European Journal of Sport Science

ISSN: 1746-1391 (Print) 1536-7290 (Online) Journal homepage: https://www.tandfonline.com/loi/tejs20

Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor

Sergio Maroto-Izquierdo, Rodrigo Fernandez-Gonzalo, Hashish R. Magdi, Saul Manzano-Rodriguez, Javier González-Gallego & José A. de Paz

To cite this article: Sergio Maroto-Izquierdo, Rodrigo Fernandez-Gonzalo, Hashish R. Magdi, Saul Manzano-Rodriguez, Javier González-Gallego & José A. de Paz (2019): Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor, European Journal of Sport Science

To link to this article: https://doi.org/10.1080/17461391.2019.1588920

Published online: 06 Apr 2019.

European Journal of Sport Science, 2019
https://doi.org/10.1080/17461391.2019.1588920

ORIGINAL ARTICLE

Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor

SERGIO MAROTO-IZQUIERDO [1], RODRIGO FERNANDEZ-GONZALO [2], HASHISH R. MAGDI[1], SAUL MANZANO-RODRIGUEZ[1], JAVIER GONZÁLEZ-GALLEGO [1], & JOSÉ A. DE PAZ [1]

[1]*Institute of Biomedicine (IBIOMED), University of León, León, Spain &* [2]*Department of Laboratory Medicine, Karolinska Institutet, and Unit of Clinical Physiology, Karolinska University Hospital, Stockholm, Sweden*

Abstract
This study aimed to analyse whether increasing the eccentric overload (EO) during resistance training, in terms of range of motion and/or velocity using an electric-motor device, would induce different muscle adaptations than conventional flywheel-EO resistance training. Forty physically active university students (21.7 ± 3.4 years) were randomly placed into one of the three training groups (EX1, EX2, FW) and a control group without training ($n = 10$ per group). Participants in the training groups completed 12 sessions (4 sets of 7 repetitions) of iso-inertial single-leg squat training over 6 weeks for the dominant leg. Resistance was generated either by an electric-motor device at two different velocities for the eccentric phase; 100% (EX1) or 150% (EX2) of concentric speed, or by a conventional flywheel device (FW). Thigh lean tissue mass, unilateral leg press one-repetition maximum (1-RM), unilateral muscle power at different percentages of the 1-RM and bilateral/unilateral vertical jump were assessed before and after the 6-week training. There were significant ($p < 0.05$–0.001) main effects of time in the 3 training groups, indicating increased thigh lean tissue mass (2.5–5.8%), 1-RM load (22.4–30.2%), vertical jump performance (9.1–32.9%) and muscle power (8.8–21.7%), without differences across experimental groups. Participants in the control group did not improve any of the variables measured. In addition, EX2 showed greater gains in eccentric average peak power during training than EX1 and FW ($p < 0.001$). Despite the different EO offered, 6 weeks of resistance training using flywheel or electric-motor devices induced similar significant gains in muscle mass, strength, muscle power and vertical jump.

Keywords: *Eccentric overload, strength, muscle power, hypertrophy, range of motion*

Highlights

- 12 sessions (4 sets of 7 repetitions) of iso-inertial RT in physically active young men induces significant skeletal muscle mass and performance adaptations.
- Eccentric-overload application over the entire ROM or over the last part of the ROM led to similar training-induced effects.
- Electric-motor devices have potential benefits for accentuated eccentric training, functioning as an ideal inertial device without requiring a maximum CON action to generate eccentric-overload, and allowing the achievement of larger percentages of eccentric-overload by increasing the eccentric velocity with respect to the concentric.
- Higher eccentric-overload percentages seems to be related with greater increases in muscle size, while lower eccentric-overload percentages seems to be related with greater increases in muscle power.

Introduction

The potential benefits of isolated or overloaded eccentric (ECC) resistance exercise, compared with concentric (CON) or conventional CON-ECC exercise regimens, have been widely studied (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Roig et al., 2009). Among different technologies allowing for eccentric overload (EO), iso-inertial flywheel resistance exercise is one of the most utilized exercise paradigms with established efficacy in different scenarios such as injury prevention/rehabilitation (de Hoyo et al., 2015; Gual, Fort-Vanmeerhaeghe, Romero-Rodriguez, & Tesch, 2016; Monajati, Larumbe-Zabala, Goss-Sampson, &

Correspondence: Sergio Maroto-Izquierdo. Institute of Biomedicine (IBIOMED), University of León, Campus de Vegazana (s/n), 24007, León, Spain. E-mail: smaroi@unileon.es

Naclerio, 2018) and performance (de Hoyo, de la Torre et al., 2015; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017; Naczk et al., 2017; Sabido, Hernandez-Davo, Botella, Navarro, & Tous-Fajardo, 2017). Furthermore, iso-inertial flywheel resistance exercise has been suggested to improve muscle function, and functionality in elderly subjects (Brzenczek-Owczarzak et al., 2013) and stroke patients (Fernandez-Gonzalo et al., 2016). Originally designed to counteract the deleterious effect of microgravity on skeletal muscle (Tesch, Fernandez-Gonzalo, & Lundberg, 2017), the superiority of flywheel-EO resistance training (RT) over weight-stack RT (i.e. guided resistance exercise machines) to promote functional and structural adaptations in terms of strength, power, muscle size, running speed, and jump ability in healthy subjects and athletes has been demonstrated (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). It appears that the greater overall load and mechanical stress placed on the muscle, caused by the maximal nature of the CON action during the entire range of motion (ROM), as well as the EO in the last portion of the ECC action, are responsible for the stronger physiological responses and training-induced musculoskeletal adaptations of flywheel RT vs. traditional gravity-dependent protocols (Tesch et al., 2017).

The different protocols that can be employed using flywheel RT are characterized by the different moment of inertia of the flywheel, which in turn is a function of its geometrical and physical properties (Sabido, Hernandez-Davo, & Pereyra-Gerber, 2018). Thus, lower inertias with higher velocities, shorter ECC-CON coupling time and greater power production were suggested to favour explosive muscle characteristics adaptations, whereas higher inertias with lower velocities were shown to call for greater work load (Martinez-Aranda & Fernandez-Gonzalo, 2017; Sabido et al., 2018). Thus, after a maximum CON action, higher moments of inertia are able to generate greater force productions and impulse in the system than smaller flywheels (Carroll et al., 2018). The energy produced in the system during this CON action is stored and maintained during the subsequent ECC action due to its inertial characteristics, and must be braked in a short and concentrated moment at the end of the ECC phase to reinforce the negative action (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). By means of this approach, EO is generated in the system, and greater amounts of overload are achieved with higher inertial loads (Carroll et al., 2018). Notwithstanding, flywheel devices require a maximum CON action to generated EO only in the last third of the ECC action (Tesch et al., 2017). Moreover, the applicability of available flywheel hardware to functional training is limited due to flywheel exercise hardware traditionally developed following pre-existing uniaxial and bilateral weight-stack training machines (Maroto-Izquierdo, Garcia-Lopez, & de Paz 2017; Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017).

