Effects of Flywheel Training With Eccentric Overload on Standing Balance, Mobility, Physical Function, Muscle Thickness, and Muscle Quality in Older Adults

Mathew W. Hill,[1] Matthew Roberts,[1] Michael J. Price,[1] and Anthony D. Kay[2]

[1]*Center for Sport, Exercise and Life Sciences, School of Life Sciences, Coventry University, Warwickshire, United Kingdom; and* [2]*Center for Physical Activity and Life Sciences, Faculty of Art, Science and Technology, University of Northampton, Northamptonshire, United Kingdom*

Abstract

Hill, MW, Roberts, M, Price, MJ, and Kay, AD. Effects of flywheel training with eccentric overload on standing balance, mobility, physical function, muscle thickness, and muscle quality in older adults. *J Strength Cond Res* XX(X): 000–000, 2021—This study investigated the effects of a 6-week eccentric overload flywheel training program on vastus lateralis (VL) and gastrocnemius medialis (GM) muscle thickness and muscle quality (echo intensity), mobility (Timed Up and Go [TUG]), physical function (sit-to-stand), and balance (postural sway) performance. Nineteen subjects were assigned to either a flywheel training group ($n = 11$, age $= 66.4 \pm 5.2$ years) or a control group ($n = 8$, age $= 65.9 \pm 3.8$ years). The flywheel group underwent twice weekly squat and calf raise exercises for 6 weeks with outcome measures assessed before and after training or a time-matched control period. Throughout the training, subjects were instructed to contract as fast as possible with maximal effort during the concentric phase and to maximally resist the pull during the eccentric phase. The alpha value was a priori set at $p < 0.05$. Statistically significant ($p < 0.05$) mean (*SD*) increases in right and left VL (7.6–9.6 ± 7.7–9.8%) and GM (8.6–8.7 ± 6.4–11.5%) muscle thickness and a reduction in VL (10.2–11.3 ± 5.9–7.9%) and GM (11.7–11.9 ± 5.6–9.6%) echo intensity were accompanied by faster TUG time (13.7 ± 7.0%) improved sit-to-stand performance (17.8–23.5 ± 7.6 – 13.4%) and reduced postural sway (29.7–42.3 ± 13.2–24.2%) after 6 weeks of flywheel training. There were no differences in any outcome measures between the treatment and control group at baseline ($p > 0.05$). Overall, we observed substantial gains in muscle thickness and muscle quality, in addition to enhanced physical function, balance, and mobility performance among older adults after flywheel training, which may have important implications for preserving the functional capacity of older adults.

Key Words: resistance training, strength, aging, functional decline, posturography, sarcopenia

Introduction

It is well established that aging results in a marked and progressive loss in skeletal muscle mass and strength (i.e., sarcopenia (10)), which contribute substantially to declines in physical function (i.e., balance and mobility (14)) and increased risk of falls (18). Progressive resistance training is widely regarded as a potent stimulus to alleviate age-related reductions in muscle strength (25) and is among the main pillars of standard care for preventing falls (1). Although traditional resistance training (i.e., concentric and eccentric actions against a constant external load) is an effective treatment strategy to counteract sarcopenia, changes in muscle strength are often not transferred to improved balance or mobility performance (31). Therefore, it is imperative to identify and develop novel exercise strategies to counteract sarcopenia, while preserving balance and mobility, to ensure older adults live independently into old age.

In recent years, there has been a recognition that there is a preservation of eccentric (muscle lengthening) force-generating capacity in older adults (38), which may enable older adults to use an eccentric-overload exercise routine more effectively than other exercise modes. Furthermore, a mounting body of evidence has also confirmed that eccentric exercise training elicits superior adaptations in muscle strength/power, muscle mass, and physical performance (i.e., mobility) when compared with concentric training in older adults (9,19,27). One of the hallmarks of eccentric contractions is a high mechanical force, presented at a relatively low metabolic demand (i.e., ~25% of that during concentric exercise at a comparable workload (20)) and reduced perceived effort (19). Crucially, many high fall-risk tasks, such as descending stairs, rely almost exclusively on eccentric muscle contractions. Therefore the unique "high force, low cost" characteristic of eccentric exercise is ideally suited to older adults and may be of particular value in preserving function and lowering fall risk.

