to produce EO during resistance training. The iso-inertial devices more frequently employed are "The Flywheel Exercise Device",[23,24] "VersaPulley",[25] and "Inertial Training and Measurement System".[26] These iso-inertial devices use the flywheel (FW) principle to produce unlimited resistance during the entire range of motion. During the CON phase the force applied unwinds a cord/strap connected to the shaft with the FW, which starts to rotate and store energy. Kinetic energy will increase as a function of the rotational speed. Once the CON action is completed, the cord/strap rewinds and the trainee must resist the pull of the FW by performing a braking, ECC muscle action. By using appropriate technique, i.e. resisting the inertial force gently during the first third of the ECC action, and then applying maximal effort to stop the movement at the end of the range of motion, EO can be produced in force/power values.[24,27] Then, the next CON action is immediately initiated.

The effects of inertial training using FW devices have been extensively investigated over the past 20 years. The majority of studies assessed the effects of eccentric overload training (EOT) on lower body muscle mass in healthy and active subjects. These studies employed a mean workload of 4 sets of 7 maximum repetitions during 5–15 weeks. Results indicate that EOT employing FW technology induce gains of 5–13% in muscle mass,[28–31] 11–39% in maximal voluntary contraction,[28–30] 12–25% in 1 repetition maximum (1 RM),[31,32] 21–90% in ECC force,[19,23,33] 10–33% in muscle power,[32,34] 6–15% in jump ability,[32,34,35] 2–10% in running speed[32,35,36] and up to 35% in electromyography activity.[29,37,38] Despite EOT being associated with a high magnitude of muscle damage and inflammatory responses during the initial phase of training, a significant attenuation of these processes occur shortly after,[31] indicating no counterproductive effects on muscle. Additionally, these devices have been shown very effective in counteracting the decrements in muscle mass and strength during weightlessness,[39–41] as well as improving muscle function, balance, gait and functional performance in elderly[42,43] and stroke patients.[44,45]

While there has been an increase use of these technology and a significant amount of research comparing the effectiveness of eccentric overload flywheel resistance training (FW-EOT) with traditional weight-stack exercise programs, there is no systematic review that summarizes the results of such studies, and adequately assess their scientific rigor. When confronting with a task of this magnitude, there are inherent methodological limitations, such as the difficulty to isolate or enhance the ECC phase from the CON,[1] and the diversity of devices employed to generate EO. To circumvent these limitations, we performed a systematic review including only training studies using FW technology to generate the EO vs. traditional free-weight or weight-stack training. Therefore, the purpose of the current review and meta-analysis was to systematically review the literature on randomised clinical trials examining the effects of FW-EOT, and how the intervention affects functional and structural muscle adaptations among athletes and healthy subjects, and to perform a quantitatively comparison of FW-EOT vs. traditional resistance exercise training in inducing gains in muscle mass, force and power.

2. Methods

This systematic review was designed following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P).[46,47] The PRISMA-P statement includes 26 points, grouped in 17 kinds of items checklist and it is designed to be used as a basis for reporting systematic review of randomised trials. A review protocol was not registered for this review.

A systematic, computerized search of the literature in PubMed, Web of Science (including Web of Science and MEDLINE results), Scopus, SportDiscus and PEDro was conducted by an independent researcher with controlled vocabulary and keywords related to eccentric training, eccentric overload training and flywheel training. Our search time frame was restricted to 22 years (1 January 1994 to 30 April 2016); 1994 was chosen because research on FW technology began that year.[23] We developed our search strategy based on the lack of reviews and meta-analysis about FW-EOT.[1,48] To do this, the search strategy used by previous reviews in the field of resistance training was employed.[48] The search language was restricted to English, and a filter containing Medical Subject Headings (MeSH) terms was applied. First, a general search including the terms "eccentric training", "eccentric exercise", "negative work" was performed. A more specific search included the terms of "eccentric-overload", "eccentric-overload training", "inertial training", "inertial exercise", "isoinertial training", "flywheel", "flywheel resistance", "gravity-independent" and "enhanced-eccentric". These terms were chosen because they have been traditionally used to describe this training methodology. The results of this specific search were then combined with the following terms: "device", "strength", "force", "power", "hypertrophy" and "muscle mass".

The reference list of all selected publications was verified to retrieve relevant publications that were not identified by the computerized search. References of selected and included original articles, abstracts and available conference proceedings were also searched, including publications, posters, abstracts or conference proceedings. To identify relevant articles, titles and abstracts of all selected publication after the first search were analyzed looking for training methods where the ECC phase was overloaded or reinforced. In the specific search, in addition to the identified citations of the first search, titles and abstracts of all recognized publications were examined in detail. Full-text papers were recovered if the abstract provided insufficient information to establish eligibility or if the article abstract had passed the first eligibility review.