Recently, different multifunctional electric-motor devices have been commercialized (Tinwala, Cronin, Haemmerle, & Ross, 2017) aiming to offer solutions to some of the limitations of flywheel technology. These devices are potentially capable of generating EO in the entire ROM. Therefore, it is not necessary to reduce the active braking phase to obtain the overload, as it occurs with the traditional flywheel devices (Tinwala et al., 2017). In addition, other possibilities to modify the training stimulus while using electric-motor driven devices are changes in the specific CON and/or ECC intensity (no need for a maximum CON action), adjustments in the transition time between CON and ECC phases, and modifications in the ECC velocity, related to the CON velocity (Tinwala et al., 2017). Interestingly, active electric-motor devices completely neutralize the friction force and parasitic inertias, becoming *a priori* ideal inertial device from a mechanical perspective.

Given the current options to produce EO during iso-inertial RT and the belief that greater EO during iso-inertial exercise may promote larger adaptations, we designed a study to investigate the effects of iso-inertial training generated by an electric-motor device, which offers EO in the whole ROM, and compare such adaptations with conventional flywheel RT in a lower limb unilateral exercise. The aim of this study was to analyse whether increasing the EO in terms of ROM and/or velocity would induce different muscle adaptations than conventional flywheel EO training.

Methods

Participants

Forty sports science undergraduate students volunteered for the study (21.7 ± 3.4 years; 75.8 ± 9.8 kg; 177.1 ± 5.4 cm). Participants were moderately active and healthy individuals, engaging in 6–8 h of recreational physical activity per week. They had no history of regular lower limb strength training and no previous muscle, joint or bone injury for the last 6 months. They were informed of the purposes and risks involved in the study before giving their informed written consent to participate. The Ethics Committee of the University of León approved the

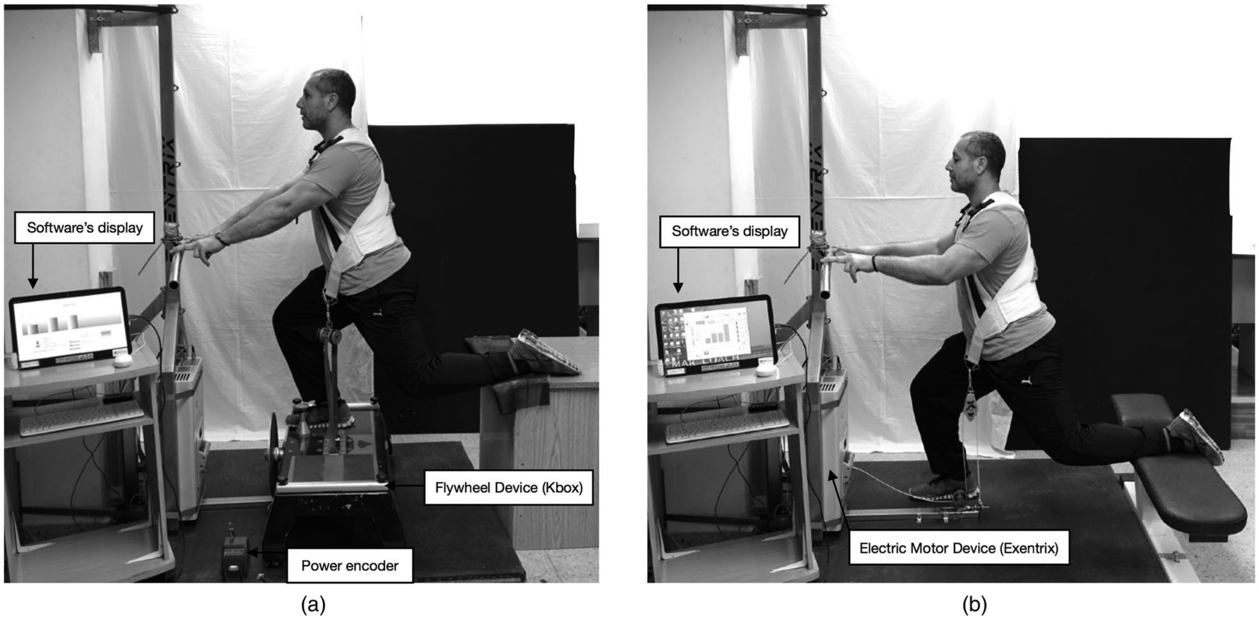

Figure 1. A. Single-leg squat exercise on the flywheel device. B: Single-leg squat exercise on the electric-motor device.

study protocols (ETICA-ULE-009-2018). All participants completed all the protocols, including two familiarization sessions, the prescribed training programme, and the pre- and post-tests.

Training program

Participants were randomly divided into 3 experimental training groups and 1 control group, which did not train. All participants included in an experimental group ($n = 30$) completed 6-weeks (12 sessions) of an iso-inertial single-leg squat training programme, using an electric-motor device (EX1 and EX2 groups) or a flywheel device (FW group) (Figure 1). Volunteers trained 2 times per week with at least 48 h of rest between sessions (Fernandez-Gonzalo, Lundberg, Alvarez-Alvarez, & de Paz, 2014). Following a standardized cycling warm-up, participants performed 4 sets of 7 maximal unilateral (dominant leg) coupled CON and ECC muscle actions in a single-leg squat position. Subjects were required to push with maximal effort through the entire CON action, which ranged from 70° of knee flexion to nearly full extension (0° = full knee extension). At the end of the CON action, the flywheel/motor strap rewound back, initiating the reversed ECC action. Before each session, the ROM was set up from 0° to 90° using a goniometer. So that in case of not stopping within the permitted range the device stopped the movement and notified it in the software. In the case of the flywheel device, subjects were instructed to resist gently during the first and second thirds of the ROM, and thereafter to apply maximal breaking force to stop the movement at about 70° of knee flexion. By means of this approach, EO is produced (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Tesch et al., 2017). An individual researcher was responsible for calibrating the ROM of each participant (i.e. length of cable used and distance from the vertical pulley to the platform) from 0° (i.e. full knee extension) to 90° employing a goniometer. In addition, the same researcher, indicated the knee angle in which they had to brake before each series and gave verbal information during the execution of each repetition. Besides, the electric-motor device is characterized by producing EO throughout the entire ROM, so it is not necessary to wait for the last third of movement to obtain EO (Tinwala et al., 2017). Therefore, the only instruction given to EX1 and EX2 participants was to stop the movement before reaching the end of the ROM. Participants were not allowed to use the other leg to produce force, positioning the non-training leg from the tibia to the foot's instep above a soft surface, at a fixed point, to avoid compensation (Figure 1). Power was measured during each repetition (CON and ECC actions; SmartCoach™, Stockholm, Sweden), and real-time feedback was provided on a computer monitor. A strong verbal encouragement was given during all repetitions performed. All subjects were familiarized (2 sessions) with the exercise prior to the first training session. Subjects in the control group did not perform any strength-training programme during the study period, as instructed.

