Does Flywheel Paradigm Training Improve Muscle Volume and Force? A Meta-Analysis

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DOES FLYWHEEL PARADIGM TRAINING IMPROVE MUSCLE VOLUME AND FORCE? A META-ANALYSIS.

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ABSTRACT

Several studies have confirmed the efficacy of flywheel paradigm training for improving or benefiting muscle volume and force. A meta-analysis of 13 studies with a total of 18 effect sizes was performed to analyse the role of various factors on the effectiveness of flywheel paradigm training. The following inclusion criteria were employed for the analysis: a) randomized studies; b) high validity and reliability instruments; c) published in a high quality peer-reviewed journal; d) healthy participants; e) studies where the eccentric programme were described; and f) studies where increases in muscle volume and force were measured before and after training. Increases in muscle volume and force were noted through the use of flywheel systems during short periods of training. The increase in muscle mass appears was not influenced by the existence of eccentric overload during the exercise. The increase in force was significantly higher with the existence of eccentric overload during the exercise. The responses identified in this analysis are essential and should be considered by strength and conditioning professionals with regard to the most appropriate dose response trends for flywheel paradigm systems to optimize the increase in muscle volume and force.

Key words: Flywheel paradigm, force, strength, eccentric overload, meta-analysis

INTRODUCTION

Resistance training produces muscular adaptations at multiple structural and functional levels (1-4). Numerous studies have demonstrated that chronic resistance exercise can produce neural changes in the first several weeks and increase hypertrophy (after 4-8 weeks) and strength within the first 4 weeks of training (5, 6). Different studies conclude that a training protocol that utilizes on the concentric (CON) or only the eccentric (ECC) phase of the movement increases both muscle mass and strength(2, 7-9), and the increases are magnified when combining CON and ECC actions (2, 10, 11). Considerable controversy is noted regarding the muscle load during the CON and ECC movement given that muscle fibres generate greater force during an ECC action compared with a CON action (12-19). Some authors argue that training protocols where exercise is overloaded during the ECC phase of movement achieve greater strength gains than those movements in which the load is constant during the CON-ECC cycle (20-22), giving rise to the concept of "eccentric overload" (EO).

Different training systems have been designed to use the inertia of rotating flywheel(s) to provide maximal resistance load during CON-ECC movements favouring EO (Flywheel Paradigm). Berg and Tesch (23, 24) introduced YoYo® Technology (Stockholm, Sweden). YoYo® Technology generates resistance by opposing the trainee's effort with the inertial force generated by a lightweight rotating flywheel such that the same inertia must be overcome during each repetition by means of accommodated loading (25). Training loads on the YoYo Technology can be regulated by increasing the speed of movement or by adding flywheels weights. There are several types of YoYo® devices that use the inertia of flywheel(s) to provide resistance load, including YoYo® Squat and YoYo® MultiGym (24), YoYo® Leg Curl (23), YoYo® Knee Extension (26), and other devices (27). The Inertial Training and Measurement System (ITMS) is another system designed and constructed by an inter-university group from the Faculty of Physical Culture in Gorzow Wielkopolski (department of the University School of Physical Education in Poznan) and the Faculty of Mechanics University of Zielona Gora (28). This device comprises a steel frame attached to the ground, encompassing an inertial wheel (flywheel) with a 506-mm radius. A rope is mounted on the flywheel circumference. Training loads on the ITMS are regulated by increasing the speed of movement or by adding weights (29). With ITMS, exercises can be performed in multiple planes of motion. Versapulley (VP, Costa Mesa, CA, USA) provides a source of linear resistance from a tether wrapped around a vertical cone-shaped shaft (30).

The tether winds around the cone. The concentric action unwinds the tether, and the eccentric action occurs during rewinding. Training loads on the VP can be regulated by increasing the speed of movement or by adding weights. With VP, exercises can also be performed in multiple planes of motion. In all systems, the kinetic energy from the concentric portion of the exercise is transferred to the eccentric portion, and an equal eccentric impulse is necessary to halt the rotation of the disc. Given that impulse is a function of both force and time, a greater amount of eccentric average force can be induced by performing the eccentric portion in less time than the concentric portion(25, 31). When this kinetic energy is decelerated in a restricted portion of the ECC action, the force exceeding that generated during the corresponding CON phase must produce ECC overload (25).

Several studies have confirmed the efficacy of flywheel training for improving or benefiting muscle volume (25-27, 29, 32, 33), force (25, 26, 28, 29, 31, 33-35), and EMG activity (28, 29, 31, 33). The flywheel paradigm also has been used as an aid in the treatment and prevention of tendon injuries (36, 37) and muscle injuries (34, 38). Most studies compared this methodology with traditional training(20, 31, 35, 39). The results mixed acute(40-45) and chronic(25, 26, 28, 29, 31-33, 35, 36, 39) training effects. Training protocols are applied to subjects between 17 and 71 years of age, and an equivalent level of physical activity was developed: sedentary, athletically active, trained subjects, injured subjects or subjects who suffered a muscular atrophy produced by weightlessness. Although many studies are available, the beneficial effect of flywheel training is not clear. Therefore, the purpose of this systematic review and meta-analysis was to determine if chronic training using a flywheel paradigm with healthy people increase muscle volumen and forcé.

METHODS

Experimental Approach to the Problem

In this investigation a meta-analysis of 13 studies with a total of 18 effect sizes was performed to analyse the role of various factors on the effectiveness of flywheel paradigm training to increases muscle volume and force. The following inclusion criteria were employed for the analysis: a) randomized studies; b) high validity and reliability instruments; c) published in a high quality peer-reviewed journal; d) healthy participants; e) studies where the eccentric programme were described; and f) studies where increases in muscle volume and force were measured before and after training. To determine the effects of the categorical independent variables on muscle volume and force effect sizes (ES), an analysis of variance (ANOVA) was used. In the case of quantitative independent variables a Pearson's (*r*) correlation test was used to examine the relationships between muscle volume and force ESs and variable values.