All articles examining FW-EOT were eligible for full-text review. An article was eligible for study inclusion if it met all of the following criteria:

1. The original article was a randomised controlled trial (RCT) or clinical controlled trial (CCT) published in peer-reviewed journals.
2. The article reported on athletes or physical active subjects of either sex who had completed an EOT protocol during at least 4 weeks with a minimum training frequency of 2 days per week.
3. The study described healthy subjects without a history of injury in the trained limb.
4. The manuscript included a FW-EOT intervention and a control or alternative intervention group, comparing training adaptations in strength and/or power, and/or muscle mass.

An article was excluded if:

1. Had subjects with any pathology or included subjects with existing, or under treatment for, musculoskeletal injuries in the trained limb.
2. Did not have the minimum requirements regarding in the training protocol (e.g, duration or frequency).
3. Reports focused on elderly above the age of 60 years.
4. Were not written in English.

All criteria were independently applied by two reviewers to the full text of the articles that passed the eligibility screening of titles and abstracts. Any disagreement was resolved by discussion.

Two investigators independently performed quality assessments of the included studies, and disagreements were resolved during a consensus meeting by a third part. The methodological quality of individual studies was assessed using the Physiotherapy Evidence Database (PEDro) scale.[49] Results from individual study analysis of quality were used to identify common areas of methodological weaknesses across studies. PEDro uses 11 criteria, and reviewed studies were awarded one point for each criterion that was clearly satisfied, for a potential maximum value of 11 points. Criteria included:

1. Eligibility criteria reported.
2. Random assignment.
3. Concealed allocation.
4. Groups similar at baseline regarding most important prognostic indicator.
5. Blinding of participants.
6. Blinding of therapists who administered the therapy.
7. Blinding of assessors who measured key outcome.
8. Measures of at least one key outcome were obtained from more than 85% of initial participants.
9. All participants received treatment or control condition as allocated.
10. Results of between-group statistical comparisons are reported.
11. Study provides point measures and measures of variability for at least one key outcome.

Although PEDro does not provide specific instructions to classify studies according to the score obtained, we have used the criteria established by others.[1,16] Thus, a study was considered of high quality when the score was greater than 5, of moderate quality when the score was 5 or 4, and of low quality when the study was scored 3 or less.

The meta-analysis was conducted using to RevMan 5.3 (The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen 2012. Free to download at http://tech.cochrane.org/revman/download) to determine the efficacy of FW-EOT in increasing strength, power and muscle mass, as well as jump ability and speed. Data were pooled in different subgroups according to five physical variables: Strength (CON, ECC or both), muscle power (isotonic or isokinetic conditions only in CON movements), hypertrophy (increases in muscle size, volume or thickness in muscle groups subjected to training), jump ability (CMJ height) and speed. Outcomes were analysed as continuous outcomes using a random effects model to calculate a standardized mean difference (SMD) and 95% CI. A p value less than 0.05 indicated a statistical significance for an overall effect, and a p value less than 0.1 indicated statistical significance for heterogeneity between studies. When the articles selected did not provide sufficient data for the analysis, authors were contacted to obtain relevant data. Studies were not included in the meta-analyses if summary statistics of means, standard deviations and number of participants allocated in each group were not available.

3. Results

Fig. 1 shows a flow chart with the different phases of the search and selection of the studies included in the review. The initial search of electronic databases identified 264 titles, of which 171 were rejected for duplication issues. Four titles/articles[32,50–52] were identified through manual search. Thus, 97 titles were identified, but 48 of them were rejected because they did not meet the intervention criteria: 20 studies of bed rest, descriptive studies, 6 studies of elderly, 5 studies with chronic patients, 2 studies of post-activation potentiation, and 3 studies with other intervention methodology. From a total of 49 abstracts that were screened, 24 were excluded because they had insufficient requirements regarding the training protocol, and 4 studies were excluded for lack of comparison between groups. Twenty-one full texts were reviewed, but only 9 studies satisfied the inclusion criteria to be considered for this review.[26,28,30,32,34–36,52,53] The main reasons for exclusion were: lack of control group (n = 4), lack of information (n = 2), combination FW-EOT with other training methodology (n = 2), and different mechanism to produce EO (n = 4).

The mean methodological quality of the studies in PEDro scale was 7 ± 0.5, out of 11, with scores ranging from 6 to 8. All studies were categorized as high quality. The most common flaws were the lack of blinding of participants, therapists and assessors. It should be considered however, that blinding of participants in these studies is a difficult requisite to satisfy. Inter-rater reliability was significantly high (ICC = 0.98).

The main characteristics of the studies included in the review regarding participants, interventions and results are illustrated in Table 1. After adjusting for dropouts, the total number of participants in the studies included was 276. Of these 276 participants, 165 performed FW-EOT. The rest (n = 111) served as controls or performed resistance training without EO. Demographic data were provided for all studies; the estimated mean age of the experimental and control groups were 25.8 ± 8.5 and 23.2 ± 10.6, respectively. The distribution of sex among studies was not proportional, with only one study including female subjects,[28] with a total of 3 women and 273 men in both the experimental and control groups.