FW participants ($n = 10$) performed the exercise using a squat flywheel device (Kinetic Box (Kbox), Exxentric AB TM, Bromma, Sweden) (Sabido et al., 2018), equipped with one 4.2-kg flywheel with a moment of inertia of 0.05 kg·m^{-2}. EX1 ($n = 10$) and EX2 ($n = 10$) participants performed the same exercise, but in an electric-motor device (Exentrix, SmartCoach™, Stockholm, Sweden). This device was configured in flywheel mode using the iso-inertial settings in the device's software (Exentrix PC Interface – V2.4, SmartCoach™) and configured with a load of 37 inertial units for both EX groups. According to the manufacturer's instructions, one inertial unit is equivalent to a moment of inertia of 0.00134 kg·m^{-2}, so the resulting moment of inertia was equivalent to the flywheel device (0.05 kg·m^{-2}). In addition, the transition time between CON and ECC phase was the minimum permitted by the system. No different training loads were selected for the CON and ECC phases. However, the software for group EX2 was configured to perform the rewind of the cable (ECC action) at a 150% faster than the CON speed. Thus, the ECC speed was 1.5 times faster than groups EX1 and FW.

Testing procedures

Dual energy X-ray absorptiometry analysis (DEXA). DEXA was performed ~1 week before and after the training programme, at the same time of day using a Lunar Prodigy® whole-body scan (GE Medical Systems, Madison, WI). A manual analysis was performed to estimate thigh lean mass (Encore® 2009 software, Lunar Corp., Madison, WI). Briefly, one rectangle mark was generated using the lower margin of the ischial tuberosities and the lower margin of the femoral condyles as thigh reference points. Lean mass was then calculated for the entire thigh. Subsequently, inside the span of the thigh rectangle a 6-cm perpendicular line was drawn from the distal to the proximal mark to establish three regions of interest (ROIs) of the thigh where lean muscle mass was estimated. Then, a 20 mm-thick slice was placed above the 6-cm distal vertical line (i.e. distal thigh ROI) (Fernandez-Gonzalo et al., 2014). In addition, two other 20-mm slices were placed 6 (i.e. medial thigh ROI) and 12 cm (i.e. proximal thigh ROI) above the first slice. Finally, lean tissue mass estimation in both total thigh and the three slices created was calculated using Encore software.

Unilateral maximal dynamic strength (1-RM). Twenty-four hours after the DEXA and jump tests, the unilateral 1-RM test was conducted on a 45°-inclined leg press device (Gerva-Sport, Madrid, Spain). Participants performed one repetition from 90° to full extension (180°) with a load corresponding to approximately 3-RM. The load was increased with 10 kg if the subject succeeded or decreased 5 kg if failed. Testing ended when subjects failed to overcome a given load in two successive trials. Unilateral 1-RM was achieved between 3 and 6 attempts, and trials were interspersed by 2-min recovery. Participants were asked to place the resting leg with the knee flexed and the foot propped on the ground. The 1-RM test was performed twice for each leg; 3–5 days before and 3–5 days after the training period.

Unilateral muscle power. Forty-eight hours after the 1-RM test muscle power test was performed, participants completed five sets of three unilateral repetitions from 90°-knee flexion to full extension (180°) in the leg-press described above, with 2-min recovery between sets. To avoid any use of the stretch-shortening cycle, each repetition started from a complete static position. Each set represented 40, 50, 60, 70, and 80% of 1-RM load, and the order of the sets was individually randomized before testing and replicated at post-tests. Subjects were asked to perform the CON phase of each repetition as fast as possible. Mean power for each repetition was sampled at 1000 Hz using an encoder (T-FORCE Dynamic Measurement System, Ergotech Consulting S.L., Murcia, Spain) and the associated software (T-Force v. 2.28). The best repetition performed at each load was used for data analysis. The warm-up protocol described for the 1-RM test was also performed prior to the muscle power test.

Vertical jump performance. Vertical jump tests were carried out immediately after the DEXA analysis. Jump height was measured for countermovement jump (CMJ), squat jump (SJ) and drop jump (DJ) performed bilaterally and unilaterally in this order on a contact platform (Globus Ergotester®, Globus, Codogne, Italy) (Murtagh et al., 2017). A warm-up of 5-min cycling, 25 reps of high knee and 25 reps of butt kicks was performed. The SJ was performed from a 90°knee flexion with hands on the hips. For the CMJ, participants started in a standing straight position and were instructed to jump as high as possible with hands on the hips. The DJ consisted of dropping oneself from a box of 45 cm and then jump as high as possible straight after landing. Participants were asked to step off the platform and jumping after the first ground contact from a self-selected knee angle, maintaining the hands at the hips during the full test. Protocols were identical for bilateral and unilateral test. The three bilateral attempts were always completed first, followed by unilateral attempts. Jump height (and contact time for DJ) was recorded to the nearest 0.1 cm (0.05 s for contact time). Three trials, with 30-seconds of recovery in between, were allowed and the best result was included in the data analysis.

