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ARTICLE

Regional and muscle-specific adaptations in knee extensor hypertrophy using flywheel versus conventional weight-stack resistance exercise

Tommy R. Lundberg, Maria T. García-Gutiérrez, Mirko Mandić, Mats Lilja, and Rodrigo Fernandez-Gonzalo

Abstract: This study compared the effects of the most frequently employed protocols of flywheel (FW) versus weight-stack (WS) resistance exercise (RE) on regional and muscle-specific adaptations of the knee extensors. Sixteen men (n = 8) and women (n = 8) performed 8 weeks (2–3 days/week) of knee extension RE employing FW technology on 1 leg (4 × 7 repetitions), while the contralateral leg performed regular WS training (4 × 8–12 repetitions). Maximal strength (1-repetition maximum (1RM) in WS) and peak FW power were determined before and after training for both legs. Partial muscle volume of vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VI), and rectus femoris were measured using magnetic resonance imaging. Additionally, quadriceps cross-sectional area was assessed at a proximal and a distal site. There were no differences ($P > 0.05$) between FW versus WS in muscle hypertrophy of the quadriceps femoris (8% vs. 9%), VL (10% vs. 11%), VM (6% vs. 8%), or VI (5% vs. 5%). Muscle hypertrophy tended ($P = 0.09$) to be greater at the distal compared with the proximal site, but there was no interaction with exercise method. Increases in 1RM and FW peak power were similar across legs, yet the increase in 1RM was greater in men (31%) than in women (20%). These findings suggest that FW and WS training induce comparable muscle-specific hypertrophy of the knee extensors. Given that these robust muscular adaptations were brought about with markedly fewer repetitions in the FW compared with WS, it seems FW training can be recommended as a particularly time-efficient exercise paradigm.

Key words: iso-inertial resistance exercise, eccentric-overload, MRI, skeletal muscle, strength training.

Résumé : Cette étude compare les effets des protocoles d'exercice de résistance (« RE ») les plus fréquemment utilisés, soient le volant d'inertie (« FW ») et les poids empilés (« WS »), sur les adaptations régionales et musculaires spécifiques des extenseurs du genou. Seize hommes (n = 8) et femmes (n = 8) réalisent des extensions du genou (RE) pendant 8 semaines (2–3 jours/semaine) en utilisant la technologie du FW d'un côté (4 × 7 répétitions); la jambe controlatérale réalise les exercices de résistance du WS (4 × 8–12 répétitions). Avant et après le programme d'entraînement, on détermine la force maximale (« 1RM ») en WS et la puissance de pointe en FW des deux jambes. On utilise l'imagerie par résonance magnétique pour la mesure du volume musculaire partiel du vastus lateralis (« VL »), du vastus medialis (« VM »), du vastus intermedius (« VI ») et du droit fémoral. De plus, on évalue la surface de section transversale du quadriceps aux niveaux proximal et distal. Il n'y a pas de différence ($P > 0{,}05$) entre FW et WS en ce qui concerne l'hypertrophie musculaire du quadriceps fémoral (8 % contre 9 %), du VL (10 % contre 11 %), du VM (6 % contre 8 %) et du VI (5 % contre 5 %). L'hypertrophie musculaire tend à être plus importante au niveau distal comparativement au niveau proximal ($P = 0{,}09$), mais on n'observe pas d'interaction avec la méthode de l'exercice. L'augmentation de la puissance de pointe (1RM et FW) est similaire d'une jambe à l'autre, mais l'augmentation de 1RM est plus marquée chez les hommes (31 %) que chez les femmes (20 %). D'après ces résultats, l'entraînement dans les conditions FW et WS induit une hypertrophie musculaire spécifique comparable des extenseurs du genou. Étant donné que ces adaptations musculaires marquées sont induites avec un nombre de répétitions nettement inférieur dans la condition FW comparativement à la condition WS, l'entraînement avec FW peut être recommandé comme paradigme d'exercice particulièrement efficace. [Traduit par la Rédaction]

Mots-clés : exercice de résistance iso-inertielle, surcharge pliométrique, IRM, muscle squelettique, entraînement à la force.

Introduction

It is generally believed that eccentric (ECC) actions can benefit muscle hypertrophic adaptations to resistance training (Farthing and Chilibeck 2003; Hather et al. 1991; Schoenfeld et al. 2017). These findings are consistent with the greater increase in protein synthesis and anabolic signaling with ECC compared with concentric (CON) muscle actions (Eliasson et al. 2006; Franchi et al. 2014; Friedmann-Bette et al. 2010). One established method to induce ECC overload, originating from the need for gravity-independent exercise devices in space, is to use the inertia of spinning flywheels (FWs) (Berg and Tesch 1994). This exercise paradigm presents a potent stimulus to increase force, power, and muscle mass in healthy subjects, athletes, elderly, and several patient cohorts (Maroto-Izquierdo et al. 2017*b*; Tesch et al. 2017).