Training interventions ranged from 4 to 10 weeks with a mean frequency of 2.33 ± 0.72 sessions per week, with a mean total of 14 ± 2 sessions per study. The total number of sets (3–6) and repetitions (6–8) per session differed across studies. Inertial Training and Measurement System (ITMS) studies used a training load of 15–20 s per set (between 8 and 11 repetitions).[26,34,52] All studies employed FW devices to produce EO. Exercise devices employed were FW leg press,[32] YoYo squat,[35] Multi-Gym FW,[31] FW supine leg curl[35,36] and FW prone leg extension device.[28,30,50,53,54] Also, three studies employed ITMS.[26,34,52] The muscle groups trained were knee extensors,[28,30,34,50,53,54] knee flexors[36] or both.[31,32,35] Also, two studies of upper limb targeting shoulder abductors[26] and elbow flexors and extensors[52] were included. In the flywheel devices, the workload is provided by the inertia of a rotating mass, which in turns depends on its geometrical and physical properties, and may vary depending on the total number of flywheels installed.[28,50] The most common moment of inertial employed was between 0.07 and 0.145 kg m^2.[28,30,32,53] Given the fact that muscles are capable of achieving higher absolute forces when contracting eccentrically as compared with concentrically,[1] it is important to quantify the intensity of the training during FW exercise. In most of the studies[28,30,32,35,36,53] subjects were asked to push with maximal effort through the entire CON action. At the end of this CON action, the FW strap winds back due to inertial forces, which initiate the

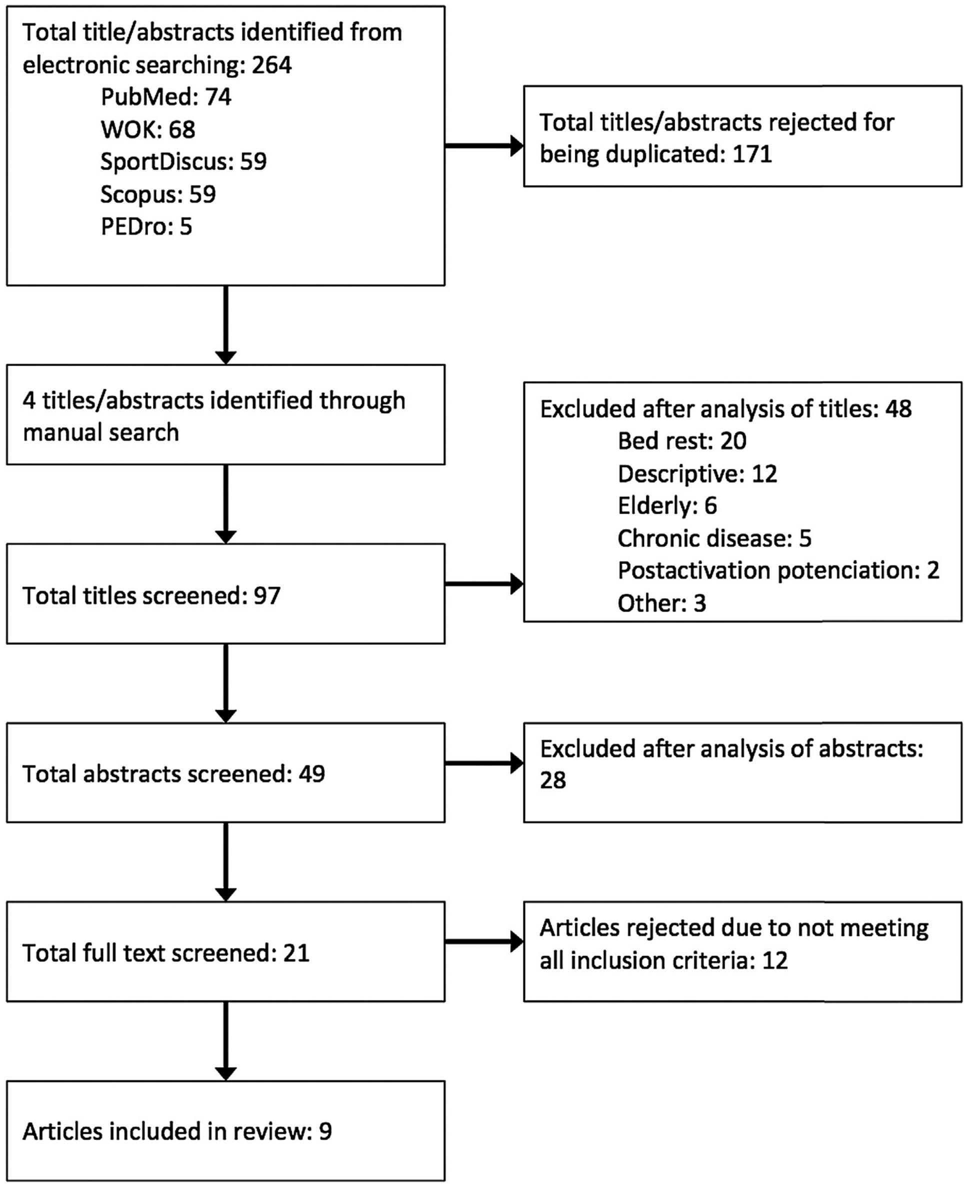

Fig. 1. Flow chart illustrating the different phases of the search and selection of the studies included in the review (PRISMA).