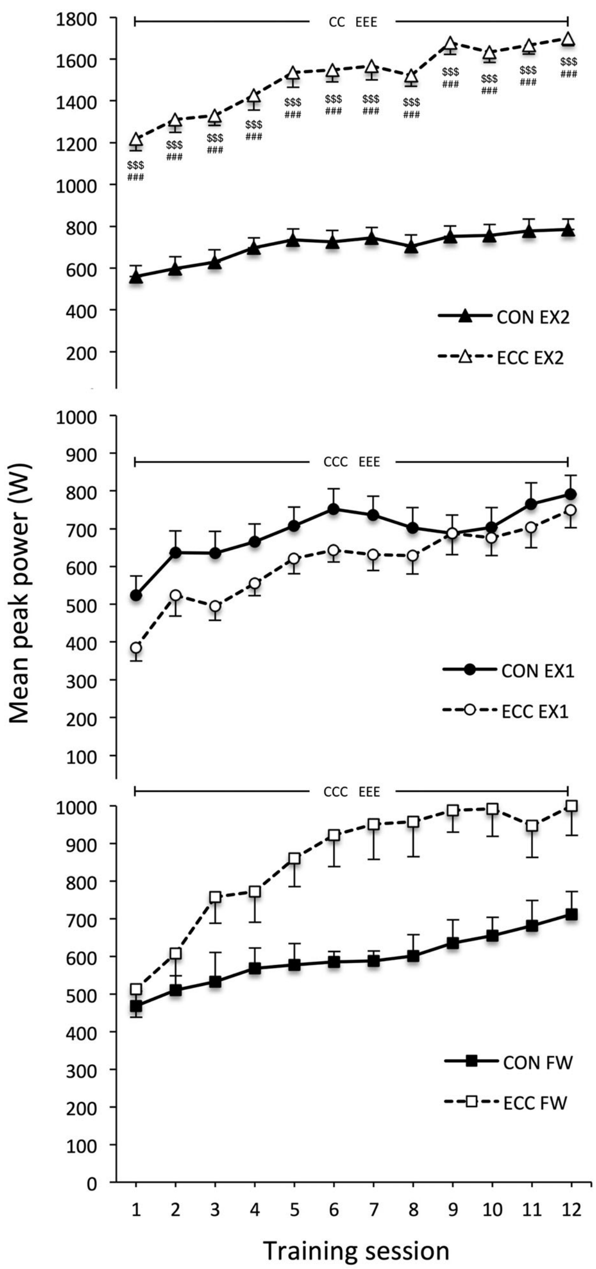

Figure 2. Mean concentric (CON) and eccentric (ECC) peak power (w) during each training session in all experimental groups (EX1, EX2 and FW). Significant effects of time (session 1 vs. session 12) (^{C} $p < 0.05$; ^{CC} $p < 0.01$; ^{CCC} $p < 0.001$ for CON; ^{E} $p < 0.05$; ^{EE} $p < 0.01$; ^{EEE} $p < 0.001$ for ECC). $^{\$}$ Significantly different form EX1 group, where $^{\$}$ $p < 0.05$, $^{\$\$}$ $p < 0.01$, and $^{\$\$\$}$ $p < 0.001$. $^{\#}$ Significantly different from FW group, where $^{\#}$ $p < 0.05$, $^{\#\#}$ $p < 0.01$, and $^{\#\#\#}$ $p < 0.001$.

Statistical analyses

Statistical analyses were performed using SPSS v.20.0 (SPSS Inc. Chicago, IL). Results were expressed as mean ± SD. Data distribution was examined for normality using the Shapiro–Wilk test. A Mixed-model analysis of variance (group x time), followed by Bonferroni post hoc tests was used to investigate differences in variables measured. The effect size (ES) was calculated for interactions between groups using Cohen's guidelines. Threshold values for ES were >0.2 (small), >0.6 (large) and >2.0 (very large) (Hopkins, Marshall, Batterham, & Hanin, 2009). The significance level was set to $p < 0.05$.

Results

A significant group x time interaction was found in the ECC average peak power of each training session, where the EX2 group showed significant differences ($p < 0.001$; ES range 3.5–6.8, Figure 2) with respect to EX1 and FW groups. No further significant interactions were observed for the other variables analysed. In addition, there was a significant main effect of time for all functional and structural variables ($p < 0.05$–.001, F range 6.0–77.2). However, the control group did not improve any of the variables measured.

There was a main effect of time ($p < 0.001$) in the distal ($F = 47.3$), medial ($F = 26.1$) and proximal ($F = 24.8$) ROIs measured and in the total thigh lean mass ($F = 48.9$). EX2 ($p < 0.001$, ES range 0.24–0.40) and FW groups ($p < 0.001$, ES range 0.41–0.56) showed significant improvements in all measurements (Table I). The EX1 group showed significant gains at distal and medial portions ($p < 0.05$, ES = 0.35 and 0.21) and in total thigh mass ($p < 0.01$, ES = 0.23). Results from control group remained similar between pre- and post-measurement.

There was a significant main effect of time in the 1-RM load ($p < 0.001$, $F = 77.2$). Thus, between pre- and post-tests the 1-RM load increased 30.2% in EX1 ($p < 0.001$; ES = 1.49), 27.6% in EX2 ($p < 0.001$; ES = 1.39) and 22.4% in FW ($p < 0.001$; ES = 1.20) (Table I).

Across sessions (Figure 2), CON average peak power increased 51% in EX1 [523.6 (±154) to 792.0 (±149) W; $p < 0.001$, ES = 1.77], 40% in EX2 [559.9 (±87) to 785.2 (±98) W; $p < 0.01$, ES = 2.43] and 52% in FW [468.0 (±118) to 712.0

Table I. Distal, medial, proximal and total thigh muscle mass; unilateral maximal dynamic strength (1-RM); and vertical jump height and DJ contact time pre- and post-training