Procedures

To evaluate the effectiveness of flywheel eccentric training for increases in muscle volume and force (N), a meta-analysis was conducted. Literature searches were conducted electronically to identify investigations that examined these topics. The research assessed ADONIS, ERIC, SPORTSDiscus, EBSCOhost, Google Scholar, MedLine and PubMed electronic databases between October and November 2015 and was updated in March 2016. Moreover, manual searches were performed in sport science-relevant journals. The references of identified articles were examined to identify additional studies that were eligible for the review. The search included all studies published in English and studies in any language for which the abstract was available in English. Key words used included eccentric, eccentric overload, flywheel, resistance training, and inertia. No age or gender restrictions were imposed during the search stage.

For the selection of studies to further review, we performed 3 steps: 1) the article titles were read, 2) the abstracts were read, and 3) the entire articles were read. In this review, only human studies and full primary research papers (i.e., not a conference abstract, letter to editor, thesis or review) were eligible for inclusion.

Studies were included if they met the following criteria based on recommendations by Campbell and Stanley(46): 1) randomized studies, 2) high validity and reliability instruments, 3) published in a high quality peer-review journal, 4) healthy participants, 5) studies where the eccentric programme was described, and 6) studies where muscle volume and force (Table 1), were measured before and after training. Following this search process, 13 articles were included in the analysis (Figure 1).

(Insert Table 1 and Figure 1 about here)

Each article was read and coded by two investigators for the following variables: 1) descriptive information (age, body mass, and height), previous experience with eccentric exercises (familiarized and not familiarized), physical activity (trained, physically active and sedentary), and gender (male, female and both); 2) programme exercises: type of exercise (knee extension, squat, leg press, leg curl, shoulder adduction, front step, and combined), eccentric overload, and type of work (unilateral or bilateral); 3) programme variables: frequency of weekly sessions, programme duration, total number of sessions, number of sets per day, number of repetitions per day and rest intervals; and 4) outcome measurements: the type of test used to identify performance gains (e.g., load cells, magnetic resonance imaging MRI, dual X-ray absorptiometry DEXA, and Bioimpedance). The mean agreement was calculated using an intraclass correlation coefficient (ICC). The coding agreement between investigators was determined by dividing the variables coded by the total number of variables. A mean agreement of 0.90 is accepted as an appropriate level of reliability for such coding procedures.(47) Any coding differences between investigators were scrutinized and resolved *a priori* to the analysis.

Gain effect size (ES) was calculated using Hedges and Olkin's *g* using the formula (1): $g = (M_{post} - M_{pre}) / SD_{pooled}$, where M_{post} is the mean for the post test, M_{pre} is the mean for the pretest, and SD_{pooled} is the pooled *SD* of the measurements (2):

$$SD_{pooled} = \frac{(M_{post} - M_{pre})}{\sqrt{((n_1 - 1) \cdot SD_1^2 + (n_2 - 1) \cdot SD_2^2)/(n_1 + n_2 - 2)}}.$$

The ES is a standardized value that permits the determination of the magnitude of the differences between the groups or experimental conditions. It has been suggested (48) that ES should be corrected for the magnitude of the sample size of each study. Therefore, correction was performed using the formula (3): 1-3 / (4*m*-9), where *m* = *n* -1, as proposed by Hedges and Olkin (47).

Statistical Analyses

To determine the effects of the categorical independent variables (previous experience, fitness activity, gender, and programme exercises [type of exercise, eccentric overload, type of work and training sessions]) on muscle volume and force effect sizes (ES), an analysis of variance

(ANOVA) was used. In the case of quantitative independent variables (e.g., age, duration of the treatment in weeks, number of total sets, number of sets per day, number of repetition per day and rest intervals) a Pearson's (*r*) correlation test was used to examine the relationships between muscle volume and force ESs and variable values. The following criteria were adopted to interpret the magnitude of the correlation (r) between the different measures: ≤0.1, trivial; >0.1–0.3, small; >0.3–0.5, moderate; >0.5–0.7, large; >0.7–0.9, very large; and >0.9–1.0, almost perfect (Hopkins et al. 2009). The α level was set at $p \leq 0.05$ for statistical significance. In addition, data were also assessed for clinical significance using an approach based on the magnitudes of change. Threshold values for assessing magnitudes of ES were < 0.35, 0.35-0.80, 0.80-1.50 and > 2.0 for trivial, small, moderate and large, respectively (48).

RESULTS

The analysis showed that the average ES of the experimental group (0.68; $n = 18$) was significantly increased ($p < 0.05$) compared with the ES of controls (0.32; $n = 2$).

Muscle Volume.

The analysis of muscle volume showed that the average ES the experimental group (0.75; $n = 7$) was significantly higher ($p < 0.05$) compared with the ES of controls (0.39; $n = 1$). Regarding the subject's characteristics, the results indicate a significant correlation for age ($r = -0.771$, $p = 0.042$) with the magnitude of the ES, and no significant correlation for body mass ($r = -0.229$) or height ($r = 0.155$) with the magnitude of the ES (Table 2). ANOVA results revealed significant effects for some of the variables measured (i.e., previous experience, $p = 0.014$). In addition, significant relationships ($p < 0.05$) were noted between the frequency of weekly sessions (FWS) ($r = 0.752$) and total sessions (TS) ($r = 0.797$) with muscle volume ES (Table 3).

(Insert Table 2, 3 about here)

Force (N).

The analysis of force revealed that the average ES in the experimental group (0.6; $n = 11$) was significantly increased ($p < 0.05$) compared with the ES of controls (0.28; $n = 1$). Regarding subject characteristics, no significant correlation for age ($r = 0.282$), body mass ($r = -0.269$) or height($r = -0.020$) with the magnitude of the ES was noted (Table 4). ANOVA results revealed significant effects for some of the variables measured (i.e., gender, $p = 0.038$; eccentric overload, $p = 0.001$). In addition, a significant relationship ($p < 0.05$) was noted between the number of repetitions per set (Nrs) ($r = 0.604$) with force ES (Table 5).

(Insert Table 4, 5 about here)

DISCUSSION

The objective of this review was to establish the chronic effects of different training protocols for the flywheel paradigm in healthy people, i.e., muscle hypertrophy and strength capacity. The main findings from this review were as follows: a) Increases in muscle mass and force were noted through the use of flywheel systems during short periods of training. b) A previous familiarization period with the flywheel system facilitates the improvements in muscle volume. c) The increase in muscle mass does not appear to be influenced by the existence of EO during the exercise. d) The increase in force was significantly higher with the existence of EO during the exercise.