The eccentric exercise training typically used in human studies involves isokinetic dynamometers or motor-controlled machines (e.g., eccentric cycling and stepping ergometers). Although these forms of exercise can be undertaken in the laboratory or research environment, such devices are costly, impractical, inaccessible, and often require clinician support, preventing wide scale application where the general population typically exercise (i.e., fitness centers or in the home). Consequently, a more practical approach

Address correspondence to Dr. Mathew Hill, matt.hill@coventry.ac.uk.

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to obtaining an eccentric overload stimulus is required. One area that has garnered attention in recent years is the emergence of inertial flywheels, in recognition that this exercise modality offers the possibility to elicit a greater eccentric loading than conventional gravity-based weight training, depending on wheel inertia and the force generated during the concentric contraction (29). During the concentric phase, force is applied to the strap/harness wore by the subject, which initiates rotation of the flywheel. Once the concentric phase is complete, the energy transferred and stored in the system rewinds the strap/harness, and the subject must resist the pull of the flywheel by performing a braking eccentric muscle contraction. However, by applying little braking force in the first third of the eccentric phase, and then applying maximal effort in a narrow window at the end range of motion, the time to dissipate the stored energy is reduced (42). Therefore, eccentric overload can be achieved by intentionally delaying the initiation of the braking force. Studies using flywheel training have reported significant improvements in physical (i.e., balance and mobility (40)) and muscular functions (i.e., strength and power (30,39)) among older adults. Although previous studies have highlighted the importance of muscle quality, rather than muscle strength or mass separately, in assessing physical performance in older adults (32), limited data exist describing the effects of flywheel training on the muscle size (3), with no data on muscle quality. Muscle quality is widely assessed using noninvasive and easily accessible ultrasound-derived measures of muscle echo intensity, whereby a greater echo intensity is associated with increases in intramuscular infiltration of fibrous and adipose tissues (i.e., lower muscle quality) (7). Crucially, there is emerging evidence that echo intensity of the knee extensors is negatively associated with mobility (i.e., timed up and go test) and physical function (i.e., 30 seconds sit-to-stand [STS]) in older adults (35,44). Therefore, exercise strategies which target muscle quality may be crucial for preserving physical function and reducing fall-risk among older adults.

Therefore, the purpose of this study was to extend previous findings beyond the regular physical outcomes (i.e., timed up-and go [TUG], STS, and postural sway) and determine the effects of a 6-week flywheel eccentric overload training program on vastus lateralis (VL) and gastrocnemius medialis (GM) muscle thickness and muscle quality compared with a control group. We hypothesized that flywheel resistance training with eccentric overload would elicit significant increases in muscle size and quality, and significantly improve performance in mobility (TUG) and physical function (STS), while eliciting significant reductions in postural sway, an important predictor of future falls (15).

Methods

Experimental Approach to the Problem

This study was designed to test the efficacy of a novel mode of exercise training on physical functional performance and muscle mass/quality in healthy older adults. This was a nonrandomized controlled (training vs. control group) trial, with assessment of outcomes at baseline (preintervention) and after an exercise-training program (postintervention). After familiarization and before group allocation, baseline measurements were completed during a single session with a minimum of 72 hours but not more than 7 days before the first training session. All outcome measures were undertaken before and after training (the control group were asked to continue with their normal habitual physical activity levels but not commence any new exercise training interventions) at the same time of the day (±1 hour) to minimize the potential impact of circadian rhythms. Outcome measures were performed in the following order: (a) muscle thickness and quality, (b) static balance, and (c) physical function (detailed below). To account for biological variation, all outcome measures were assessed 3 times (within-session) to determine reliability. Postintervention outcomes were measured 3–7 days after the final training session. All testing and training were performed by the same investigator.