	EX1 group					EX2 group					FW group					CONTROL group				
	PRE	POST	Δ%	ES	*P*	PRE	POST	Δ%	ES	*P*	PRE	POST	Δ%	ES	*P*	PRE	POST	Δ%	ES	*P*
Muscle thigh																				
Distal (g)	189.0 ± 15.0	194.6 ± 17.4	2.9	0.35	*	194.9 ± 31.7	205.3 ± 34.8	5.4	0.31	***	186.7 ± 20	197.4 ± 18.2	5.7	0.56	***	200.3 ± 33.5	202.8 ± 36.2	1.3	0.07	
Medial (g)	309.3 ± 37.7	317.1 ± 36.1	2.5	0.21	*	324.2 ± 50.2	336.7 ± 55.8	3.9	0.24	***	305.3 ± 30.5	317.4 ± 25.6	4.0	0.43	***	328.3 ± 48.4	332.0 ± 50.0	1.1	0.07	
Proximal (g)	418.6 ± 38.5	425.8 ± 41.7	1.7	0.18		431.0 ± 51.7	452.2 ± 54.0	4.9	0.41	***	426.8 ± 37.8	441.1 ± 32.5	3.4	0.41	***	443.6 ± 59.4	444.8 ± 58.2	0.3	0.02	
Total (g)	6793.9 ± 758.3	6967.9 ± 776.2	3.4	0.30	**	6912.2 ± 974.9	7222 ± 1073.8	4.5	0.30	***	6549.2 ± 708.8	6881 ± 791.2	5.1	0.44	***	6783.0 ± 1102.9	6684.3 ± 995.1	−1.5	0.09	
Strength																				
1-RM load (kg)	187.8 ± 36.7	244.4 ± 39.1	30.2	1.49	***	177.2 ± 41.8	226.1 ± 26.9	27.6	1.39	***	210.0 ± 34.7	256.1 ± 41.6	21.9	1.20	***	225.0 ± 40.3	225.7 ± 46.9	0.3	0.02	
UL Vertical Jump																				
CMJ (cm)	21.6 ± 3.3	23.7 ± 3.2	9.8	0.65	*	21.8 ± 3.5	23.8 ± 3.3	9.1	0.59	*	21.1 ± 4.2	23.8 ± 3.1	12.8	0.73	**	23.8 ± 7.4	21.4 ± 5.3	−9.9	0.37	*
SJ (cm)	20.5 ± 3.6	22.8 ± 3.2	11.2	0.67	*	21.3 ± 3.8	22.7 ± 3.2	6.6	0.40		19.7 ± 3.8	23.1 ± 2.7	17.3	1.03	***	22.8 ± 7.9	20.8 ± 4.3	−8.8	0.31	
DJ (cm)	18.3 ± 4.4	21.6 ± 2.9	18.0	0.89	***	18.4 ± 4.4	21.4 ± 2.9	15.9	0.81	***	18.3 ± 2.6	21.5 ± 2.2	17.5	1.33	***	19.9 ± 4.1	18.9 ± 3.8	−5.0	0.25	
DJ CT (ms)	0.577 ± 0.16	0.386 ± 0.08	33.1	1.51	***	0.499 ± 0.12	0.364 ± 0.05	27.1	1.47	***	0.525 ± 0.10	0.463 ± 0.07	11.8	0.72		0.528 ± 0.07	0.524 ± 0.13	−0.8	0.04	
BL Vertical Jump																				
CMJ (cm)	38.5 ± 4.3	40.6 ± 4.1	5.5	0.50	***	39.1 ± 6.4	42.2 ± 6.9	8.0	0.47	***	38.7 ± 6.9	41.3 ± 6.4	6.9	0.39	***	40.2 ± 4.6	39.6 ± 4.3	−1.6	0.13	
SJ (cm)	36.2 ± 3.9	38.6 ± 3.9	6.6	0.62	***	37.1 ± 5.2	39.7 ± 5.8	7.0	0.47	***	37.2 ± 5.6	39.1 ± 4.8	4.8	0.36	**	38.3 ± 4.7	38.6 ± 5.3	0.6	0.08	
DJ (cm)	35.7 ± 4.7	38.6 ± 5.2	8.4	0.59	*	36.7 ± 8.4	40.9 ± 8.4	11.3	0,5	***	35.6 ± 8.8	39.1 ± 5.8	9.5	0.47	**	38.2 ± 6.0	37.1 ± 5.4	−2.8	0.19	
DJ CT (ms)	0.502 ± 0.15	0.417 ± 0.08	16.9	0.71		0.451 ± 0.12	0.389 ± 0.08	13.9	0.61		0.458 ± 0.11	0.428 ± 0.10	6.7	0.29		0.488 ± 0.09	0.518 ± 0.09	6.0	0.33	

Abbreviation: 1-RM: One-Repetition Maximum; BL: Bilateral; CMJ: Countermovement Jump; DJ: Drop Jump; DJ CT: Drop Jump Contact Time; UL: Unilateral; *Significantly different from pre-training value, where $^{*}p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$.

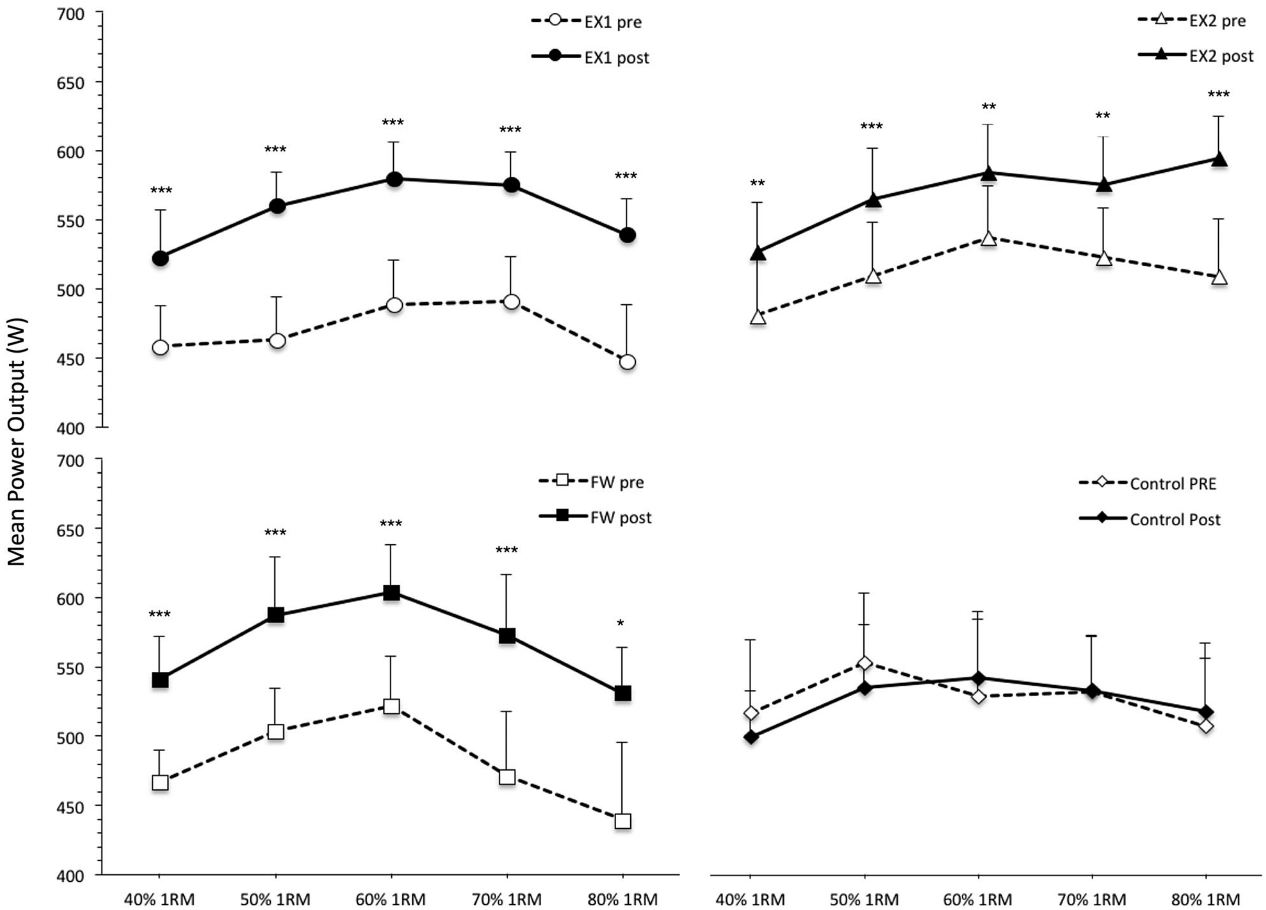

Figure 3. Mean leg press power (w) at different percentages of 1-RM before (pre) and after (post) training. * Significantly different from pre-training value, where * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