The idea behind FW resistance exercise (RE) is based on the inherent characteristics of FWs to first store and then release kinetic energy. The energy that can be produced by the trainee and hence stored in the system is unlimited, and therefore all

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T.R. Lundberg, M. Mandić, M. Lilja, and R. Fernandez-Gonzalo. Division of Clinical Physiology, Department of Laboratory Medicine, Karolinska Institutet, and Unit of Clinical Physiology, Karolinska University Hospital, Huddinge C1 88 14186 Stockholm, Sweden.
M.T. García-Gutiérrez. Laboratory of Physiology, European University Miguel de Cervantes, Valladolid, Spain; Alberta Giménez Higher Education Center, University of Comillas, Costa de Saragossa 16, 07013 Palma de Mallorca, Spain.
Corresponding author: Rodrigo Fernandez-Gonzalo (email: rodrigo.gonzalo@ki.se).

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repetitions during FW exercise can be performed at maximal effort during the entire range of motion in the CON action. In friction-free devices, the energy generated during the CON phase equals the energy the trainee must resist during the ECC phase. Thus, if the ECC braking action is purposely delayed, brief episodes of ECC-overload (in terms of force and power) are produced (Fernandez-Gonzalo et al. 2014; Martinez-Aranda and Fernandez-Gonzalo 2017; Norrbrand et al. 2008; Tesch et al. 2005).

FW RE induces muscle adaptations in terms of force, power, and hypertrophy that typically exceed those produced by regular free weights or weight-stack (WS) (Maroto-Izquierdo et al. 2017*a*, 2017*b*; Norrbrand et al. 2008). However, when it comes to exercise-induced strength adaptations, this view has been recently challenged (Vicens-Bordas et al. 2018). Part of this controversy is due to the inherent difficulties to directly compare FW versus conventional RE protocols in terms of volume and/or intensity, for example. In addition to this, all the studies that have compared these 2 exercise regimes have used a parallel-group design (Maroto-Izquierdo et al. 2017*a*; Vicens-Bordas et al. 2018). This type of analysis is greatly influenced by the inter-individual variability in baseline values and responsiveness to training (Timmons 2011). To overcome these issues, we have successfully used a 1-legged exercise model, allowing for unique intra-individual comparisons of different training protocols (Fernandez-Gonzalo et al. 2013; Lundberg et al. 2012, 2016). Indeed, by using this approach, inherent confounding factors such as genetic variance, training history, and nutrient status are controlled for (MacInnis et al. 2017). Therefore, this model could be employed to systematically compare exercise-induced adaptations to FW versus conventional RE.

While the effects of FW versus weight training on muscle hypertrophy have been researched, it is unclear whether there are inter-muscular differences in the hypertrophic response across the individual muscles exercised, even when the movement employed is similar (Matta et al. 2015, 2017). Thus, even when 2 different RE methods induce the same magnitude of hypertrophy of, for example, the quadriceps muscle group, the individual muscles (i.e., vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VI), and rectus femoris (RF)) may show divergent responses. Such selective hypertrophy could influence the movement pattern, angle-specific strength, and ultimately performance during a specific task (Earp et al. 2015). In fact, recent research has shown that the molecular response to acute exercise may not only differ between CON and ECC actions, but there may also be region-specific differences along the length of the muscle (Franchi et al. 2018).

Given this background, we conducted a study comparing hypertrophy and strength adaptations to FW versus WS RE using a unilateral within-subject design. Given the difficulty to match volume and intensity between the 2 RE regimens evaluated, we employed an established protocol for FW RE training (Tesch et al. 2017), i.e., 4 sets of 7 maximal repetitions per session, and the American College of Sports Medicine (ACSM) guidelines for WS RE (4 sets of 8–12 repetitions maximum (RM)) (ACSM position stand 2009; Garber et al. 2011). We hypothesized that both RE regimens would increase force and muscle mass, but that FW RE would accentuate these adaptations.

Materials and methods

Overall study design

Sixteen healthy men and women performed 8 weeks of knee extension RE employing FW technology on 1 leg, while the contralateral leg performed regular WS training. Maximal strength (1RM) and FW peak power were determined before and after the training intervention for both legs. Cross-sectional area (CSA; in millimeters) of VL, VM, VI, and RF were measured using magnetic resonance imaging (MRI), and muscle volume was calculated thereafter. Additionally, quadriceps cross-sectional area was assessed at a proximal and a distal site.