Muscle Volume

Several studies argue that eccentric contractions cause greater muscle damage (41, 49-52), increased production of muscle fibre proteins (53, 54), and therefore, greater muscle hypertrophy compared with concentric contractions (2, 10, 11, 53-55). The muscle exhibits an increased capacity to generate force in the eccentric phase compared with concentric phase (12-14, 16-19, 56). However, studies that overload the eccentric phase with respect to the concentric phase reported small increments in hypertrophy (2, 57) or no effects (7), suggesting that the use of EO per se may not sufficiently stimulate the generation of muscle mass (25). Related to our systematic review, some authors claim that flywheel paradigm training, which allows for brief episodes of enhanced force in eccentric over concentric actions, prompted increases in muscle size (25, 26, 32, 33). However, in our analysis, we identified no differences between the existence of eccentric overload and an increase in muscle mass in the studies included in this review (see Table 2). For participants performing knee extension exercises in an ITMS system without EO (3 times per week and 3x28-31 repetitions each day), Naczk et al. (29) reported increases of 9.8 (ES 0.85)to 15.1% (ES 0.83) in quadriceps muscle mass. These values were slightly higher than the values (6.8% to 6.6%, ES 1.5) reported by other studies using a knee extension exercise in the same age group (33), and in a group of older participants (25, 26), performing an eccentric training with EO. These values are also greater than the thigh muscle mass increase reported by Fernandez-Gonzalo et al. (32) for both men (4.6%, ES 0.71) and women (5.4%, ES 0.67) training with an EO on a leg press YoYo® system. Using a similar protocol in a YoYo® system knee extension, Lundberg et al. (58) proposed that a leg undergoes exhaustive aerobic work 6 hours before training, whereas the other leg exclusively trains with the flywheel system. The group that performed aerobic work exhibited an increase in muscle mass very similar to that obtained without EO (14%, ES 0.62). This study demonstrates a large increase in hypertrophy of type I fibres, an increase in skeletal muscle aerobic capacity, and a loss of muscle strength. These findings suggest that this hypertrophy was influenced by aerobic work. However, Carmona et al. (42) showed that squat training performed in a Versapulley system obtained significant serum increases in fast myosin isoforms after 48 h, the improvements were maintained after 144 h, and the slow myosin isoform concentration in blood did not change. All these results could indicate that the higher increase in muscle mass without eccentric overload systems could be influenced by an increased number of repetitions per set. It is possible that the technique used to assess the increase in muscle mass might influence the results of this review; however, the analysis shows no significant difference. Despite these increases through the evaluation with bioelectrical impedance, the results obtained were two-fold enhanced compared with that obtained by MRI or DXA (see Table 1).

Our analysis reveals a negative correlation between subject age and the size of the effect produced by increased muscle mass after training processes (Table 2). Although almost no study used a long familiarization period, the ANOVA results revealed significant effects for previous experience (Table 2). Seynnes et al. (33) proposed monitoring the evolution of increased muscle mass over 35 days of training with the flywheel system. During the first 10 days, an apparent increase in muscle mass was not generated, and an increase of 6.8% with a large effect sizes (ES 1.5) was attained 35 days after starting training. The increased muscle mass through flywheel paradigm systems during the 5-week training periods was not significantly different from that obtained with traditional systems with the same workload (25). Norrbrand et al. (25) reported two-fold greater quadriceps hypertrophy with training on YoYo® knee extension system (6%, ES 0.38) compared with the weight stack system (3%, ES 0.11) without significant differences. Similar to our analysis, Tesch et al. (26) revealed a significant increase in quadriceps muscle mass with the flywheel system, whereas hypertrophy increased significantly in the rectus femoris exclusively with the weight stack system. Seynnes et al. (33) used the same protocol and reported an increase in muscle mass similar to Norrbrand et al. (25). A significant increase in the fascicular length of the vastus lateralis of the quadriceps was observed. These authors argued that training with EO in the flywheel system compared with traditional systems led to a faster increases of sarcomeres in series than in parallel. This finding could explain why no differences in the cross section of muscle are noted after short periods of training with both systems. It is interesting to evaluate the increase in muscle mass after long training periods. In fact, our analysis reveals a positive correlation with the number of sessions per week and the total number of sessions (Table 3). However, consulted studies measuring the increase in muscle mass do not exceed 6 weeks or 15 training sessions.

Force (N)

The training based on the flywheel paradigm produced a significant increase in the MVC over short periods of training (5 weeks), 2 to 3 days per week, with an average of 3-4 sets per day and a rest between sets of 2 minutes (see Table 1). Dynamic training with flywheel paradigm improved the specific capacity to generate force during both the concentric and eccentric phases. Through our analysis, we can see how the protocols that did not generate eccentric overload exhibited significantly greater effect sizes than the protocols that generated EO. Thus, performing 15 training sessions of knee extension without EO in a ITMS system with and without an additional 10-kg load, Naczk et al. (29) achieved 25.2% (ES 0.93) and 23.3% (ES 0.77) increases in maximum force. Similarly, Naczk et al. (28) applies the same ITEMS system for shoulder abduction-adduction training in adult women during 12 sessions with and without 5-kg overload and achieved increases of 11.8% (ES 0.55) and 13.7% (ES 0.81) in maximum force, respectively. Most of the protocols using an eccentric overload achieved a small effect size (25, 26, 31, 33). However, Seynnes et al. (33) achieved an increase of 38%

MVC with experienced subjects, but did not provide the effect size. Possible explanations include the following: protocols potentially used an eccentric overload and inexperienced subjects, and the ability to produce an eccentric overload appears to require some experience or a process of familiarization with the flywheel paradigm system. Tous-Fajardo et al. (43) analysed the acute effect of a series of 6 repetitions with the YoYo® Leg Curl system and observed that subjects, with experience in flywheel training, generated a higher peak force during the ECC phase than the CON phase (EO). Importantly, this effect did not occur in inexperienced subjects. The experience and inexperienced CON average force were higher than ECC average force. Moras & Vázquez-Guerrero (44) and Norrbrand et al. (45) assessed a squat exercise in the Versapulley system and a leg press in the YoYo® multi gym, respectively, using subjects that were not familiarized with flywheel systems, where EO was not generated, and the average CON force was higher than ECC. Nevertheless, Askling et al. (38) trained experienced subjects for 10 weeks for 1-2 days per week with 4x8 repetitions on a YoYo® Leg Curl system and noted increased peak eccentric (16%, ES 0.95) and concentric (13%, ES 0.95) torque. These authors argued that this increase produced a 67% reduction in the incidence of hamstring injuries. These results are consistent with those obtained by De Hoyo et al.(34) who reported a 65% (ES 0.48) reduction in injury severity and a significantly reduced incidence of match play per 1000 hours when performing YoYo® squat and YoYo® leg curls for 10 weeks, 1-2 days per week, and 3-6x6 repetitions.