(±180) W; $p < 0.001$, ES = 1.60]. The corresponding increases in ECC average peak power were 95% in EX1 [384.8 (±105) to 750.0 (±142) W; $p < 0.001$, ES = 2.92], 39% in EX2 [1217.0 (±168.7) to 1701.1 (±108.3) W; $p < 0.001$, ES = 3.41] and 95% in FW [512.8 (±223) to 997.8 (±254) w; $p < 0.001$, ES = 2.03]. The mean EO produced in terms of power (% above CON average peak power) was −13.3% in EX1, 114.1% in EX2 and 43.6% in FW. Mean EO produced in terms of force (% above CON force) was 17.2% for EX1 and 50.7% for EX2. No force measurements were recorded in the FW group during training.

Regarding mean power output, there was a significant main effect of time for all the loads tested ($p < 0.001$, F range 21.4–57.4) (Figure 3). Thus, EX1 experimented a significant ($p < 0.001$) increase in all loads ranging from 14.2–21.1% (ES range 0.68–1.17). Similarly, the FW group showed gains in all loads measured, with an improvement of 15.8–21.7% in the loads 40–70% ($p < 0.001$; ES range 0.75–0.91), and 15.3% at the 80% 1-RM ($p < 0.05$; ES = 0.62). Likewise, EX2 increased power output in all 1-RM percentages (9–10.8%, $p < 0.01$, ES range 0.41–0.51), with the highest increase at 50% 1-RM (10.8%, $p < 0.001$, ES = 0.49) and at 80% 1-RM (16.8%, $p < 0.001$, ES = 0.79). Before training, maximal mean power was reached at the load corresponding to 60% of 1-RM by all training groups. Meanwhile, EX2 reached maximal mean power output at 80% of 1-RM after the training period.

A significant time effect ($p < 0.05$–.000, F range 6.0–51.5) was observed in CMJ, SJ, and DJ height in unilateral and bilateral tests (Table I). Regarding bilateral vertical jump height, the three training groups achieved significant improvements ($p < 0.05$–.001; ES range 0.36–0.67). Regarding unilateral vertical jump height, FW ($p < 0.01$–.001, ES range 0.73–1.33) and EX1 groups ($p < 0.05$–.001; ES range 0.65–0.89) achieved significant improvements in all tests, while the EX2 group improved significantly the CMJ ($p < 0.05$, ES = 0.59) and the DJ ($p < 0.001$, ES = 0.81). In addition, EX1 and EX2 groups were the only ones that reduced the unilateral DJ contact time ($p < 0.001$, ES = 1.51 and 1.47, respectively).

Discussion

The aim of this study was to determine whether increasing the EO during iso-inertial resistance exercise training, in terms of ROM and/or velocity, would induce different muscle adaptations than conventional flywheel EO training. After 6-week training (12 sessions), the three experimental groups (EX1, EX2 and FW) showed comparable increases in maximum unilateral dynamic strength, unilateral muscle power at different loads, muscle hypertrophy, and both bilateral and unilateral vertical jump height. Therefore, it seems that the magnitude of EO offered by either flywheel or motor-driven iso-inertial RT does not have a major impact on the resistance exercise-induced muscle adaptations.

Based on our results, iso-inertial RT with EO performed in an electric-motor device is an effective resistance exercise method to induce functional and structural muscle adaptations in physically active men, without the need to perform a maximum braking action in the last third of the ROM. In addition, larger EO percentages may be achieved by increasing the speed of cable recoil in an electric-motor driven device (e.g. EX2 group). These results support previous data describing the effects produced by iso-inertial devices on skeletal muscle. Thus, five- to 15-week flywheel EO-RT programmes of the lower limbs (bilaterally), have shown strong skeletal muscle adaptations (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017), including gains in muscle mass (Norrbrand, Fluckey, Pozzo, & Tesch, 2008; Seynnes, de Boer, & Narici, 2007), maximal voluntary contraction (Norrbrand et al., 2008; Seynnes et al., 2007; Tesch et al., 2017), 1-RM load (Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), ECC force (Hortobagyi, Devita, Money, & Barrier, 2001), muscle power (Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), jump ability (de Hoyo, Pozzo et al., 2015; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), running speed (de Hoyo, Pozzo et al., 2015; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), and electromyography activity (Norrbrand, Tous-Fajardo, Vargas, & Tesch, 2011; Pozzo, Alkner, Norrbrand, Farina, & Tesch, 2006). Indeed, chronic exercise training employing non-gravitational iso-inertial technology produces early and vigorous neuromuscular adaptations, which appear to be more effective than those noted after traditional weight-training (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Tesch et al., 2017). The current study goes one step further, indicating that applying the EO over the entire ROM, by means of an electric-motor device, does not enhance the training-induced effects generated by a conventional inertial flywheel in which the EO is produced only in the last third of the ROM.