Subjects

Recreationally active men (n = 8) and women (n = 8), aged 18–35 years, were recruited from the Stockholm region (age, 26 ± 4 years; height, 173 ± 13 cm; body mass, 79 ± 22 kg). All subjects were given oral and written information about the study before giving written informed consent to participate. Subjects completed a brief medical screening, including blood sampling, and a detailed health and exercise history anamnesis prior to inclusion. Subjects were excluded if they presented any contraindication for performing high-intensity resistance training using the lower-limbs. The group of subjects investigated was the control group in a single-blind randomized controlled trial analyzing the effects of anti-inflammatory drugs on muscle hypertrophy (Lilja et al. 2018). Thus, while whole-quadriceps size was reported in that study, we now re-examined the MRI images for the individual muscle (VL, VM, VI, RF) and the regional (proximal/distal) analysis. The study was approved by the regional ethical review board in Stockholm.

Exercise equipment and familiarization

The training was performed unilaterally, yet for both legs, on 2 different training devices. Each of the subjects' legs was randomized, in a counterbalanced manner based on initial strength levels, to either a FW knee-extension training device (YoYo Technology Inc., Stockholm, Sweden) or a traditional WS device (World Class, Stockholm, Sweden). The FW machine was equipped with a 5-kg (men) or 3.5-kg (women) FW (moment inertia 0.075 $kg \cdot m^{-2}$ or 0.05 $kg \cdot m^{-2}$) to provide inertial resistance during coupled CON and ECC actions. The WS device employed constant external loading and weight plates of 5, 2, and 1 kg were used to set and adjust the load. In both training devices, the subjects were seated (90° hip angle, 80° knee angle) and performed the knee extension from ~80° knee joint angle to ~175° (almost full extension). To customize machine settings and familiarize subjects with the exercise procedures used during training and testing, all subjects reported to the laboratory 3 times within 2 weeks prior to starting the study.

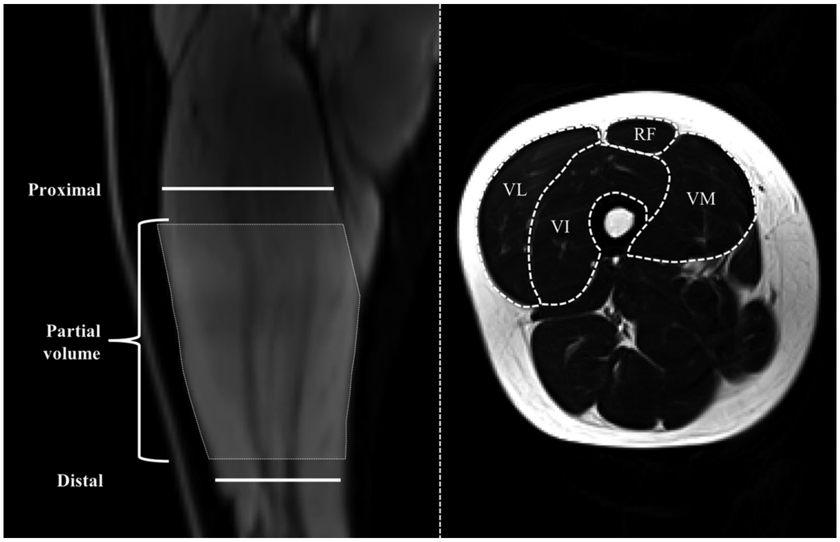
Pre- and post-testing

All tests were performed using identical protocols both before and after the 8-week training intervention. Tests were always performed unilaterally with the right leg as starting leg (hence the FW vs. WS leg was randomized). The tests were scheduled on 2 different days within ~1 week, starting with muscle strength/power assessments followed by the MRI scan. To accommodate for the postexercise biopsy that was taken in the original study (Lilja et al. 2018), the post-testing of strength was done prior to 1 of the final training sessions during the last (eighth) training week. A minimum of 48 h of rest preceded this test session. The MRI scan was then conducted 6 days after the training intervention ended. On the strength-testing day, FW ergometer peak power and WS 1RM were assessed unilaterally in both legs. Peak power in the FW device (averaged across CON–ECC actions, sets, and repetitions) was calculated from measures of rotational velocity (SmartCoach, Stockholm, Sweden). The subjects performed 2 sets of 7 repetitions at maximal effort with 2 min of rest between sets. After a 5-min resting period, the 1RM WS test was performed. The starting weight for the test was determined on the basis of previous familiarization sessions, aiming to reach 1RM within 3–5 attempts. Subjects were instructed to raise the lever arm to ~175° knee joint angle in order for the repetition to be accepted as 1RM. Each attempt was separated by 2 min of rest. In all of the tests, the subjects were instructed to provide maximal effort, and strong verbal encouragement was provided from the research staff. Subjects were blinded to test results.