Training for five weeks of training with flywheel paradigm systems produces a greater increase in force than in muscle volume (25, 26, 28, 29, 33). This finding can be attributed to increased motor unit recruitment during exercise (59), increased synchronization of motor units (60, 61) and an increase in EMG activity (3, 31). We must emphasize that we could not include in this review an analysis of the variable "EMG activity" due to the small number of studies using the same "gold standard" for measuring this variable. However, conflicting results regarding the correlation of increased strength and root mean square EMG activity are noted that demonstrate a nonexclusive influence of neural processes in the increase of the maximum voluntary force. Thus, in a study of sedentary subjects that trained for 5 weeks on a YoYo® knee extension, Tesch et al. (26) reported a 11-12% (ES 0.14) increase in MVC in both CON and ECC phases without modifying the EMG activity of the vastus lateralis, vastus medialis and rectus femoris of the quadriceps. Performing a similar training, Seynnes et al. (33) reported proportional increases in both the maximal voluntary contraction and the EMG activity of the vastus lateralis of the quadriceps during the entire training process, reaching increases of 38.9 and 34.8%, respectively, at the end of the training. Similarly, performing the same training in untrained subjects, Norrbrand et al.(31) achieved an 8.1% (ES 0.52) increase in maximal voluntary contraction and an increase in EMG activity of the vastus lateralis of the quadriceps, whereas the EMG activity of the vastus medialis during CON phase and all muscles during ECC phase did not change. One of the possible reasons for the non-linearity between MVC and EMG involves the differences in the type of fibre that composes the structure of the muscle evaluated (62, 63), which was not analysed in this review. Another possible explanation involves previous experience in training with these systems. Studies on chronic and acute effects using flywheel systems showed that during the execution of the exercise, the EMG activities were similar than obtained during MVC in subjects without experience (27, 45) and higher in subjects with experience (43) compared with those obtained during MVC. Onambele et al. (35) showed that EMG activity was 32% higher during the CON phase and 42% lower during the ECC phase in older subjects without prior experience using a YoYo® knee extension compared with a traditional machine. Nevertheless, Norrbrand et al. (45) denote a trend ($p<0.05$) for increased EMG activity in the ECC phase of the rectus femoris in experienced subjects using a YoYo® multi gym compared with using a barbell in half squat exercises.

The literature concludes that the use of a training system based on flywheel paradigm generates higher improvements in maximum voluntary force compared with traditional methodologies (25, 35). Norrbrand et al. (25) performing a training with a YoYo® knee extension system, reported an increase of 11.6% (ES 0.47) in the MVC at 90º knee-flexion, and they found no differences at 120º knee-flexion or in both angles using a weight stack system. Performing a similar training, Onambele et al. (35) reported an increase of 17% (ES 2.4) in the MVC, which was significantly higher than the 8% (ES 0.66) obtained with a traditional machine. Nevertheless, Norrbrand et al. (31) did not obtain significant differences between the flywheel and weight stack despite the two-fold increase in MVC with the YoYo® knee extension system. Similarly, De Hoyo et al. (39) compared a front step exercise VP vs. half traditional squat for 6 weeks and reported that training under flywheel paradigm resulted in a 10% improvement in the MVC and a higher improvement in the effect size compared with the traditional system (ES 1.02 vs. 0.45); however, significant differences between both training methods were not achieved.

There are no studies that measure the MVC exclusively in women, but studies using a mixed sample (men and women) obtained a small effect size compared with studies in men that obtained a moderate effect size. Fernandez-Gonzalo, et al. (40) reported a 25% (ES 7.6) increase in 1 RM in men and a 20% (ES 3.6) increase in women without significant differences between sexes. Similarly, Caruso et al. (64) assessed the acute effects of the execution of twin exercises and soleus 3x10 reps. Men generated more EMG activity than women for soleus and lateral twin exercises, but medial calf activity only occurred in the first repetition. Regarding force, men have a greater ability to increase absolute and relative levels; however, more studies are needed to corroborate this assessment.

PRACTICAL APPLICATION

The ability to produce an eccentric overload in the flywheel system appears to require some experience. A significant increases in muscle mass was noted through the use of flywheel systems during short periods of training. A previous familiarization period with the flywheel system facilitates the improvements obtained. The increase in muscle mass appears was not influenced by the existence of EO during the exercise. In addition, chronic training under flywheel paradigm systems is related to improve the force. The increase in force was significantly higher with the existence of EO during the exercise. The responses identified in this analysis are essential and should be considered by strength and conditioning professionals with regard to the most appropriate dose response trends for flywheel paradigm systems to optimize the increase in muscle volume and force.

REFERENCES

1. Aagaard, P, Andersen, JL, Dyhre-Poulsen, P, Leffers, AM, Wagner, A, Magnusson, SP, Halkjaer-Kristensen, J, Simonsen, EB. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. J Physiol 534:613-23, 2001.
2. Higbie, EJ, Cureton, KJ, Warren, GL, Prior, BM. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. J Appl Physiol (1985) 81:2173-81, 1996.
3. Moritani, T, deVries, HA. Neural factors versus hypertrophy in the time course of muscle strength gain. Am J Phys Med 58:115-30, 1979.
4. Narici, MV, Roi, GS, Landoni, L, Minetti, AE, Cerretelli, P. Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. Eur J Appl Physiol Occup Physiol 59:310-9, 1989.
5. Schuenke, MD, Herman, JR, Gliders, RM, Hagerman, FC, Hikida, RS, Rana, SR, Ragg, KE, Staron, RS. Early-phase muscular adaptations in response to slow-speed versus traditional resistance-training regimens. Eur J Appl Physiol 112:3585-95, 2012.
6. Staron, RS, Karapondo, DL, Kraemer, WJ, Fry, AC, Gordon, SE, Falkel, JE, Hagerman, FC, Hikida, RS. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. J Appl Physiol (1985) 76:1247-55, 1994.