Subjects

Effect sizes (Cohen's d) were calculated from similar studies from mean changes in plantar flexor muscle thickness ($d = 0.78$) (22), knee extensor echo intensity ($d = 1.20$) (34), 5 times STS ($d = 1.80$), TUG ($d = 2.0$) (9), anteroposterior postural sway ($d = 1.88$), and mediolateral postural sway [$d = 1.69$] (30). The sample size was estimated using an a priori power analysis (G*Power software [Version 3.1.9.4]) for plantar flexor muscle thickness (i.e., variable with the smallest effect size) using the following parameters (power = 0.80, alpha = 0.05, and effect size = 0.78) and revealed that a total of 10 subjects per group would be sufficient for finding statistically significant effects of flywheel training on physical function, mobility, static balance, muscle thickness, and muscle quality. To account for possible attrition (20%), 24 subjects were invited to the first screening stage after recruitment by word of mouth from a health and fitness center. During the training period, 3 subjects withdrew from the control group, and 2 subjects withdrew from the training group for unrelated personal reasons, with data analysis conducted on a final sample of 19 subjects (training = 11 and control = 8). A total of 19 community-dwelling older adults were included in the final analyses. Subjects were assigned to either a training (± SD; $n = 11$, 5 women, age [range: 60–68 years] = 66.4 ± 5.2 years, height = 1.7 ± 0.1 m, mass = 74.1 ± 13.1 kg, and body mass index [BMI] = 26.0 ± 2.9 kg·m^{-2}) or control ($n = 8$, 4 women, age [range 60–73 years] = 65.9 ± 3.8 years, height = 1.7 ± 0.1 m, mass 76.5 ± 11.3 = 1 kg, and BMI = 25.6 ± 2.8 kg·m^{-2}) group. Although we acknowledge that the efficacy of a training program can lead to biased and overestimated estimates of effects in nonrandomized designs, given the exploratory and pragmatic nature of the study, we chose to allocate subjects to the training or control groups based on subject's individual preferences. Subjects were moderately active (IPAQ; training group = 3.1 ± 1.3 h·wk^{-1}, control = 3.0 ± 0.8 h·wk^{-1}) and reported low concern about falling during physical and social activities (Falls Efficacy Scale [FES-I]; training group = 17.5 ± 1.9, control = 18.0 ± 2.0). All subjects had been a member of a fitness center for the previous 6 months and were involved in endurance and resistance exercise at least twice a week. Before enrollment, all interested subjects completed a health screening questionnaire to identify any contraindications that could affect their ability to perform the required exercise training and testing. Inclusion criteria were as follows: (a) community-dwelling men and women aged >60 years who had no history or fear of falling, determined by the FES-I, (b) being capable of walking without the use of an assistive device, and (c) and being physically active (defined by meeting the American College of Sports Medicines physical activity recommendations of a minimum 150 min·wk^{-1} moderate intensity physical activity; (28)). The 16 item FES-I was used as a self-reported questionnaire to measure concern about falling during physical and social activities on a 4-point Likert scale (1 = not at all concerned to 4 = very concerned). Scores of 16–19, 20–27, and 28–64 indicate low, moderate, and high concern about falling, respectively (4).

Exclusion criteria included being unable to stand unassisted and any history of neurological (e.g., stroke and Parkinson's), musculoskeletal (e.g., tendinitis), severe cognitive problems (e.g., dementia), and/or cardiovascular or pulmonary diseases (e.g., coronary heart disease, chronic obstructive pulmonary disease) that prevented their ability to exercise safely. Given the high prevalence of osteoarthritis in adults over 65 years, individuals who self-reported to lower extremity osteoarthritis were not excluded from the study. After ethical approval (P79002) by the Coventry University Ethical Review Board and before conducting the experiment, all subjects gave their written informed consent. All risks associated with the experimental procedures were explained before testing began with the study conducted in accordance with the guidelines outlined in the Declaration of Helsinki (1964).