reversed ECC action. During the first third of the ECC action, subjects were instructed to resist gently, and thereafter to apply maximal breaking force to stop the movement. Then, the next CON action was instantly initiated. In these studies, CON and ECC power during training was assessed with an encoder or by means of rate perceived exertion.[32] Some studies adjusted the inertia to the higher CON power output.[35] Only one study failed to use any methodology to quantify the load during training.[36]

Individual main effect analysis, overall pooled estimate and measures of heterogeneity are illustrated in Fig. 2. This figure depicts SMD and 95% CI of the included studies for strength, muscle power, muscle hypertrophy, jump height and running speed adaptations following EOT. The overall pooled estimate from the main effects analysis was 0.63 (95% CI 0.49–0.76) with a significant ($p < 0.001$) Z overall effect of 9.17. No significant heterogeneity (heterogeneity p value = 0.78) was found.

Meta-analyses of subgroups demonstrated significance differences in training-induced adaptations favouring FW-EOT vs. control group in both CON and ECC strength (SMD 0.66; 95% CI 0.44–0.89), muscle power (SMD 0.8; 95% CI 0.53–1.07), muscle hypertrophy (SMD 0.57; 95% CI 0.25–0.9), vertical jump performance (SMD 0.46; 95% CI 0.09–0.83) and running speed (SMD 0.41; 95% CI 0.0–0.82) (Fig. 2).

4. Discussion

This is the first systematic review that analyses the efficacy of eccentric overload flywheel resistance training as a method to improve strength, muscle power and muscle mass. In addition, the statistical approach employed, allows comparing the efficacy of FW-EOT vs. traditional resistance exercise training in eliciting functional and structural muscle adaptations in athletes and healthy subjects. The search performed yielded 9 studies that met the inclusion criteria.[26,28,30,32,34–36,52,53] Using data from these sources, strong effects towards higher gains after FW training compared with other methodologies, in terms of force, muscle power and hypertrophy, as well as jump ability and speed were found. The heterogeneity among studies in the subgroup analysis reported in the current investigation was mainly caused by the different methods of evaluation employed in each investigation. Interestingly, the

Table 1
Characteristics of the studies included.

Study	Participants[a]	Muscle group	Interventions	Results[b]
Askling et al.[36]	30 male field soccer athletes from 2 Swedish premier league teams	Knee flexors	Exp (n = 15), additional training: leg curl FW device 10 weeks (16 sessions) 4 sets of 8 reps/session	Significant increases in CON and ECC peak torque and running speed in exp. No training effects in control group. No difference between groups
de Hoyo et al.[35]	33 junior soccer players (under 17 to under 19)	Knee extensors and flexors	Exp (n = 18): Half-squat and leg curl FW device 10 weeks (15 sessions) 3–5 sets of 6 reps/session	Significant increases in CMJ and running speed in exp. No differences in control group
Maroto-Izquierdo et al.[32]	29 professional handball players	Knee extensors and flexors	Exp (n = 15): Leg press FW device 6 weeks (15 sessions) 4 sets of 7 reps/session	Exp showed significant increases in 1 RM, muscle power in all % of 1 RM, SJ and CMJ, running speed, agility T-test and muscle mass. Control showed smaller training effect in 1 RM, SJ and running speed
Naczk et al.[34]	58 male physical education students	Knee extensors	2 training groups: T0 (no additional load) and T10 (10 kg additional load). 2 control groups ITMS 5 weeks (15 sessions) 3 sets of 15 s/set	Significant increases in muscle force, muscle power, CMJ, SJ and muscle mass No significant differences between training groups
Naczk et al.[26]	46 male physical education students	Shoulder abductors	Exp (n = 33) divided in 3 groups: T0 (no additional load), T5 (5 kg additional load) and T10 (10 kg additional load) ITMS 4 weeks (12 sessions) 3 sets of 20 s/set	All groups showed significant training effects in torque and power No significant differences between training groups
Naczk et al.[52]	38 male physical education students	Elbow flexors and extensors	Exp (n = 20) divided in 2 groups: TF (7.5 rad s^{-1}) and TS (5.76 rad s^{-1}) ITMS 5 weeks (15 sessions) 3 sets of 15 s/set. Flexion and extension, right and left arms worked separately	Greater improvements in elbow flexor force and power in TF than in TS Elbow extensor force and power increased significantly only in TF
Norrbrand et al.[30]	15 men (mean age 39)	Knee extensors	5 weeks (12 sessions) Exp (n = 7). Seated knee extension FW device 4 sets of 7 reps/session Control (n = 8). Standard seated weight stack machine 4 sets of 7 RM/session	QF volume improved significantly in both groups, greater gains in exp
Norrbrand et al.[53]	17 men (mean age 39)	Knee extensors	Same protocol than Norrbrand et al.[30]	Both groups improved significantly MVC and strength. Higher EMG activity in ECC in exp
Tesch et al.[28]	10 middle-age (30–53 year) men and women	Knee extensors	Unilateral (left) leg extension exercise in a seated knee extension FW device 5 weeks (12 sessions) 4 sets of 7 reps/session	CON and ECC strength, maximal isometric strength and QF volume increased significantly