7. Colliander, EB, Tesch, PA. Effects of eccentric and concentric muscle actions in resistance training. Acta Physiol Scand 140:31-9, 1990.
8. Jones, DA, Rutherford, OM. Human muscle strength training: the effects of three different regimens and the nature of the resultant changes. J Physiol 391:1-11, 1987.
9. Seger, JY, Arvidsson, B, Thorstensson, A. Specific effects of eccentric and concentric training on muscle strength and morphology in humans. Eur J Appl Physiol Occup Physiol 79:49-57, 1998.
10. Hortobagyi, T, Hill, JP, Houmard, JA, Fraser, DD, Lambert, NJ, Israel, RG. Adaptive responses to muscle lengthening and shortening in humans. J Appl Physiol (1985) 80:765-72, 1996.
11. Hather, BM, Tesch, PA, Buchanan, P, Dudley, GA. Influence of eccentric actions on skeletal muscle adaptations to resistance training. Acta Physiol Scand 143:177-85, 1991.
12. Katz, B. The relation between force and speed in muscular contraction. J Physiol 96:45-64, 1939.
13. Komi, PV, Buskirk, ER. Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscle. Ergonomics 15:417-34, 1972.
14. Komi, PV, Viitasalo, JT. Changes in motor unit activity and metabolism in human skeletal muscle during and after repeated eccentric and concentric contractions. Acta Physiol Scand 100:246-54, 1977.
15. Tesch, PA, Dudley, GA, Duvoisin, MR, Hather, BM, Harris, RT. Force and EMG signal patterns during repeated bouts of concentric or eccentric muscle actions. Acta Physiol Scand 138:263-71, 1990.
16. Enoka, RM. Eccentric contractions require unique activation strategies by the nervous system. J Appl Physiol (1985) 81:2339-46, 1996.
17. Crenshaw, AG, Karlsson, S, Styf, J, Backlund, T, Friden, J. Knee extension torque and intramuscular pressure of the vastus lateralis muscle during eccentric and concentric activities. Eur J Appl Physiol Occup Physiol 70:13-9, 1995.
18. Westing, SH, Cresswell, AG, Thorstensson, A. Muscle activation during maximal voluntary eccentric and concentric knee extension. Eur J Appl Physiol Occup Physiol 62:104-8, 1991.
19. Westing, SH, Seger, JY. Eccentric and concentric torque-velocity characteristics, torque output comparisons, and gravity effect torque corrections for the quadriceps and hamstring muscles in females. Int J Sports Med 10:175-80, 1989.
20. Hortobagyi, T, Devita, P, Money, J, Barrier, J. Effects of standard and eccentric overload strength training in young women. Med Sci Sports Exerc 33:1206-12, 2001.
21. Brandenburg, JP, Docherty, D. The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. J Strength Cond Res 16:25-32, 2002.
22. Doan, BK, Newton, RU, Marsit, JL, Triplett-McBride, NT, Koziris, LP, Fry, AC, Kraemer, WJ. Effects of increased eccentric loading on bench press 1RM. J Strength Cond Res 16:9-13, 2002.
23. Berg, HE, Tesch, A. A gravity-independent ergometer to be used for resistance training in space. Aviat Space Environ Med 65:752-6, 1994.
24. Berg, HE, Tesch, PA. Force and power characteristics of a resistive exercise device for use in space. Acta Astronaut 42:219-30, 1998.
25. Norrbrand, L, Fluckey, JD, Pozzo, M, Tesch, PA. Resistance training using eccentric overload induces early adaptations in skeletal muscle size. Eur J Appl Physiol 102:271-81, 2008.

26. Tesch, PA, Ekberg, A, Lindquist, DM, Trieschmann, JT. Muscle hypertrophy following 5-week resistance training using a non-gravity-dependent exercise system. Acta Physiol Scand 180:89-98, 2004.
27. Alkner, BA, Tesch, PA. Efficacy of a gravity-independent resistance exercise device as a countermeasure to muscle atrophy during 29-day bed rest. Acta Physiol Scand 181:345-57, 2004.
28. Naczk, M, Brzenczek-Owczarzak, W, Arlet, J, Naczk, A, Adach, Z. Training effectiveness of the inertial training and measurement system. J Hum Kinet 44:19-28, 2014.
29. Naczk, M, Naczk, A, Brzenczek-Owczarzak, W, Arlet, J, Adach, Z. Impact of Inertial Training on Strength and Power Performance in Young Active Men. J Strength Cond Res 30:2107-13, 2016.
30. Chiu, LZ, Salem, GJ. Comparison of joint kinetics during free weight and flywheel resistance exercise. J Strength Cond Res 20:555-62, 2006.
31. Norrbrand, L, Pozzo, M, Tesch, PA. Flywheel resistance training calls for greater eccentric muscle activation than weight training. Eur J Appl Physiol 110:997-1005, 2010.
32. Fernandez-Gonzalo, R, Irimia, JM, Cusso, R, Gustafsson, T, Linne, A, Tesch, PA. Flywheel resistance exercise to maintain muscle oxidative potential during unloading. Aviat Space Environ Med 85:694-9, 2014.
33. Seynnes, OR, de Boer, M, Narici, MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. J Appl Physiol (1985) 102:368-73, 2007.
34. de Hoyo, M, Pozzo, M, Sanudo, B, Carrasco, L, Gonzalo-Skok, O, Dominguez-Cobo, S, Moran-Camacho, E. Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. Int J Sports Physiol Perform 10:46-52, 2015.
35. Onambele, GL, Maganaris, CN, Mian, OS, Tam, E, Rejc, E, McEwan, IM, Narici, MV. Neuromuscular and balance responses to flywheel inertial versus weight training in older persons. J Biomech 41:3133-8, 2008.
36. Gual, G, Fort-Vanmeerhaeghe, A, Romero-Rodriguez, D, Tesch, PA. Effects of In-Season Inertial Resistance Training With Eccentric Overload in a Sports Population at Risk for Patellar Tendinopathy. J Strength Cond Res 30:1834-42, 2016.
37. Romero-Rodriguez, D, Gual, G, Tesch, PA. Efficacy of an inertial resistance training paradigm in the treatment of patellar tendinopathy in athletes: a case-series study. Phys Ther Sport 12:43-8, 2011.
38. Askling, C, Karlsson, J, Thorstensson, A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. Scand J Med Sci Sports 13:244-50, 2003.
39. de Hoyo, M, Sanudo, B, Carrasco, L, Dominguez-Cobo, S, Mateo-Cortes, J, Cadenas-Sanchez, MM, Nimphius, S. Effects of Traditional Versus Horizontal Inertial Flywheel Power Training on Common Sport-Related Tasks. J Hum Kinet 47:155-67, 2015.
40. Fernandez-Gonzalo, R, Lundberg, TR, Alvarez-Alvarez, L, de Paz, JA. Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. Eur J Appl Physiol 114:1075-84, 2014.
41. Garcia-Lopez, D, Cuevas, MJ, Almar, M, Lima, E, De Paz, JA, Gonzalez-Gallego, J. Effects of eccentric exercise on NF-kappaB activation in blood mononuclear cells. Med Sci Sports Exerc 39:653-64, 2007.