Procedures

The thickness of the VL and GM muscles were recorded using B-mode ultrasound imaging (LOGIQ Book XP; General Electric, Bedford, United Kingdom) and a wide-band linear probe (8L-RS; General Electric) with a 39-mm wide field of view and coupling gel (Ultrasound gel, Dahlhausen, Cologne, Germany) between the probe and skin. To ensure consistent imaging of the right VL (RVL) and left VL (LVL) between trials, subjects were seated in a chair with hips and knees at 90°, with the shod feet flat on the floor and heels resting against the chair leg. A tape measure (Korbond, Lincolnshire, United Kingdom) was used to enable the positioning of the probe midthigh, inline, and equidistant from the lateral proximal border of the patella to the greater trochanter. The probe was then manipulated until the superficial and deep aponeuroses could be visualized enabling longitudinal imaging of the VL muscle. To ensure consistent imaging of the right and left GM (LGM) (right GM [RGM]), subjects remained seated with one knee fully extended and the foot in the anatomical position resting against a wall. The GM-Achilles muscle tendon junction (MTJ) was visualized using ultrasound, and the probe was then positioned equidistant from the popliteal fossa and the MTJ, and the probe then manipulated until the superficial and deep aponeuroses could be visualized enabling longitudinal imaging of the GM muscle. Three images (with the probe removed and replaced) were recorded at rest on both the left and right VL and GM muscles with muscle thickness measured at the center of the image from the superficial to deep aponeurosis, with the average of 3 measurements used in subsequent analysis.

To assess muscle quality, the 3 images were recorded with ultrasound settings standardized (frequency: 8 MHz, gain: 34 dB, and dynamic range: 81, depth: 4 cm) across subjects and then exported to a photo editing software (ImageJ, LOCI, University of WI) where a polygon region of interest was drawn using the imaging software bordering the VL and GM superior and deep aponeuroses and lateral edges of the ultrasound images (12). Echogenicity was used to determine muscle quality by converting the ultrasound images to a grayscale histogram with values ranging from 0 to 255 arbitrary units within the ultrasound image used to calculate the mean grayscale histogram within the muscle (37), with lower values signifying greater muscle quality and function (43). The mean echogenicity from 3 images for each muscle was used in subsequent analyses. The same technician performed all scans.

Center of pressure (COP) measures of postural sway served as a measure of balance performance. Subjects performed six 30 seconds quiet standing trials on a force platform (AMTI, Accu-Gait, Watertown, MA) under 2 alternating visual conditions (eyes open and eyes closed [EC]) in a counterbalanced order. Subjects practiced each postural task 3 times before recorded trials. To ensure continuity during trials, unshod foot position was standardized by instructing subjects to stand with the feet together (i.e., Romberg stance). Subjects' hands were clasped together in front of their body and were instructed to look straight ahead at a target 1.5 m away, which was adjusted to the eye level of each individual. Ground reaction force data were sampled at 100 Hz (AMTI, Netforce, Watertown, MA) and filtered with a fourth-order low-pass (6 Hz) Butterworth filter (BioAnalysis, V2.2, AMTI). The total displacement of COP in the anteroposterior and mediolateral directions (both cm) and mean COP velocity ($cm{\cdot}s^{-1}$) were subsequently calculated (AMTI, BioAnalysis, Version 2.2). The amplitude of displacement reflects the distance between the maximum and minimum COP displacement for each direction (where the greater the value, the worse the postural stability), whereas the mean COP velocity reflects the efficiency of the postural control system (the smaller the velocity, the better the postural control). The means of the 3 trials in each condition were used in the subsequent analysis.