Moreover, this is the first study to analyse the EO generated by two different iso-inertial devices. Fernandez-Gonzalo et al. (Fernandez-Gonzalo et al., 2014) and Sabido et al. (Sabido et al., 2018) pinpointed that bilateral lower limb RT in an inertial device is capable of generating between 15 and 30% of EO (% above CON average peak power). According to others (Martinez-Aranda & Fernandez-Gonzalo, 2017), iso-inertial technology devices, are capable of generating EO between 20 and 25% (% above CON peak force) in unilateral mono-articular exercises of the lower limb using an inertia of 0.05 kg·m^2 (i.e. knee extension). Our results show a slightly higher average EO in terms of average peak power (46%, with a range between 10 and 62% throughout the different training sessions in the FW group). This may be due to the differences in exercise type (Nunez et al., 2018), since the applied force is quite higher in the training leg in an unilateral multi-joint squat exercise than in one of the training legs in a bilateral training regime due to the bilateral deficit (Weir, Housh, Housh, & Weir, 1995). Regarding the EO generated in the groups that were trained with the electric-motor device, thus producing the force in the ECC during the whole ROM (EX1 and EX2), and taking as reference the FW group, the EO was higher in the EX2 group (114%, with a range between 105 and 123% in terms of average peak power; and 50.7%, with a range between 42.2 and 60.4% in terms of peak force throughout the different training sessions). However, the EX1 group only showed EO in relation to CON peak force (17.2%, with a range between 14.9 and 21.1% throughout the different training sessions). This could be due to the fact that EO was achieved through the entire ROM, and not only in the last third, as FW group, taking more time to slow down the movement, so ECC power production was lower. Consequently, although the EX1 group did not show EO in terms of average peak power, the overload in terms of peak force is similar to that demonstrated in flywheel devices by other authors (Martinez-Aranda & Fernandez-Gonzalo, 2017). Therefore, our data seem to indicate that increasing the ECC speed is a good alternative to generate higher values of EO in terms of both average peak power and peak force throughout the entire ROM.

New training trends demand unilateral daily-life and sports specific exercises (Thompson, 2017), in which several planes, muscle groups, and joints are involved at the same time, with a greater demand for stability and performing gestures similar to those that appear in sports practice (e.g. braking, changes of direction, throwing or striking) (Gonzalo-Skok et al., 2017). This is something that traditional flywheel hardware designed for single-plane exercise movements (e.g. knee extension exercise) does not allow. Yet, multifunctional flywheel devices do offer more possibilities in this area (e.g. Squat Flywheel device). Therefore, the exercise selected for this study was the single-leg squat, in order to combine the benefits of unilateral and specific training with those achieved by eccentric-overload flywheel training. In addition, the electric-motor device is multifunctional, allowing exercises practically in any plane of movement. However, since the motor-driven hardware did not allow to perform exercises requiring higher power than 1300 W, an unilateral exercise was selected to perform the training programme with the maximum levels of strength and speed, yet within the device's range of power. Moreover, it has been recently shown that flywheel unilateral resistance training generates similar or greater adaptations than bilateral training regarding muscle mass, power, and sport-specific skills, such as running with a change of direction or vertical jump (Nunez et al., 2018). Gonzalo-Skok and coworkers (Gonzalo-Skok et al., 2017) suggested the incorporation of 1-limb exercises to any training routine, since most sports movements are performed unilaterally.

Regarding maximal dynamic strength, the three experimental groups showed important increases from pre- to post-tests. Previous studies have shown improvements between 12 and 25% in the same muscle groups trained with inertial devices (Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017). Therefore, the current FW group (+22.4%) data is supported by previous results. Even without significant differences between groups, it seemed EX1 and EX2 groups showed slightly higher gains in 1-RM load (30.2% and 27.6%, respectively), than those shown by FW group as well as by other studies using inertial technology (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Tesch et al., 2017). This could be due to the fact that participants in EX1 and EX2 applied the braking force through the whole ROM of the ECC phase, although such hypothesis needs to be further validated.

EO-RT induces substantial gains in muscle power (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). Fernandez-Gonzalo et al. (2014) and Maroto-Izquierdo et al. (Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017) analysed the effects of flywheel RT on different percentages of the 1-RM (40–90% 1-RM load), showing increases in the range of 5–30%, which are similar to the results observed in the FW group of the current study. After 6 weeks of RT with an electric-motor device in iso-inertial mode, similar adaptations were observed in muscle power at different percentages of the 1-RM (40–80%) when the ECC velocity was not enhanced (EX1: 14.2–21%). However, these adaptations appeared to be slightly lower in the EX2 group (8.8–10.8%). Although, the higher EO produced by EX2 participants seemed to have a particular effect on the power produced at high loads, i.e. 80% of 1-RM (16.8%). Hence, it seems that muscle power adaptations do not only depend on the moment of inertia used (Martinez-Aranda & Fernandez-Gonzalo, 2017; Sabido et al., 2018) or the training velocity developed (Carroll et al., 2018), but also on the EO induced.

The training-induced power adaptations are also evident in the increments obtained in muscle power between sessions 1 and 12. Thus, iso-inertial training in a vertical plane appears to be an effective tool to increase power. Therefore, such training is recommended to increase vertical jump performance (Gonzalo-Skok et al., 2017), as shown by the current data where all experimental groups improved vertical jump performance. In the case of the DJ, where the stretch-shortening cycle becomes a critical factor, EX1 and EX2 groups significantly reduced the contact time. This could potentially be explained by the similarity of the gesture between training and the jump test, and the emphasis on a short transition between ECC-CON actions in EX1 and EX2.

The efficacy of EO-RT to induce muscle hypertrophy has been well documented (Norrbrand et al., 2008; Tesch et al., 2017). Throughout the scientific literature, flywheel devices have shown a great efficacy to induce gains in muscle volume/mass in young men and women (Fernandez-Gonzalo et al., 2014) and in well-trained athletes (Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017). Such changes seem to be greater than those induced by other RT modalities (i.e. weight training) (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). The greater muscle mass plays an undisputed role in all adaptations related to muscle strength, power, and vertical jump (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). The results showed by the FW group are in the same line as data from previous studies in which hypertrophy was measured by DEXA (Fernandez-Gonzalo et al., 2014). These results were also observed in the EX2 group. Although it has been demonstrated that muscle adaptations are greater when the ROM employed during training is larger (McMahon, Morse, Burden, Winwood, & Onambele, 2014), and the working angle is an important factor to consider when iso-inertial RT is carried out (Maroto-Izquierdo, Garcia-Lopez, Fernandez-

Gonzalo et al., 2017), no significant differences were observed between groups in the present work. The EX1 group showed a smaller effect size on muscle mass increases, which could be related to the magnitude of the EO. However, although results obtained through DEXA analysis are correlated with Magnetic Resonance Imaging and represents a valid approach to estimate muscle mass (Fernandez-Gonzalo et al., 2014), we did not include any other architectural parameter among our variables. Furthermore, although time-under-tension and training-induced adaptations are similar between groups, the measurement of muscle activation during exercise could provide deeper insights into the comparison between different iso-iniertial devices. However, muscle activation during exercise (e.g. electromyography) has not been measured in this work. Therefore, one of the limitations of this study is the lack of inclusion of other physiological parameters to provide more information on the functional and structural adaptations found. Future research should include these neurophysiological parameters to deepen on the effects of iso-inertial training with different devices and the underpinning physiological mechanisms.