42. Carmona, G, Guerrero, M, Cusso, R, Padulles, JM, Moras, G, Lloret, M, Bedini, JL, Cadefau, JA. Muscle enzyme and fiber type-specific sarcomere protein increases in serum after inertial concentric-eccentric exercise. Scand J Med Sci Sports 25:e547-57, 2015.
43. Tous-Fajardo, J, Maldonado, RA, Quintana, JM, Pozzo, M, Tesch, PA. The flywheel leg-curl machine: offering eccentric overload for hamstring development. Int J Sports Physiol Perform 1:293-8, 2006.
44. Moras, G, Vazquez-Guerrero, J. Force production during squats performed with a rotational resistance device under stable versus unstable conditions. J Phys Ther Sci 27:3401-6, 2015.
45. Norrbrand, L, Tous-Fajardo, J, Vargas, R, Tesch, PA. Quadriceps muscle use in the flywheel and barbell squat. Aviat Space Environ Med 82:13-9, 2011.
46. Campbell, DT, Stanley, JC. 2015. Experimental and quasi-experimental designs for research. Ravenio Books, 2015.
47. Hedges, LV, Olkin I. Statistical methods for meta-analysis. Academic press, 2014.
48. Rhea, MR, Alvar, BA, Burkett, LN, Ball, SD. A meta-analysis to determine the dose response for strength development. Med Sci Sports Exerc 35:456-64, 2003.
49. Allen, DG. Eccentric muscle damage: mechanisms of early reduction of force. Acta Physiol Scand 171:311-9, 2001.
50. Gibala, MJ, MacDougall, JD, Tarnopolsky, MA, Stauber, WT, Elorriaga, A. Changes in human skeletal muscle ultrastructure and force production after acute resistance exercise. J Appl Physiol (1985) 78:702-8, 1995.
51. Milias, GA, Nomikos, T, Fragopoulou, E, Athanasopoulos, S, Antonopoulou, S. Effects of eccentric exercise-induced muscle injury on blood levels of platelet activating factor (PAF) and other inflammatory markers. Eur J Appl Physiol 95:504-13, 2005.
52. Paulsen, G, Mikkelsen, UR, Raastad, T, Peake, JM. Leucocytes, cytokines and satellite cells: what role do they play in muscle damage and regeneration following eccentric exercise? Exerc Immunol Rev 18:42-97, 2012.
53. Bamman, MM, Shipp, JR, Jiang, J, Gower, BA, Hunter, GR, Goodman, A, McLafferty, CL, Urban, RJ. Mechanical load increases muscle IGF-I and androgen receptor mRNA concentrations in humans. Am J Physiol Endocrinol Metab 280:E383-90, 2001.
54. Moore, DR, Phillips, SM, Babraj, JA, Smith, K, Rennie, MJ. Myofibrillar and collagen protein synthesis in human skeletal muscle in young men after maximal shortening and lengthening contractions. Am J Physiol Endocrinol Metab 288:E1153-9, 2005.
55. Roig, M, O'Brien, K, Kirk, G, Murray, R, McKinnon, P, Shadgan, B, Reid, WD. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. Br J Sports Med 43:556-68, 2009.
56. Tesch, PA, Thorsson, A, Colliander, EB. Effects of eccentric and concentric resistance training on skeletal muscle substrates, enzyme activities and capillary supply. Acta Physiol Scand 140:575-80, 1990.
57. English, KL, Loehr, JA, Lee, SM, Smith, SM. Early-phase musculoskeletal adaptations to different levels of eccentric resistance after 8 weeks of lower body training. Eur J Appl Physiol 114:2263-80, 2014.
58. Lundberg, TR, Fernandez-Gonzalo, R, Gustafsson, T, Tesch, PA. Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. J Appl Physiol (1985) 114:81-9, 2013.

59. Hakkinen, K, Komi, PV. Electromyographic changes during strength training and detraining. Med Sci Sports Exerc 15:455-60, 1983.
60. Milner-Brown, HS, Stein, RB, Lee, RG. Synchronization of human motor units: possible roles of exercise and supraspinal reflexes. Electroencephalogr Clin Neurophysiol 38:245-54, 1975.
61. Sale, DG. Neural adaptation to resistance training. Med Sci Sports Exerc 20:S135-45, 1988.
62. Kuroda, E, Klissouras, V, Milsum, JH. Electrical and metabolic activities and fatigue in human isometric contraction. J Appl Physiol 29:358-67, 1970.
63. Woods, JJ, Bigland-Ritchie, B. Linear and non-linear surface EMG/force relationships in human muscles. An anatomical/functional argument for the existence of both. Am J Phys Med 62:287-99, 1983.
64. Caruso, JF, Hernandez, DA, Porter, A, Schweikert, T, Saito, K, Cho, M, De Garmo, N, Nelson, NM. Integrated electromyography and performance outcomes to inertial resistance exercise. J Strength Cond Res 20:151-6, 2006.

Figure captions

Figure 1. Flow of study selection

Table 1. Summary of characteristics of all studies meeting the inclusion criteria. Muscle volume and force.

