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

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Abstract

This study compared the effects of the most frequently employed protocols of flywheel vs. weight-stack 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/wk) of knee extension RE employing flywheel technology (FW) on one leg (4x7 repetitions), while the contralateral leg performed regular weight-stack (WS) training (4x8-12 repetitions). Maximal strength (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 (RF) were measured using magnetic resonance imaging (MRI). Additionally, quadriceps (QF) cross-sectional area was assessed at a proximal and a distal site. There were no differences ($P>0.05$) between FW vs. WS in muscle hypertrophy of the QF (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

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 (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. 2017b; Tesch et al. 2017).

The idea behind flywheel resistance exercise (RE) is based on the inherent characteristics of flywheels 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 repetitions during flywheel 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).

Flywheel RE induces muscle adaptations in terms of force, power, and hypertrophy that typically exceed those produced by regular free weights or weight-stack (Maroto-Izquierdo et al. 2017a; Maroto-Izquierdo et al. 2017b; 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 flywheel vs. conventional RE protocols in terms of volume and/or intensity, for example. In addition to this, all the studies that have compared these two exercise regimes have used a parallel-group design (Maroto-Izquierdo et al. 2017a; 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 one-legged exercise model, allowing for unique intra-individual comparisons of different training protocols (Fernandez-Gonzalo et al. 2013; Lundberg et al. 2012; Lundberg et al. 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 flywheel vs. conventional RE.

While the effects of flywheel vs. 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; Matta et al. 2017). Thus, even when two different RE methods induce the same magnitude of hypertrophy of e.g. 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 flywheel vs. weight-stack RE using a unilateral within-subject design. Given the difficulty to match volume and intensity between the two RE regimens evaluated, we employed an established protocol for flywheel 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 weight-stack RE (4 sets of 8-12 RM) (ACSM position stand, 2009; Garber et al. 2011). We hypothesized that both RE regimens would increase force and muscle mass, but that flywheel RE would accentuate these adaptations.

Material & Methods

Overall study design

Sixteen healthy men and women performed 8 weeks of knee extension RE employing flywheel technology on one leg, while the contralateral leg performed regular weight-stack training. Maximal strength (one-repetition-maximum; 1RM) and flywheel peak power were determined before and after the training intervention for both legs. Cross-sectional area of mm. 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), 18-35 years old, were recruited from the Stockholm-region (age; 26 ± 4 yr, 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 two different training devices. Each of the subjects' legs was randomized, in a counterbalanced manner based on initial strength levels, to either a flywheel knee-extension training device (FW; YoYo Technology Inc., Stockholm, Sweden) or a traditional weight-stack device (WS; World Class, Stockholm, Sweden). The FW machine was equipped with a 5-kg (men) or 3.5-kg (women) flywheel (moment inertia $0.075 \text{ kg}\cdot\text{m}^2$ or $0.05 \text{ kg}\cdot\text{m}^2$) 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 $\sim 80^\circ$ knee joint angle to $\sim 175^\circ$ (almost full extension). In order to customize machine settings and familiarize subjects with the exercise procedures used during training and testing, all subjects reported to the laboratory three times within two 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 two different days within ~one week, starting with muscle strength/power assessments followed by the MRI scan. To accommodate for the post-exercise biopsy that was taken in the original study (Lilja et al. 2018), the post-testing of strength was done prior to one of the final training sessions during the last (8th) training week. A minimum of 48-h rest preceded this test session. The MRI scan was then conducted 6 days after the training intervention ended. On the strength-testing day, flywheel ergometer peak power and weight-stack 1RM were assessed unilaterally in both legs. Peak power in the flywheel 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 rest between sets. After a 5-min resting period, the 1RM weight-stack 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 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.

Magnetic resonance imaging

Cross-sectional images were obtained using a 1.5-Tesla Siemens Magnetom Aera (Siemens Healthcare, Germany) unit; Turbo spin 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 x 0.95 x 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. In order 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 were blinded to the time-point of the specific images. Cross-sectional area (CSA) of the four muscles of quadriceps femoris were analyzed individually, i.e. VL, VM, VI, and RF. Measurements started from the first image not displaying m. 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 (Image J, National Institutes of Health, Bethesda, MD). The average of two measures showing less than 1% difference between values was multiplied by slice thickness to obtain muscle volume. Quadriceps partial volume, calculated as the sum of the four 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 two different evaluators and two 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 (SEM) was 3.0%. The region selected for partial muscle volume assessment (Fig. 1) was based on our previous studies where we have 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 one proximal and one 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 non-existent 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 two and three times every other week, starting with two sessions the first week. Training was performed unilaterally in each device. Subjects were instructed to progressively increase their effort during one warm-up set. After a 2-min rest, the subjects performed 4 x 7 repetitions in the FW (2 min rest between sets) using the leg that had been randomized as “FW-leg”, and 4 x 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 mean $\pm$ standard deviation (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 four individual muscles (i.e. VL, VI, VM, RF), a two-way ANOVA with repeated measures for time (pre vs. post) 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 three-way ANOVA with repeated measures for site (proximal vs. distal), time (pre vs. post), 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 two-way ANOVA with repeated measures for time (pre vs. post) and device (FW vs. WS). Finally, any potential sex difference in the adaptations induced by FW and WS was analyzed with a three-way ANOVA with repeated measures for time (pre vs. post), device (FW vs. WS), whereas sex (women vs. men) was a between-group factor. When significant interactions were found, simple effect tests 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 SPSS v.25 (SPSS, Chicago, IL, USA).