Conclusions

In summary, 6 weeks of RT with EO in physically active young men induced significant gains in strength, muscle power at different loads, vertical jump and lean tissue mass. The adaptations generated by an active electric-motor device, which produces EO throughout the entire ROM, were similar to those produced by a traditional flywheel device, where the EO occurs during the last part of the ROM. However, an electric-motor device allowed for modifications in the CON and ECC loads independently, as well as changes in the ECC speed with respect to the CON speed, which translated into higher EO. Therefore, the electric-motor devices have potential benefits for eccentrically reinforced training, functioning as an ideal inertial device without requiring a maximum CON action to generate EO. Such characteristic could be an interesting asset in clinical and sport performance environments.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Sergio Maroto-Izquierdo is supported by the Ministry of Education of Spain [grant number FPU014/05732]; Ministerio de Educación, Cultura y Deporte

ORCID

Sergio Maroto-Izquierdo http://orcid.org/0000-0002-6696-5636
Rodrigo Fernandez-Gonzalo http://orcid.org/0000-0003-2816-9855
Javier González-Gallego http://orcid.org/0000-0002-4386-9342
José A. de Paz http://orcid.org/0000-0002-4389-1777

References

Brzenczek-Owczarzak, W., Naczk, M., Arlet, J., Forjasz, J., Jedrzejczak, T., & Adach, Z. (2013). Estimation of the efficacy of inertial training in older women. *Journal of Aging and Physical Activity*, *21*(4), 433–443. doi:10.1123/japa.21.4.433

Carroll, K. M., Wagle, J. P., Sato, K., Taber, C. B., Yoshida, N., Bingham, G. E., & Stone, M. H. (2018). Characterising overload in inertial flywheel devices for use in exercise training. *Sports Biomechanics*, 1–12. doi:10.1080/14763141.2018.1433715

de Hoyo, M., de la Torre, A., Pradas, F., Sanudo, B., Carrasco, L., Mateo-Cortes, J., & Gonzalo-Skok, O. (2015). Effects of eccentric overload bout on change of direction and performance in soccer players. *International Journal of Sports Medicine*, *36*(4), 308–314. doi:10.1055/s-0034-1395521

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

Fernandez-Gonzalo, R., Fernandez-Gonzalo, S., Turon, M., Prieto, C., Tesch, P. A., & Garcia-Carreira Mdel, C. (2016). Muscle, functional and cognitive adaptations after flywheel resistance training in stroke patients: A pilot randomized controlled trial. *Journal of NeuroEngineering and Rehabilitation*, *13* (37), doi:10.1186/s12984-016-0144-7

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

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

Gual, G., Fort-Vanmeerhaeghe, A., Romero-Rodriguez, D., & Tesch, P. A. (2016). Effects of in-season inertial resistance training with eccentric overload in a sports population at risk for patellar tendinopathy. *Journal of Strength and Conditioning Research*, *30*(7), 1834–1842. doi:10.1519/JSC.0000000000001286

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

Hortobagyi, T., Devita, P., Money, J., & Barrier, J. (2001). Effects of standard and eccentric overload strength training in young women. *Medicine & Science in Sports & Exercise*, *33*(7), 1206–1212.

Maroto-Izquierdo, S., Garcia-Lopez, D., & de Paz, J. A. (2017). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball Players. *Journal of Human Kinetics*, *60*, 133–143. doi:10.1515/hukin-2017-0096

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

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

McMahon, G. E., Morse, C. I., Burden, A., Winwood, K., & Onambele, G. L. (2014). Impact of range of motion during ecologically valid resistance training protocols on muscle size, subcutaneous fat, and strength. *Journal of Strength and Conditioning Research*, *28*(1), 245–255. doi:10.1519/JSC.0b013e318297143a

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M., & Naclerio, F. (2018). Injury prevention programs based on flywheel vs. body weight resistance in recreational athletes. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000002878

Murtagh, C. F., Vanrenterghem, J., O'Boyle, A., Morgans, R., Drust, B., & Erskine, R. M. (2017). Unilateral jumps in different directions: A novel assessment of soccer-associated power? *Journal of Science and Medicine in Sport*, *20*(11), 1018–1023. doi:10.1016/j.jsams.2017.03.016

Naczk, M., Lopacinski, A., Brzenczek-Owczarzak, W., Arlet, J., Naczk, A., & Adach, Z. (2017). Influence of short-term inertial training on swimming performance in young swimmers. *European Journal of Sport Science*, *17*(4), 369–377. doi:10.1080/17461391.2016.1241304

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

Norrbrand, L., Tous-Fajardo, J., Vargas, R., & Tesch, P. A. (2011). Quadriceps muscle use in the flywheel and barbell squat. *Aviation, Space, and Environmental Medicine*, *82*(1), 13–19. doi:10.3357/ASEM.2867.2011

Nunez, F. J., Santalla, A., Carrasquila, I., Asian, J. A., Reina, J. I., & Suarez-Arrones, L. J. (2018). The effects of unilateral and bilateral eccentric overload training on hypertrophy, muscle power and COD performance, and its determinants, in team sport players. *PLoS One*, *13*(3), e0193841. doi:10.1371/journal.pone.0193841

Pozzo, M., Alkner, B., Norrbrand, L., Farina, D., & Tesch, P. A. (2006). Muscle-fiber conduction velocity during concentric and eccentric actions on a flywheel exercise device. *Muscle & Nerve*, *34*(2), 169–177. doi:10.1002/mus.20574

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

Sabido, R., Hernandez-Davo, J. L., Botella, J., Navarro, A., & Tous-Fajardo, J. (2017). Effects of adding a weekly eccentric-overload training session on strength and athletic performance in team-handball players. *European Journal of Sport Science*, *17*(5), 530–538. doi:10.1080/17461391.2017.1282046

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

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

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

Thompson, W. R. (2017). Worldwide survey of fitness trends for 2018: The CREP edition. *ACSM's Health & Fitness Journal*, *21*(6), 10–19. doi:10.1249/FIT.0000000000000341

Tinwala, F., Cronin, J., Haemmerle, E., & Ross, A. (2017). Eccentric strength training: A review of the available technology. *Strength & Conditioning Journal*, *39*(1), 32–47. doi:10.1519/SSC.0000000000000262

Weir, J. P., Housh, D. J., Housh, T. J., & Weir, L. L. (1995). The effect of unilateral eccentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit. *The Journal of Orthopaedic and Sports Physical Therapy*, *22*(5), 207–215. doi:10.2519/jospt.1995.22.5.207