MRI

Cross-sectional images were obtained using a 1.5-Tesla Siemens Magnetom Aera (Siemens Healthcare, Germany) unit; Turbo spin

Fig. 1. To the left, selected region for the partial muscle volume and proximal and distal cross-sectional area assessment. To the right, identification of the 4 individual quadriceps muscles that were individually traced (RF, rectus femoris; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis). See ~~method~~ section for further details.



echo, T2 weighted, TE 110 ms, TR 5723 ms, NSA 3, FOV 48.5 cm, scan time 4 min, 50 s, and voxel size 0.95 × 0.95 × 10 mm. Fifty continuous images, from the top of caput femoris down to level of the knee joint, with 10-mm slice thickness, were obtained for each subject. To minimize the influence of fluid shift on muscle volume, subjects were resting in the supine position for 1 h prior to any scan (Berg et al. 1993). A custom-made foot-restrain device ensured a fixed limb position with no compression of thigh muscles. Scout images were obtained to confirm identical positioning in pre- and post-scans. Although pre–post images were analyzed in parallel to ensure identical anatomical judgements, the researcher who performed the analysis was blinded to the time-point of the specific images. CSA of the 4 muscles of quadriceps femoris were analyzed individually, i.e., VL, VM, VI, and RF. Measurements started from the first image not displaying musculus gluteus maximus and ended with the last image in which m. RF appeared. Within this segment (range 9–18 images depending on muscle length of the individual), every third image (Alkner and Tesch 2004) was assessed by manual planimetry using imaging software (ImageJ, National Institutes of Health, Bethesda, Md., USA). The average of 2 measures showing less than 1% difference between values was multi-plied by slice thickness to obtain muscle volume. Quadriceps partial volume, calculated as the sum of the 4 individual muscles, were compared with previously published data where only volume of total quadriceps femoris was measured (Lilja et al. 2018). The intra-class correlation between 2 different evaluators and 2 different methods to assess partial muscle volume (i.e., total quadriceps vs. sum of individual muscles) was 0.99, and the standard error of measurement was 3.0%. F1 The region selected for partial muscle volume assessment (Fig. 1) was based on our previous studies where we analyzed muscle-specific compartments within the knee extensors and noted that it is possible to identify the individual muscle borders within this segment of the thigh (Lundberg et al. 2013). However, to get a better appreciation of potential region-specific responses to WS and FW training, we also measured the CSA of quadriceps at 1 proximal and 1 distal site outside the region for muscle volume assessment. The proximal image was 50 mm proximal to the image where gluteus maximus first disappeared, and the distal site was taken 30 mm distal to where the muscle belly of RF was not seen (Fig. 1). Since the VM is very small at the proximal site, and the muscle belly of RF is nonexistent at the distal site, we chose to analyze only quadriceps CSA at these sites.

Training protocols

The subjects performed 20 training session during the 8-week intervention. The sessions were scheduled 2 and 3 times every other week, starting with 2 sessions the first week. Training was performed unilaterally in each device. Subjects were instructed to progressively increase their effort during 1 warm-up set. After a 2-min rest, the subjects performed 4 × 7 repetitions in the FW (2 min of rest between sets) using the leg that had been randomized as the “FW-leg”, and 4 × 8–12 repetitions in the WS using the “WS-leg”. Total number of repetitions for each exercise was recorded. The starting order of the machines was altered in every training session. Increases in WS load during training were implemented when the subject could perform 13 or more repetitions during a set. Since the resistance generated in FW is mainly dependent of the subject’s effort, i.e., the kinetic energy invested in the concentric phase (Tesch et al. 2017), no modification in the inertia (load) was done. Peak power during FW exercise was measured for each repetition in each training session during the whole intervention, and subjects were instructed to perform each repetition with maximal effort.

Data analysis

All results are presented as means ± SD. The number of repetitions in FW and WS were compared using a Student’s *t* test. To analyze hypertrophic adaptations in m. quadriceps femoris, and in the 4 individual muscles (i.e., VL, VI, VM, RF), a 2-way ANOVA with repeated measures for time (pre- vs. post-training) and exercise device (FW vs. WS) was employed. Potential changes in individual muscle volumes were studied using a 2-way ANOVA with repeated measures for muscle (VI, VL, VM, RF) and device (FW vs. WS) using the delta change (%) from pre- to post-training. In addition, to assess any difference in muscle hypertrophy at the proximal and distal sites of m. quadriceps femoris, a 3-way ANOVA with repeated measures for site (proximal vs. distal), time (pre- vs. post-training), and device (FW vs. WS) was performed. Performance data in WS and FW, i.e., 1RM and merged CON–ECC peak power, respectively, were analyzed using a 2-way ANOVA with repeated measures for time (pre- vs. post-training) and device (FW vs. WS). Finally, any potential sex difference in the adaptations induced by FW and WS was analyzed with a 3-way ANOVA with repeated measures for time (pre- vs. post-training), device (FW vs. WS), whereas sex (women vs. men) was a between-group factor. When significant interactions were found, simple effect tests

Fig. 2. (A) The relative increase in muscle volume of the 4 different quadriceps muscles, as well as the sum of the 4 of them (quadriceps femoris; QF). FW, flywheel; RF, rectus femoris; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis; WS, weight-stack. Significant post hoc differences ($P < 0.05$): *compared with all other muscles; †compared with VI. (B) The relative increase in quadriceps cross-sectional area at the selected proximal and distal site of the knee extensors in response to weight-stack (WS) and flywheel (FW) training.