After the postural control assessment, subjects completed the Timed Up and Go Test (TUG), as described by Podsiadlo and Richardson (33). Subjects were instructed to stand up from a chair without using their hands, walk 3 m as safely as possible, walk around a cone, and walk back to the chair and sit down. Subjects were asked to perform the TUG at their preferred walking speed. The time taken to complete the test was recorded using a stopwatch (nearest 0.01 seconds). A total of 3 trials were recorded, and the fastest trial was included in the subsequent analyses. Two minutes later, subjects completed the 30-second STS test (16). Subjects were instructed to sit down on a chair (seat height 45 cm) with arms folded across the chest and feet shoulder width apart. Subjects were required to stand up fully with complete knee and hip extension and sit down as quickly and as many times as possible within 30 seconds, with subjects verbally encouraged throughout the duration of the test. In addition to the total number of repetitions performed in the 30 seconds STS, the time taken for the first 5 repetitions was also recorded (2). The time taken to complete the test was recorded using a stopwatch (nearest 0.01 seconds). Among community-dwelling older adults, test-retest reliability (intraclass correlation coefficient [ICC]) of the TUG (ICC = 0.99; (33)), 30 seconds STS (ICC = 0.92; (16)) and 5 times STS (ICC = 0.89; (23)) is excellent.

Before starting the training program, subjects completed 2 familiarization sessions, involving harness fitting, explanation of safety precautions, and practicing exercises. The 6-week eccentric overload training program was performed twice weekly (totaling 12 sessions) on a flywheel device (Kbox 4, Exxentric AM TM, Bromma, Sweden), with a minimum of 48 h rest between each session. All training sessions were performed in a local fitness center and were supervised by a researcher, who was also an experienced and qualified personal trainer. All training sessions took place between 9:00 and 11:00 hours (morning session) and 13:00 and 15:00 hours (afternoon session). After a 5-minute warm-up involving submaximal contractions, subjects completed 4 sets of squats and calf raises, in that order. Subjects were instructed to contract as fast as possible with maximal effort during the entire ascent (concentric) phase and to maximally resist the pull during the descent (eccentric) phase where the flywheel strap rewound back, initiating the overload during the eccentric action, with strong verbal encouragement given during all repetitions. All subjects were reminded to resist gently during the first third of the eccentric phase, and apply maximal braking force