Authors	Year	Gr	n	G	Age	Bm	H	PhA	Exp	TE	EO	Wk	FWS	TS	Nset	Nrs	Nrd	RI	TW	%	ES	Test
Muscle volume																						
Fernandez-Gonzalo et al.	2014	E	16	M	23	75	178	PA	N	LP	Y	5	2,5	14	4	7	28	2	B	4.6	0.71	DXA
Fernandez-Gonzalo et al.	2014	E	16	F	24	59	164	PA	N	LP	Y	6	2,5	14	4	7	28	2	B	5.4	0.67	DXA
Naczk, et al.	2016	E	19	M	21.6	77.2	179.2	PA	N	KE	N	5	3	15	3	31	93	2	U	9.83	0.85	BIA
Naczk, et al.	2016	E	18	M	21.7	77.3	179.3	PA	N	KE	N	5	3	15	3	28	84	2	U	15.1	0.83	BIA
Norrbrand et al	2008	E	7	M	39.1	86.1	178	PA	N	KE	Y	5	2,5	12	4	7	28	2	U	6.2	0.38	MRI
Seynnes et al.	2007	E	7	B	20	74.6	179.3	PA	Y	KE	Y	5	3	15	4	7	28	2	B	6.8	1.5	MRI
Tesch et al.	2004	E	11	B	42	79	179	S	N	KE	Y	5	2,5	12	4	7	28	2	U	7	0.36	MRI
Tesch et al.	2004	C	10	B	40	80	176	S	N	-	-	-	-	-	-	-	-	-	-	-8	0.39	MRI
Force																						
De hoyo et al.	2015	E	11	M	22	77.4	176.6	T	Y	HS	N	6	3	18	6,5	8	52	-	U	10	1.02	FG
Naczk, et al.	2016	E	19	M	21.6	77.2	179.2	PA	N	KE	N	5	3	15	3	31	93	2	U	25	0.93	FG
Naczk, et al.	2016	E	18	M	21.7	77.3	179.3	PA	N	KE	N	5	3	15	3	28	84	2	U	23.3	0.77	FG
Naczk, et al.	2014	E	11	M	20.4	74.2	182.8	PA	N	KE	N	4	3	12	3	31	93	2	U	14.99	0.83	FG
Naczk, et al.	2014	E	11	M	20.9	73	178.5	PA	N	SA	N	4	3	12	3	28	84	2	U	11.8	0.55	FG
Naczk, et al.	2014	E	11	M	21.0	76.2	178.5	PA	N	SA	N	4	3	12	3	26	78	2	U	13.7	0.81	FG
Naczk, et al.	2014	C	13	M	22.3	73.8	177.2	PA	N	-	-	-	-	-	-	-	-	-	-	2.78	0.25	FG
Norrbrand et al.	2008	E	7	M	39.1	86.1	178	PA	N	KE	Y	5	2,5	12	4	7	28	2	U	11	0.2	FG
Norrbrand et al.	2010	E	9	M	38.8	85.4	183.9	PA	N	KE	Y	5	2,5	12	4	7	28	2	U	8.1	0.52	FG
Onambele et al.	2008	E	12	B	69.6	-	-	PA	N	KE	N	12	-	-	2	10,5	21	5	B	8	0.6	FG
Seynnes et. al.	2007	E	7	B	20	74.6	179.3	PA	Y	KE	Y	5	3	15	4	7	28	2	B	38.9	-	FG
Tesh et al.	2004	E	11	B	42	79	179	S	N	KE	Y	5	2,5	12	4	7	28	2	U	11.1	0.14	FG

Gr: Group (E: Experimental group; C: Control Group); G: Gender (M: male, F: female, B: both); Bm: Body mass (kg); H: Height (cm); PhA: Physical activity (S: Sedentary; PA: Physical Active; T:Trained); Exp: Previous experience with eccentric exercise (Y/N); TE: Type of exercise (LP: Leg Press; KE: Knee Extension);EO: Eccentic Overload(Y/N); Wk: weeks program duration; FWS: frequency of weekly sessions; TS: Total sessions; Nset: number of sets per day; Nrs: number of repetition per set; Nrd:number of repetition per day; RI:rest intervals (min); TW: type of work (U: Unilateral, B: Bilateral); Vmusc or force (%); ES: Effects size; Test: type of test used to identify performance gains (MRI: Magnetic Resonance Imaging; BIA: Bioelectrical Impedance; DXA: Dual energy X-ray absorptiometry; FG: Force Gauge).

Table 2. MUSCLE VOLUME. Analysis of variance results on the differences of ES between subject characteristics and various elements of eccentric training independent variables of program elements.

Independent Variables	% of change ± *SD*	*F*	Level	ES	*SD*	*n*	*r*	*p*
Subject Characteristics								
Age (y)						14	-0.771	0.042*
Body mass (kg)						14	-0.229	0.621
Height (cm)						14	0.155	0.740
Previous Experience		$F(1,7) = 13.891$	$p = 0.014$*					
Familiarized	6.80 ± 0.00			1.50	-	1		
Not familiarized	8.02 ± 3.90			0.63	0.21	6		
Physical Activity		$F(1,7) = 1.330$	$p = 0.301$					
Physical Active	7.98 ± 3.91			0.82	0.37	6		
Sedentary	7.00 ± 0.00			0.36	-	1		
Gender		$F(2,7) = 0.212$	$p = 0.817$					
Male	8.93 ± 4.65			0.69	0.21	4		
Female	5.40 ± 0.00			0.67	-	1		
Both	6.90 ± 0.14			0.93	0.80	2		
Program Exercises								
Type of Exercise		$F(1,7) = 0.073$	$p = 0.798$					
Leg Press	5.00 ± 0.56			0.69	0.02	2		
Knee extension	8.98 ± 3.69			0.78	0.46	5		
Eccentric Overload		$F(1,7) = 0.112$	$p = 0.751$					
No	12.46 ± 3.72			0.84	0.01	2		
Yes	6.00 ± 1.00			0.72	0.46	5		
Type of work		$F(1,7) = 1.638$	$p = 0.257$					
Unilateral	9.53 ± 4.02			0.60	0.27	4		
Bilateral	5.60 ± 1.11			0.96	0.46	3		

ES = Effect size; n = sample; Level = alpha level; r = Pearson Correlation coefficient; p = alpha level

* p< 0.05,** p< 0.01

Table 3. MUSCLE VOLUME. Pearson correlation coefficients (r) (95% Confidence Limits) between various program elements and training gains.