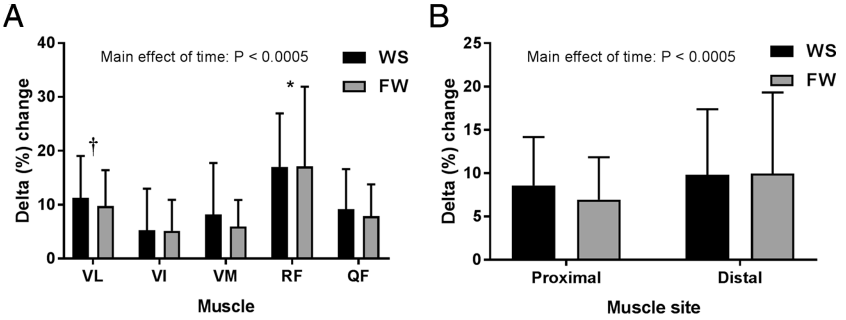
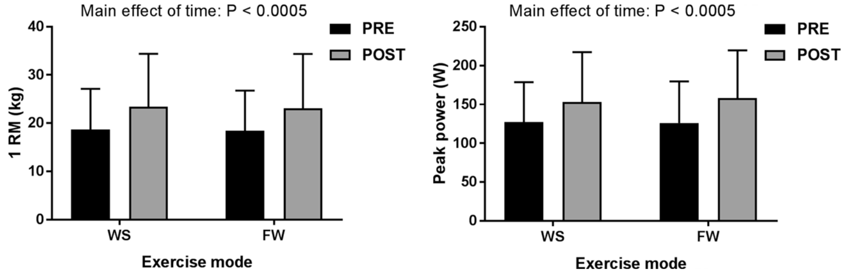


Fig. 3. 1-repetition maximum (RM) (left) and peak power (right) assessed before (PRE) and after (POST) training for each leg.



were employed. The false discovery rate procedure was used to compensate for multiple post hoc comparisons (Curran-Everett 2000). The level of significance was set at 5% ($P < 0.05$). All statistical analysis was performed using IBM SPSS version 25 (IBM Corp., Armonk, N.Y., USA).

Results

The training compliance was 98%. The number of repetitions performed by the WS leg (687 ± 73 repetitions) was significantly greater ($P < 0.0005$) than the FW leg (529 ± 17 repetitions). Thus, the average number of repetitions per set was 9 in the WS device, compared with 7 (set a priori) in the FW device. Progression of training load/power (30%–40%) over the 8 weeks in WS and FW was reported previously (Lilja et al. 2018).

Both exercise regimes induced a marked hypertrophy response of m. quadriceps femoris, indicated by a significant main effect of time ($F = 26.5$; $P < 0.0005$). There was no interaction effect (8% and 9% increase in quadriceps volume for FW and WS, respectively). Similar results were found for all individual muscles, with a main effect of time (VL: $F = 37.5$ and $P < 0.0005$; VI: $F = 7.5$ and $P < 0.015$; VM: $F = 14.7$ and $P < 0.002$; RF: F = 27.3 and $P < 0.0005$), with no interaction effects (Fig. 2A).

A main effect of muscle ($F = 22.3$, $P < 0.0005$) was found in the analysis of muscle volume gains of VL, VI, VM, and RF (Fig. 2A). Thus, RF showed greater relative increase in muscle volume than VL ($P = 0.01$ for both FW and WS), VI ($P < 0.0005$ for both FW and WS), and VM ($P = 0.005$ for FW; $P = 0.001$ for WS). In addition, greater relative changes of VL were found when compared with VI in both FW ($P < 0.0005$) and WS ($P = 0.007$).

Regarding the training-induced hypertrophic response at the distal and proximal segments of the quadriceps, there was a main effect of time ($F = 81.3$, $P < 0.0005$) due to overall greater quadriceps volume at post- compared with pre-training, independently of exercise paradigm and regional site (Fig. 2B). There was a trend towards a significant time × site interaction ($P = 0.09$) due to slightly greater increase in quadriceps CSA at the distal segment of the muscle (9.9%) compared with the proximal site (7.8%), independently of training paradigm (Fig. 2B).

A main effect of time was found in the analysis of 1RM ($P < 0.0005$; $F = 21.7$), with no interaction effect. Thus, the WS leg increased 1RM by 26.3%, while the leg performing FW showed a 25.3% improvement (Fig. 3). Similarly, there was a main effect of time for peak power in the FW test ($P < 0.0005$; $F = 25.7$), with the WS leg showing a 22.1% increase, compared with 29.2% for FW (Fig. 3). There was no interaction effect.