% 1 RM, percentage repetition maximum; AE, aerobic exercise; CMJ, countermovement jump; CSA, cross-sectional area; con, concentric; ecc, eccentric; Ext, experimental group; MVC, maximal voluntary contraction; QF, quadriceps; RE, resistance exercise; RF, rectus femoris; SJ, squat jump; TF, faster training group; TS, slower training group; VL, vastus lateralis; VI, vastus intermedius.

[a] Number of participants at the end of the studies.
[b] Only results for the outcomes of interest are provided.

only studies assessing FW-EOT adaptations in the upper limbs were the ones reporting the largest effect sizes (ES between 0.52 and 1.75) of all investigations analyzed.[26,52]

During traditional CON-ECC resistance exercise performed at maximal intensity, the ECC phase is clearly under-loaded (e.g. about 40–50%).[55] Multiple studies using different protocols have shown the critical role of the ECC muscle action to improve contractile characteristics and muscle size in humans.[3,55,56] Therefore, it seems reasonable to believe that applying eccentric overload during resistance exercise could increase force production capability.[19] Indeed, studies employing eccentric overload training by means of inertial gravity-independent devices (i.e. FW), show robust increments in force production.[27,31,33,35] The current systematic review confirm these data, showing that resistance training offering brief episodes of EO employing FW devices, is associated with significantly greater improvements in maximal dynamic strength when compared to traditional resistance exercise programs. These results are supported by Fernandez-Gonzalo et al.,[31] who reported increases of 25% in maximal dynamic strength in both men (ES = 1.78) and women (ES = 0.62). Furthermore, those studies assessing both CON and ECC force, showed larger increments in ECC than CON force.[36,51] Also, Martinez-Aranda and Fernandez-Gonzalo have