Results

The training compliance was 98%. The number of repetitions performed by the WS leg (687 ± 73 reps) was significantly greater ($P < 0.0005$) than the FW leg (529 ± 17 reps). Thus, the average number of repetitions per set was 9 in the WS device, compared to 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. 2 A).

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. 2 A). 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 to pre-training, independently of exercise paradigm and regional site (Fig. 2 B). There was a trend towards a significant time $\times$ 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. 2 B).

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 x 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 x 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 flywheel resistance training, emphasizing ECC overload, compared with traditional weight-stack training. The results generally showed comparable adaptations in muscle size and strength between the two training methods employed. The two 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 flywheel and weight-stack training can be used to induce early muscular adaptations in both men and women. However, given that 22% fewer repetitions were performed in the flywheel exercise, it seems this training paradigm is more time-efficient.

The addition of ECC overload with flywheel exercise did generally not result in superior adaptations compared with regular weight-stack training in the current study. This is in contrast to the earlier study by Norrbrand et al. where quadriceps volume increased 6% with flywheel training compared with 3% with weight-stack 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 flywheel training is more effective than weight-stack training on an “adaptation per repetition” basis, whereas similar gains can be achieved if the total number of repetitions is increased in the weight-stack device, as done in the current study. It should be noted, however, that performing fewer repetitions in the flywheel exercise does not necessarily mean that less work is conducted. In fact, it has been estimated that work per set performed in the flywheel device is greater than with weight-stack training despite similar number of repetitions conducted (Norrbrand et al. 2008). One possible explanation for the generally greater efficacy of flywheel compared with weight-stack training could be that each repetition in the flywheel device, provided that the effort is maximal, is performed with maximal possible loading. This is due to the inherent characteristics of the flywheel 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, flywheel training offers very potent loading in both the CON and ECC action. In contrast, with regular weight-stack 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 four quadriceps muscles) hypertrophic responses between the two exercise modes. Overall, the results were very similar

between flywheel and weight-stack 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 flywheel exercise did not result in altered regional knee-extensor adaptations compared with weight-stack training.

Both exercise modes were effective in increasing strength (about 20-30% increase in 1RM and flywheel 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 flywheel and weight-stack 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 flywheel or weight-stack 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 flywheel 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 flywheel 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 pre-

training 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 flywheel training and regular weights when it comes to changes in pennation angle, fascicle length and/or tendon/extracellular matrix adaptations. Furthermore, we did not measure muscle activation through e.g. electromyography. A previous report, however, suggested that muscle activation, particularly in the ECC action, is greater with flywheel training than with regular weights (Norrbrand et al. 2010). Thus, this factor could also contribute to the greater efficacy of flywheel training.

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

In summary, we report that when employing the two most frequent protocols for either flywheel or weight-stack knee extension resistance training, the two training methods

generally result in similar gains in muscle size and strength. The muscle hypertrophic response was also very similar between the two 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 flywheel compared with the weight-stack mode, it seems flywheel training can be recommended as a particularly time-efficient exercise paradigm.

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Conflict of interest

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

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Draft

Figure legends

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 four individual quadriceps muscles that were individually traced (VL = vastus lateralis, VI = vastus intermedius, VM = vastus medialis, RF = rectus femoris). See method section for further details.

Fig. 2 A; The relative increase in muscle volume of the four different quadriceps muscles, as well as the sum of the four of them (QF). VL = vastus lateralis, VI = vastus intermedius, VM = vastus medialis, RF = rectus femoris, WS = weight-stack, FW = flywheel. Significant post-hoc differences ($P < 0.05$): * vs. all other muscles; # vs. 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 1RM (left) and peak power (right) assessed before (PRE) and after (POST) training for each leg.

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

	WS				FW			
	PRE	POST	Mean difference (95% CI)	ES	PRE	POST	Mean difference (95% CI)	ES
Vastus lateralis (cm³) ^{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 (cm³) ^{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 (cm³) ^{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 (cm³) ^{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 (cm³) ^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 (cm²) ^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 (cm²) ^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 mean ± SD. CI; 95% confidence interval, ES; effect size (difference in mean / pooled SD), CSA; cross-sectional area, WS; weight-stack, FW; flywheel. Significant main effects ($P < 0.05$); ^a main effect of time, ^b main effect of muscle, ^c interaction time × sex. Significant simple effects ($P < 0.05$); * 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.

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196x76mm (300 x 300 DPI)

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

198x69mm (300 x 300 DPI)