Finally, the analysis conducted to explore potential differences across sexes showed no interaction effects for CSA (Table 1). Thus, the graphs displaying CSA data are merged across men and women. There was, however, a time × sex interaction in 1RM ($P = 0.016$; $F = 7.4$). Thus, men increased 1RM ($P < 0.0005$; 31.4%) more than women (20.2%), independently of exercise mode (Table 1). There was a trend towards a significant time × sex interaction in FW peak power ($P = 0.11$), with men showing slightly greater (27.7%) increases than women (23.5%), independently of exercise mode (Table 1).

Discussion

Spurred by the increased interest in ECC-training methods, this study set out to scrutinize muscle and region-specific adaptations to FW resistance training, emphasizing ECC overload, compared with traditional WS training. The results generally showed comparable adaptations in muscle size and strength between the 2 training methods employed. The 2 training paradigms were also very comparable with regard to muscle-specific hypertrophy within the knee extensors, where the increase in volumes were RF > VL > VM > VI in both exercise modes. Collectively, these findings suggest that both FW and WS training can be used to induce early muscular adaptations in both men and women. However, given that 22% fewer repetitions were performed in the FW exercise, it seems this training paradigm is more time-efficient.

The addition of ECC overload with FW exercise did generally not result in superior adaptations compared with regular WS

Table 1. Absolute values for men, women, and both sexes together (merged) for the variables analyzed.

	WS				FW			
	Pre-training	Post-training	Mean difference (95% CI)	ES	Pre-training	Post-training	Mean difference (95% CI)	ES
Vastus lateralis (cm^3)^{a,b}								
Men	404.9±91.2	448.0±82.4	43.1 (25.8–60.3)	0.50	427.3±97.6	464.0±88.3	36.7 (16.3–57.0)	0.39
Women	228.6±45.7	251.6±42.9	23.0 (9.9–36.1)	0.52	212.6±42.6	233.8±50.1	21.2 (9.0–33.4)	0.46
Merged†	316.8±114.7	349.8±119.6	33.0 (22.1–44.0)	0.28	320.0±132.6	348.9±137.6	28.9 (17.8–40.1)	0.21
Vastus intermedius (cm^3)^{a,b}								
Men	400.1±144.1	411.3±133.2	11.2 (−12.0–34.4)	0.08	429.1±174.3	439.5±157.8	10.4 (−7.9–28.6)	0.06
Women	212.9±45.3	225.3±45.8	12.4 (6.4–18.3)	0.27	212.8±43.9	224.8±42.0	11.9 (5.1–18.8)	0.28
Merged	306.5±141.4	318.3±135.9	11.8 (1.4–22.2)	0.09	321.0±166.0	332.1±157.3	11.1 (2.6–19.7)	0.07
Vastus medialis (cm^3)^{a,b}								
Men	341.1±106.9	364.9±97.7	23.8 (−2.1–49.7)	0.23	343.2±84.5	365.5±84.0	22.3 (7.4–37.2)	0.27
Women	163.5±34.2	175.6±34.6	12.1 (5.2–19.0)	0.35	156.0±25.6	163.3±25.8	7.3 (3.8–10.8)	0.28
Merged	252.3±119.6	270.3±120.7	18.0 (5.9–30.1)	0.15	249.6±113.9	264.4±120.4	14.8 (6.9–22.7)	0.13
Rectus femoris (cm^3)^{a,b}								
Men	107.8±29.9	123.1±31.7	15.3 (6.1–24.5)	0.50	114.0±26.3	127.6±29.2	13.6 (0.1–27.1)	0.49
Women	63.6±23.7	75.3±28.4	11.7 (6.0–17.4)	0.45	63.5±27.6	75.9±31.2	12.4 (5.8–19.0)	0.42
Merged*	85.7±34.6	99.2±38.1	13.5 (8.7–18.3)	0.37	88.7±36.9	101.8±39.6	13.0 (6.5–19.6)	0.34
Quadriceps (cm^3)^{a}								
Men	1253.9±356.5	1347.3±322.5	93.4 (26.1–160.6)	0.28	1313.6±360.0	1396.6±332.2	82.9 (25.8–140.1)	0.24
Women	668.7±135.5	727.8±131.9	59.2 (35.8–82.5)	0.44	645.0±127.5	697.8±135.7	52.8 (28.9–76.7)	0.40
Merged	961.3±399.0	1037.5±398.7	76.3 (43.9–108.7)	0.19	979.3±432.8	1047.2±436.2	67.9 (39.7–96.1)	0.16
Quadriceps CSA proximal (cm^2)^{a}								
Men	74.4±23.8	79.4±23.2	5.0 (2.5–7.5)	0.21	72.1±22.8	77.8±23.0	5.7 (3.8–7.6)	0.25
Women	46.5±9.5	50.8±10.4	4.3 (1.2–7.5)	0.44	47.5±10.4	49.8±10.0	2.2 (0.6–3.8)	0.22
Merged	60.5±22.7	65.1±22.8	4.7 (2.9–6.5)	0.21	59.8±21.3	63.8±22.4	4.0 (2.4–5.6)	0.18
Quadriceps CSA distal (cm^2)^{a}								
Men	48.2±12.7	51.7±11.3	3.4 (1.6–5.2)	0.29	49.7±14.7	54.1±12.5	4.4 (0.9–7.9)	0.33
Women	31.2±7.9	34.2±6.7	3.0 (1.1–5.0)	0.41	32.2±8.2	34.7±8.2	2.5 (0.8–4.3)	0.31
Merged	39.7±13.5	43.0±12.7	3.2 (2.1–4.4)	0.25	40.9±14.6	44.4±14.3	3.5 (1.7–5.2)	0.24
1RM in WS (kg)^{a,c}								
Men‡	24.5±8.0	31.4±10.2	6.9 (3.1–10.7)	0.76	24.0±8.3	31.0±11.1	7.0 (2.7–11.3)	0.72
Women	12.9±3.4	15.4±3.0	2.5 (1.6–3.4)	0.77	12.9±2.8	15.1±2.5	2.3 (1.7–2.8)	0.84
Merged	18.7±8.4	23.4±11.0	4.7 (2.6–6.8)	0.48	18.4±8.3	23.1±11.3	4.6 (2.3–6.9)	0.47
Peak power in FW (W)^{a}								
Men	158.3±52.1	194.9±66.3	36.6 (14.6–58.6)	0.62	157.3±58.6	196.4±64.6	39.1 (12.4–65.8)	0.63
Women	96.6±27.0	111.0±22.3	14.4 (−4.1–32.9)	0.59	94.7±22.6	119.8±24.9	25.1 (16.3–33.9)	1.06
Merged	127.4±51.2	153.0±64.5	25.5 (11.6–39.4)	0.44	126.0±53.7	158.1±61.7	32.1 (19.3–44.9)	0.56