Study or Subgroup	Eccentric Overload Mean	SD	Total	Weight training Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
1.1.1 Strength								
Norrbrand et al. (2010)	47	128	9	29	152.9	8	2.0%	0.12 [−0.83, 1.08]
Tesch et al. (2004)	50	269	10	5	226	10	2.3%	0.17 [−0.71, 1.05]
Maroto-Izquierdo et al. (2016)	31.6	60.81	15	19.1	53.13	14	3.4%	0.21 [−0.52, 0.94]
Naczk et al. (2016) ext TS	8	20.16	10	0	25.64	9	2.2%	0.33 [−0.57, 1.24]
Naczk et al. (2014) T5	9.99	24.04	11	2.35	12.81	13	2.7%	0.39 [−0.42, 1.21]
Askling et al. (2003) CON	20	33.42	15	3	31	15	3.4%	0.51 [−0.22, 1.24]
Naczk et al. (2014) T10	11.99	22.13	11	2.35	12.81	13	2.7%	0.53 [−0.29, 1.35]
Naczk et al. (2014) T0	13.62	23.17	11	2.35	12.81	13	2.7%	0.60 [−0.23, 1.42]
Naczk et al. (2016) flex TS	17	17.47	10	0	32.18	9	2.1%	0.64 [−0.29, 1.57]
Naczk et al. (2016) ext TF	14	26.11	10	−2	20.64	9	2.1%	0.65 [−0.28, 1.57]
Askling et al. (2003) ECC	28	32.56	15	−2	34	15	3.2%	0.88 [0.12, 1.63]
Naczk et al. (2016) flex TF	34	25.66	10	1	24.16	9	1.8%	1.26 [0.26, 2.27]
Naczk et al. (2013) T10	53	29.86	18	4	26.96	10	2.2%	1.65 [0.74, 2.55]
Naczk et al. (2013) T0	47	25.18	19	−5	37.9	11	2.4%	1.67 [0.80, 2.54]
Subtotal (95% CI)			**174**			**158**	**35.0%**	**0.66 [0.44, 0.89]**
Heterogeneity: $Chi^2 = 16.48$, df = 13 (P = 0.22); $I^2 = 21\%$								
Test for overall effect: Z = 5.73 (P < 0.00001)								
1.1.2 Muscle Power								
Naczk et al. (2016) ext TS	12	41.24	10	−6	53.07	9	2.2%	0.36 [−0.55, 1.27]
Naczk et al. (2014) T10	18.75	41.28	11	3.02	30.57	13	2.7%	0.42 [−0.39, 1.24]
Naczk et al. (2014) T5	27.28	54.48	11	3.02	30.57	13	2.7%	0.54 [−0.28, 1.36]
Naczk et al. (2016) flex TS	19	26.38	10	−11	70.52	9	2.1%	0.55 [−0.37, 1.47]
Naczk et al. (2014) T0	26.81	48.23	11	3.02	30.57	13	2.7%	0.58 [−0.24, 1.40]
Naczk et al. (2016) ext TF	30	60.02	10	−15	46.33	9	2.0%	0.80 [−0.15, 1.74]
Maroto-Izquierdo et al. (2016)	129.24	76.13	15	57.46	67.16	14	3.0%	0.97 [0.19, 1.75]
Naczk et al. (2016) flex TF	59	66.8	10	−3	51.77	9	1.9%	0.98 [0.02, 1.95]
Naczk et al. (2013) T0	102	75.04	19	−8	84.02	11	2.6%	1.37 [0.54, 2.20]
Naczk et al. (2013) T10	100	73.62	18	−5	73.75	10	2.4%	1.38 [0.52, 2.25]
Subtotal (95% CI)			**125**			**110**	**24.3%**	**0.80 [0.53, 1.07]**
Heterogeneity: $Chi^2 = 6.49$, df = 9 (P = 0.69); $I^2 = 0\%$								
Test for overall effect: Z = 5.75 (P < 0.00001)								
1.1.3 Hypertrophy								
Norrbrand et al. (2008)	80	315.16	7	42	526.93	8	1.7%	0.08 [−0.93, 1.10]
Tesch et al. (2004)	71	421	10	−13	387	10	2.3%	0.20 [−0.68, 1.08]
Naczk et al. (2016) TS	0.4	0.72	10	0	0.72	9	2.1%	0.53 [−0.39, 1.45]
Naczk et al. (2013) T0	3.66	5.14	19	0.56	4.95	11	3.1%	0.59 [−0.17, 1.35]
Naczk et al. (2016) TF	0.46	0.72	10	0	0.72	9	2.1%	0.61 [−0.32, 1.54]
Naczk et al. (2013) T10	4.99	6.86	18	0.56	4.95	10	2.8%	0.69 [−0.11, 1.48]
Maroto-Izquierdo et al. (2016)	6.2	5.1	15	1.2	4.24	14	2.9%	1.03 [0.25, 1.82]
Subtotal (95% CI)			**89**			**71**	**17.2%**	**0.57 [0.25, 0.90]**
Heterogeneity: $Chi^2 = 3.02$, df = 6 (P = 0.81); $I^2 = 0\%$								
Test for overall effect: Z = 3.47 (P = 0.0005)								
1.1.4 Jump								
Maroto-Izquierdo et al. (2016)	3.49	7.89	15	1.12	5.84	14	3.3%	0.33 [−0.40, 1.06]
Naczk et al. (2013) T0	6.81	19.08	19	−0.43	8.12	11	3.2%	0.44 [−0.31, 1.19]
Naczk et al. (2013) T10	3.15	6.62	18	−0.43	8.12	10	2.9%	0.48 [−0.30, 1.27]
De Hoyo et al. (2015)	2.6	5.87	18	−0.6	4.67	15	3.7%	0.58 [−0.12, 1.28]
Subtotal (95% CI)			**70**			**50**	**13.1%**	**0.46 [0.09, 0.83]**
Heterogeneity: $Chi^2 = 0.24$, df = 3 (P = 0.97); $I^2 = 0\%$								
Test for overall effect: Z = 2.44 (P = 0.01)								
1.1.5 Speed								
De Hoyo et al. (2015)	0.04	0.184	18	−0.01	0.17	15	3.8%	0.27 [−0.41, 0.96]
Askling et al. (2003)	0.08	0.215	15	0	0.141	15	3.4%	0.43 [−0.30, 1.15]
Maroto-Izquierdo et al. (2016)	0.38	0.361	15	0.19	0.306	14	3.2%	0.55 [−0.19, 1.29]
Subtotal (95% CI)			**48**			**44**	**10.5%**	**0.41 [−0.00, 0.82]**
Heterogeneity: $Chi^2 = 0.29$, df = 2 (P = 0.87); $I^2 = 0\%$								
Test for overall effect: Z = 1.94 (P = 0.05)								
Total (95% CI)			**506**			**433**	**100.0%**	**0.63 [0.49, 0.76]**
Heterogeneity: $Chi^2 = 30.06$, df = 37 (P = 0.78); $I^2 = 0\%$								
Test for overall effect: Z = 9.17 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 3.54$, df = 4 (P = 0.47), $I^2 = 0\%$								