Training Program Variables	*n*	*r*	*p*
Frequency session/week	7	0.752 ± 0.16	0.052*
Program duration (wk)	7	-0.101 ± 0.01	0.830
Total of session	7	0.797 ± 0.15	0.032*
Number of sets per day	7	-0.148 ± 0.01	0.751
Number of rep. per day	7	0.149 ± 0.01	0.750
Rest	7	0.120 ± 0.01	0.798

n = sample; r = Pearson Correlation coefficient; p = alpha level

Table 4. FORCE (N). Analysis of variance results on the differences of ES between subject characteristics and various elements of eccentric training independent variables of program elements.

Independent Variables	% of change ± *SD*	*F*	Level	ES	*SD*	*n*	*r*	*p*
Subject Characteristics								
Age (y)						11	0.282	0.400
Body mass (kg)						10	-0.269	0.452
Height (cm)						10	-0.020	0.957
Previous Experience		$F(1,11) = 0.093$	$p = 0.768$					
Not Familiarized	14.11 ± 6.13			0.59	0.27	9		
Familiarized	24.45 ± 20.43			0.51	0.72	2		
Physical Activity		$F(2,11) = 2.039$	$p = 0.193$					
Trained	10.00 ± 0.00			1.02	-	1		
Physical Active	17.19 ± 10.13			0.57	0.30	9		
Sedentary	11.10 ± 0.00			0.14	-	1		
Gender		$F(1,11) = 5.937$	$p = 0.038$*					
Male	14.73 ± 6.19			0.70	0.26	8		
Both	19.33 ± 17.01			0.24	0.31	3		
Program Exercises								
Type of Exercise		$F(2,11) = 1.957$	$p = 0.203$					
Knee Extension	17.91 ± 11.60			0.45	0.34	7		
Shoulder Adduction	13.49 ± 1.60			0.73	0.15	3		
Front step	10.00 ± 0.00			1.02	-	1		
Eccentric Overload		$F(1,11) = 23.910$	$p = 0.001$**					
No	15.25 ± 6.51			0.78	0.16	7		
Yes	17.27 ± 14.48			0.21	0.21	4		
Type of work		$F(1,11) = 1.792$	$p = 0.214$					
Unilateral	14.33 ± 5.92			0.64	0.31	9		
Bilateral	23.45 ± 21.84			0.30	0.42	2		

ES = Effect size; n = sample; Level = alpha level; r = Pearson Correlation coefficient; p = alpha level

* p< 0.05,** p< 0.01

Table 5. FORCE (N). Pearson correlation coefficients (r) (95% Confidence Limits) between various program elements and training gains.

Training Program Variables	***n***	***r***	***p***
Frequency session/week	11	0.561 ± 0.14	0.091
Program duration (wk)	11	0.018 ± 0.02	0.959
Total of session	11	0.376 ± 0.12	0.284
Number of sets per day	11	0.017 ± 0.01	0.961
Number of rep. per set	11	0.604 ± 0.14	0.049*
Rest	11	0.071 ± 0.04	0.846

n = sample; r = Pearson Correlation coefficient; p = alpha level

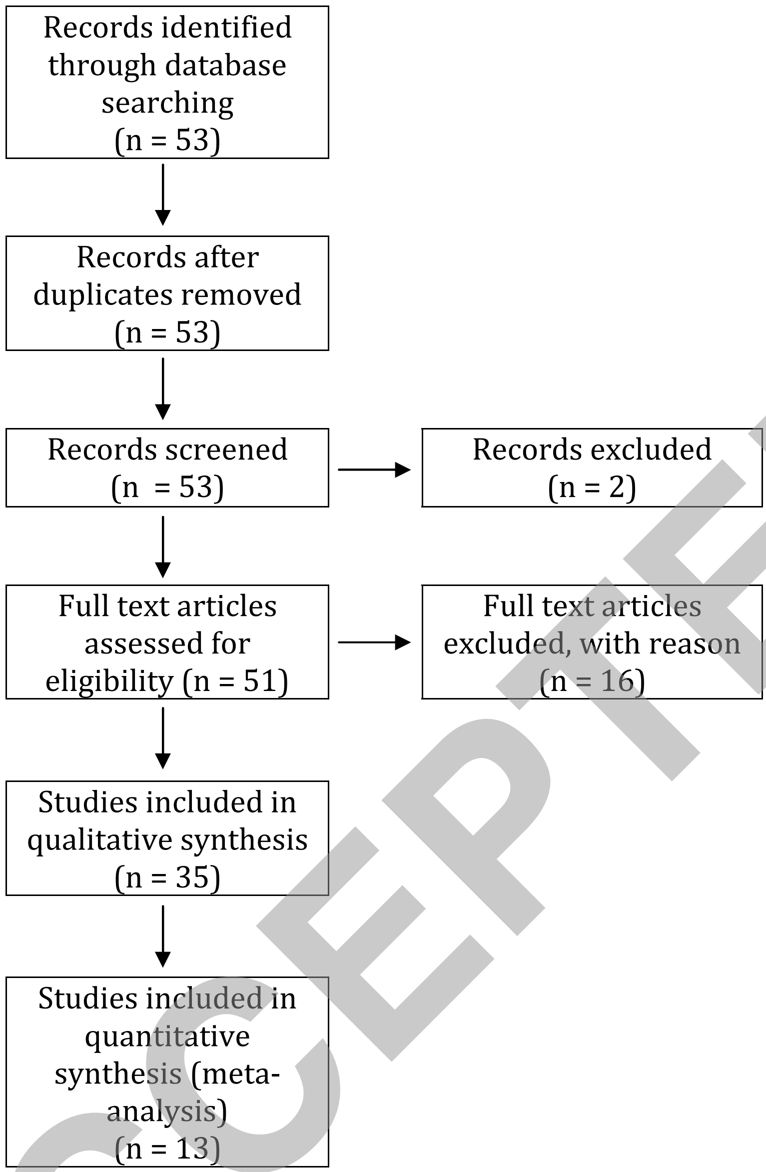

Figure 1. Flow of study selection