Note: Data are means ± SD. 1RM, 1-repetition maximum; 95% CI, 95% confidence interval; CSA, cross-sectional area; ES, effect size (difference in mean/pooled SD); FW, flywheel; WS, weight-stack. Significant main effects ($P < 0.05$) are as follows: ^{a}main effect of time; ^{b}main effect of muscle; ^{c}interaction time × sex. Significant simple effects ($P < 0.05$) are as follows: *greater increase than vastus lateralis, medialis, and intermedius independently of exercise mode; †greater increase than vastus intermedius independently of exercise mode; ‡greater increase than women independently of exercise mode.

training in the current study. This is in contrast to the earlier study by Norrbrand et al. where quadriceps volume increased 6% with FW training compared with 3% with WS training (Norrbrand et al. 2008). The most likely reason for the discrepancy between studies is that in the Norrbrand et al. study, the number of repetitions performed were 7 in both exercise modes, whereas we chose to employ the "typical" program conducted with these exercise devices (Garber et al. 2011; Norrbrand et al. 2008). Taken together, it seems that FW training is more effective than WS training on an "adaptation per repetition" basis, whereas similar gains can be achieved if the total number of repetitions is increased in the WS device, as done in the current study. It should be noted, however, that performing fewer repetitions in the FW exercise does not necessarily mean that less work is conducted. In fact, it has been estimated that work per set performed in the FW device is greater than with WS training despite similar number of repetitions conducted (Norrbrand et al. 2008). One possible explanation for the generally greater efficacy of FW compared with WS training could be that each repetition in the FW device, provided that the effort is maximal, is performed with maximal possible loading. This is due to the inherent characteristics of the FW device, where force production is solely limited by the trainee's ability to accelerate the wheel in the CON action. The following ECC action must subsequently absorb the energy produced in the CON action. By delaying the braking action into a narrow window, the force produced in the ECC action will be greater than when using regular weights (Norrbrand et al. 2008). Thus, FW training offers very potent loading in both the CON and ECC action. In contrast, with regular WS training, only the last repetitions close to failure offers optimal loading at the angle representing the sticking point. Further, without assisted spotting, free weights cannot provide ECC overload, which is considered to boost the anabolic response to resistance exercise (Eliasson et al. 2006; Franchi et al. 2014; Friedmann-Bette et al. 2010).