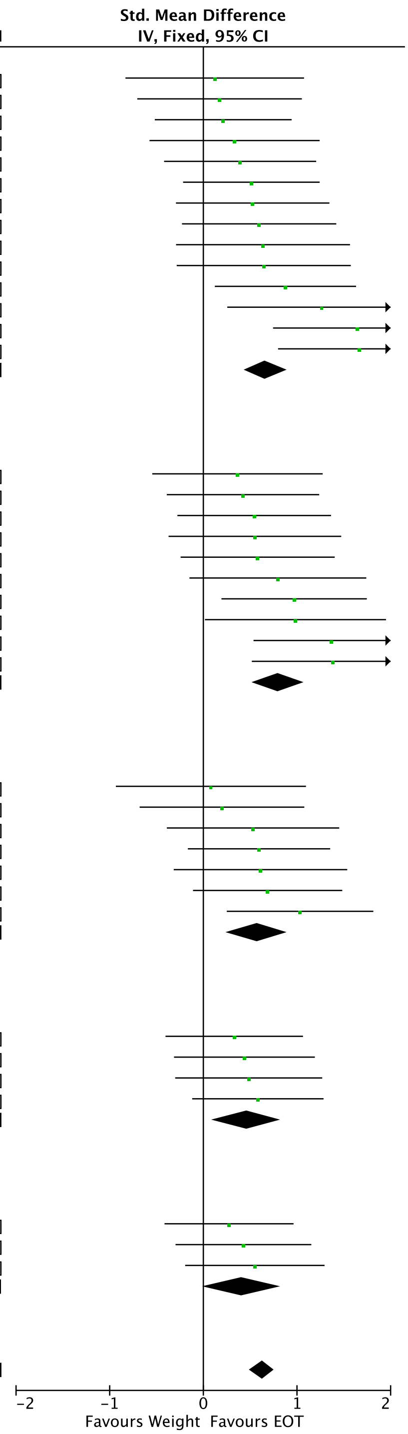

Fig. 2. Forest plot with meta-analysis of standardized mean difference showing comparison of eccentric overload training versus control/weight training on strength (N), muscle power (W), muscle hypertrophy (cm^3, mm or kg), jump height (cm) and running speed (s).

recently shown that the EO produced in terms of force/torque during FW exercise (% above CON) is ∼25% for both men and women.[57] This EO seems to be maintained over the duration of the training period. In addition, anecdotal data seem to indicate that the use of lower inertia[26,34] or high movement velocity[52] during FW training may induce greater force gains. However, this hypothesis needs to be tested in future investigations.

Originally, FW devices were created to counteract the muscle mass and strength losses during space-like, microgravity situations.[39–41,58,59] Thus, the efficacy of FW training to reduce the muscle atrophy and neuromuscular deconditioning during unloading has been analyzed in multiple occasions during the last 15 years, eliminating or greatly reducing loss in muscle mass during long term bed rest studies,[39–41,58] and even increasing muscle volume during unilateral lower limb suspension.[41] The results of the current meta-analyses indicate that not only FW-EOT is effective in increasing muscle mass, but also that is more potent than traditional resistance training in inducing hypertrophy adaptations ($p < 0.001$). The high variability in the effect size of the different studies in terms of muscle hypertrophy after EOT employing FW vs. traditional resistance exercise training could be partly explained by the different methods used to evaluate changes in muscle mass. While some studies used bioelectrical impedance[34,52] or ultrasonography,[32] only 2 studies employed magnetic resonance imaging,[28,30] which is considered the "gold-standard" for muscle mass assessment.[1] Thus, even though all studies showed benefits on muscle mass, magnetic resonance imaging studies were those showing the lower effect (ES = 0.23–0.34). In addition to the studies included in the meta-analysis, two additional investigations[29,31] reported significant gains in muscle mass in young subjects after FW-EOT employing magnetic resonance imaging and DXA, respectively. Interestingly, it seems that adding aerobic exercise 6 h[50] or 15 min[51] prior to FW-EOT elicits even greater muscle hypertrophy (ES = 0.57 and 0.27, respectively) than FW-EOT alone (ES = 0.31 and 0.14, respectively). Finally, the largest effect of FW-EOT training in muscle mass were found in a study describing FW-induced adaptations in well-trained athletes (ES = 0.6 in FW-EOT group versus ES = 0.38 in weight training group).[32] Indeed, the EO produced during FW training is generally greater in athletes with experience in FW training, highlighting the importance of an appropriate technique to maximize the benefits of this training paradigm.[27] In addition, a proper technique during FW training may impact the working angle, where the main gains in strength and muscle mass occur.[60,61] This is an important factor to consider in future studies because muscle mass gains are greater when the ROM employed during training is longer.[62]