A particular interest in the current study was to explore whether there would be any difference in regional (proximal vs. distal) and muscle-specific (i.e., within the 4 quadriceps muscles) hypertrophic responses between the 2 exercise modes. Overall, the results were very similar between FW and WS training in this regard. Both training modes induced the greatest hypertrophy in RF, followed by VL, VM and VI. This is consistent with the bulk of literature assessing knee extension exercise, where typically RF show the greatest hypertrophy, followed by either VL or VM, and significantly lower magnitude of hypertrophy in the VI (Narici et al. 1996; Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2004). The explanation for divergent hypertrophic responses across specific muscles within the same muscle group could be related to differences in muscle activation and hence protein synthesis along the muscle belly. In support, Narici et al. reported greater activation of RF compared with the other quadriceps muscles in the ECC action of knee extensions (Narici et al. 1996).

Regarding the region-specific analysis, there was a tendency for a greater hypertrophic effect at the distal compared with the proximal site. This is similar to previous research indicating that the increase in individual muscle sizes is somewhat greater at the distal site (Narici et al. 1996; Seynnes et al. 2007; Wakahara et al. 2017). The justification for assessing potential differences in the hypertrophic response across different anatomical sites along the muscle stems from the inherent differences in the characteristics of the training devices. This could lead to differences in the amount of stimuli transmitted along the muscle length longitudinally and/or laterally. Thus, divergent force transmission patterns could lead to modifications in the amount of mechanical loading and hence mechanotransduction responses proximally and distally (Franchi et al. 2018). Also, regional differences could be produced by heterogeneity of muscle architecture (Blazevich et al. 2006). Apparently, however, the ECC overload and different nature of the loading pattern associated with FW exercise did not result in altered regional knee-extensor adaptations compared with WS training.

Both exercise modes were effective in increasing strength (about 20%–30% increase in 1RM and FW peak power). While the loading strategy differs between exercise modes, both exercises are still very similar in the sense that they are isolated knee extensions performed in the seated position. Thus, it seems that the overall biomechanical similarity between exercises, rather than any difference in the CON and ECC loading pattern, dictates the overall strength increase in unilateral knee extensions. In support, in our previous study we reported that the FW and WS protocols also induced similar strength gains when assessed with isokinetic dynamometry (Lilja et al. 2018).

There were generally minor sex differences in muscle hypertrophic adaptations to FW or WS training. Thus overall, the results were grouped combining both men and women. The reason for a post hoc sex analysis was, however, justified by our earlier observation that while muscle size seems to increase similarly between men and women with FW training, there could be subtle differences in strength and power adaptations (Fernandez-Gonzalo et al. 2014). In agreement with this, in the current study, the increase in 1RM strength was greater in men than in women. Supporting previous reports (Fernandez-Gonzalo et al. 2014), there were also differences in FW peak power, even though they did not reach statistical significance ($P = 0.11$). Given that the increase in muscle size was similar between men and women, the reason for the greater strength increase in men could perhaps be due to neural factors, i.e., muscle fiber recruitment or motor unit firing rate, different fiber-type changes, or variations in architectural adaptations. This should be addressed in future investigations.

A strength of the current study was the within-subject design where each subject performed both training modes randomized across legs. Thus, given that this approach controls for pretraining differences, genetic factors, and diet, any differences in adaptations across legs should with great confidence be attributed to the training method. A limitation, however, was that we did not measure any architectural factor within the muscle apart from muscle size. Thus, it cannot be excluded that there are important differences between FW training and regular weights when it comes to changes in pennation angle, fascicle length, and/or tendon/ECM adaptations. Furthermore, we did not measure muscle activation through electromyography. A previous report, however, suggested that muscle activation, particularly in the ECC action, is greater with FW training than with regular weights (Norrbrand et al. 2010). Thus, this factor could also contribute to the greater efficacy of FW training.

We acknowledge that this study did not match the 2 legs for number of repetitions and/or work performed. Therefore, we cannot with certainty conclude that increasing the number of repetitions in the FW protocol would lead to superior adaptations compared with WS training. Based on previous reports (Maroto-Izquierdo et al. 2017*b*; Norrbrand et al. 2008), however, it seems that when the 2 training methods are more closely matched in terms of repetitions/work performed, FW training promotes accentuated increases in muscle hypertrophy and strength compared with regular weights. Finally, it should be appreciated that the eccentric loading provided by FW exercise is not necessarily comparable to eccentric overload achieved through other exercise modalities, such as isotonic eccentric loading. Thus, generalizability to other eccentric training modalities should be done with caution.

In summary, we report that when employing the 2 most frequent protocols for either FW or WS knee extension resistance training, the 2 training methods generally result in similar gains in muscle size and strength. The muscle hypertrophic response was also very similar between the 2 methods when comparing inter-muscular responses within the quadriceps muscle group, as well as when examining different regional sites along the muscle group. Furthermore, the adaptations were generally similar between men and women, even though the men increased maximal strength to a greater extent than the women. Given that these robust muscular adaptations were brought about with markedly fewer repetitions in the FW compared with the WS mode, it seems FW training can be recommended as a particularly time-efficient exercise paradigm.

Conflict of interest statement

No conflicts of interest, financial or otherwise, are declared by the authors.

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