The greatest overall effect of subgroups analysis was found for the variable "muscle power" ($Z = 5.75$; $p < 0.001$. SMD 0.8 W; 95% CI 0.53–1.07). Thus, regardless of the specific exercise device or muscle group analysed, FW-EOT induced very robust adaptations in terms of muscle power, which are greater than those seen after traditional resistance exercise training. Apart from the studies included in the meta-analysis, the first investigation assessing FW-induced adaptations in muscle power at different loads (i.e. 40–80% of 1 RM) was Fernandez-Gonzalo et al.,[31] who interestingly, showed that power increments at high percentages of 1 RM were greater for men than women. Expanding on these data, FW-EOT induced power gains at high loads (70–90%) of 1 RM in athletes.[32] These major improvements in muscle power may be explained by the particular characteristics of the FW training to induce EO, since the EO is usually applied in the last portion of the range of motion during the ECC action. That is, the EO is produced mainly at a joint angle close to 70° during leg press[32] and elbow flexion exercise,[52] or at 90° during knee extension,[28,30,34,53] just before the subsequent CON action is initiated. This exercise technique would maximize the stretch shortening cycle, allowing for greater production of force during the first part of the CON action,[32] and therefore, a higher velocity during the entire movement (i.e. increased power).

The significant improvements in vertical jump after FW training corroborate the efficacy of this training model to induce positive power adaptations in healthy and well-trained subjects. Thus, the articles included in the current meta-analysis indicate that vertical jump improvements induced by FW-EOT are higher than traditional resistance training, as long as the jump modality used to assess jumping ability includes an eccentric phase (i.e. a counter movement jump, CMJ). Of note however, De Hoyo et al.[63] showed that under specific circumstances, i.e. FW exercise (VersaPulley device) performed in the horizontal plane vs. free weights using guided (vertical) squat exercise, gains in jumping height were lower for FW than traditional training (ES = 0.4 and 0.9, respectively). Therefore, vertical FW training is recommended to increase jumping ability.

The selection of running speed as an outcome in this meta-analysis is based on the fact that it is an important performance factor in many sports, and it is usually related with vertical jump and multi-joint strength training. Although the findings in this variable showed the lowest significance of all outcomes analysed ($p < 0.05$), FW-EOT training appeared more effective to improve running speed than traditional resistance training[32,35,36] (ES between 0.3 and 1.45 in FW-EOT groups and −0.08 and 0.55 in control groups). These results are supported by Tous-Fajardo et al.,[64] not included in the meta-analysis, who showed greater improvements in soccer-specific performance tasks such as change of direction and linear running speed, after a combined FW-EOT and vibration training protocol vs. conventional training (plyometric, speed and weight-loaded training). Adding to this, from a molecular perspective, it seems EOT favours increments of mRNA levels of genes preferentially expressed in fast glycolytic fibers, ultimately inducing a faster muscle phenotype. Such changes may help the muscle to become better suited for explosive, high-speed actions.[65]

5. Conclusion

Although free weights and weight-stack machines are the most popular modes of resistance training, the results of this systematic review indicate that brief episodes of eccentric overload induced by flywheel devices, and performed at high intensity are associated with greater improvements in both concentric and eccentric force, muscle power and muscle hypertrophy in healthy and well-trained subjects. In addition, eccentric overload training appeared to be more effective than traditional resistance exercise in promoting increases in capacities highly related to athletic performance, such as vertical jump height and running speed. The efficacy of eccentric overload flywheel training to promote functional and structural adaptations is possibly mediated by the capacity to achieve higher forces during the eccentric muscle action, which maximizes the stretch-shortening cycle and thus, the capacity to produce greater force in the subsequent concentric action. However, these gains could even be greater considering the possibilities offered by FW technology. Thus, it appears at high speed and with light moments of inertia is the most effective training protocol to induced muscle adaptations employing FW. Finally, muscle power is the training outcome that experienced the greatest increase after a period of FW-EOT in healthy subjects and athletes. Future studies should analyse FW resistance training with eccentric overload programs using and comparing different training devices, volumes, intensities and exercise modes to fine-tune FW training routines.

Practical implications

Iso-inertial flywheel resistance exercise, a technology originally developed to combat muscle deconditioning during spaceflight, is a powerful tool to induce muscle force and power increments, as well as muscle hypertrophy in healthy subjects and athletes.

The available scientific literature indicates flywheel resistance exercise, calling for brief episodes of eccentric overload, triggers significantly greater skeletal muscle adaptations (i.e. strength, power and muscle mass) compared to traditional, gravity-dependent resistance exercise paradigms.

Eccentric overload flywheel resistance exercise boosts performance-related abilities (i.e. jump height and running speed). The magnitude of these adaptations is greater than those reported after weight-stack or free weight resistance training, which highlights the efficacy of iso-inertial exercise training.

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