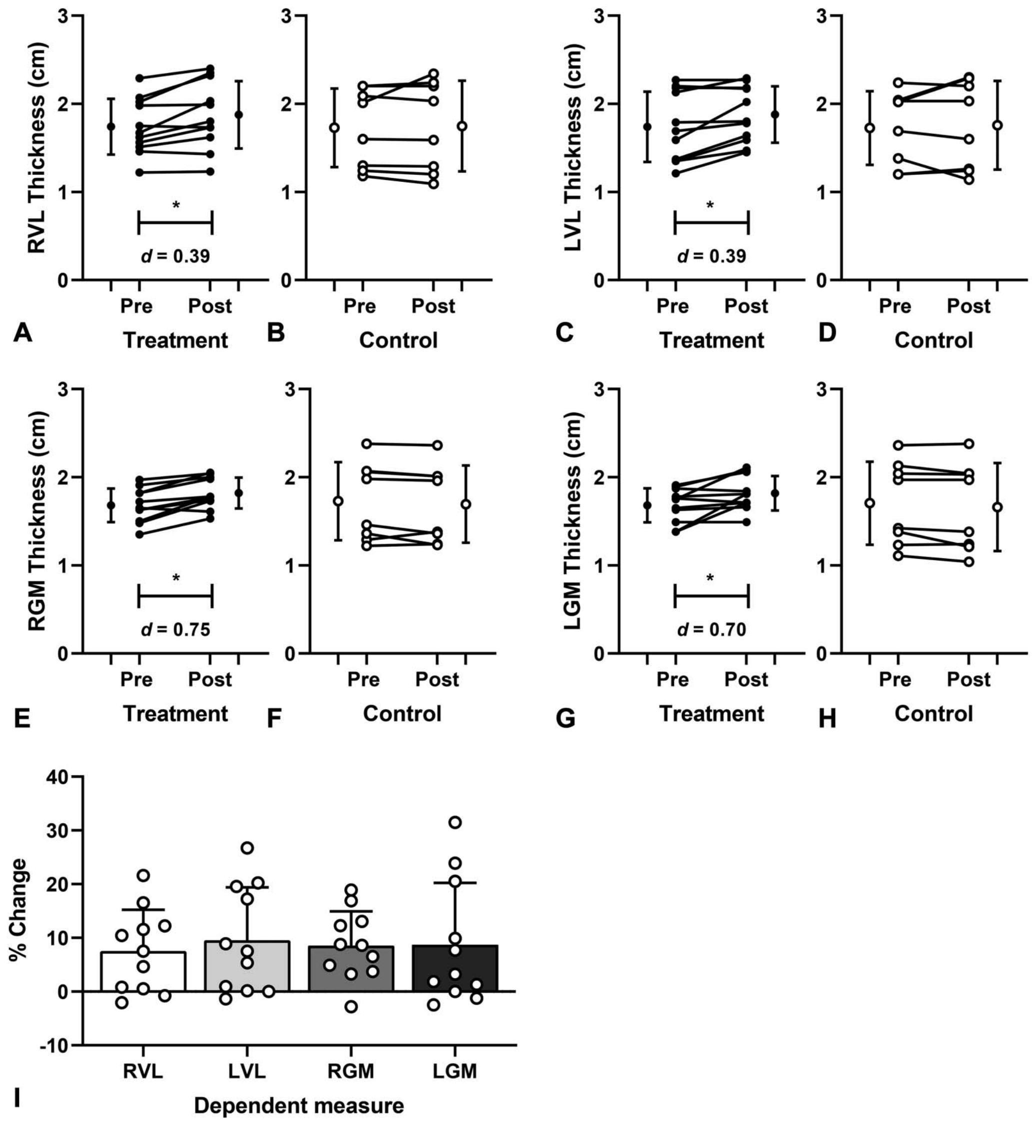

Figure 1. Mean ± *SD* and individual pretraining and post-training absolute values in muscle thickness of the (A and B) right vastus lateralis (RVL), (C and D) left vastus lateralis (LVL), (E and F) right gastrocnemius medialis (RGM), and (G and H) left gastrocnemius medialis (LGM) in the training and control groups, and (I) training group percentage change data. *Significantly different to pretraining ($p < 0.05$).

thereafter, allowing for eccentric overload. The KBox was initially equipped with a flywheel inertial load of 0.025 $kg{\cdot}m^{-2}$, which was increased by 0.025 $kg{\cdot}m^{-2}$ every other week (i.e., final inertial load of 0.075 $kg{\cdot}m^{-2}$) to ensure adequate overload and progression. We also progressively increased the inertial load to avoid the risk of an excessively high velocity concentric phase of the movement and to reduce the risk of muscle damage. The number of contractions was also sequentially incremented from 8 repetitions for the first 2 weeks, 10 repetitions for the second 2 weeks, and 12 repetitions for the final 2 weeks. Before each set, subjects completed 3 prerepetitions (not included in prescribed rep ranges) to accelerate the flywheel to the desired speed. All repetitions were completed with subjects holding onto a secure structure for balance. To determine weekly training intensity, the average power (W), concentric peak power (W), and eccentric peak power (W) were calculated and recorded using the kMeter 2 app (version 2.3; Exxentric). After each set, subjects were asked to rate their perceived exertion from 0 to 10 using the CR-10 rating of perceived exertion (RPE) scale, with the average of the 4 sets used to determine weekly RPE. A minimum of 80% of exercise program compliance was required for subjects to be included in the final statistical analyses. Subjects in the training group were asked to refrain from strenuous physical activity and caffeine/alcohol consumption 12 hours before training sessions. The control group were asked to continue with their normal training that they were involved in before the experimental period (accumulating a minimum 150 $min{\cdot}wk^{-1}$ moderate intensity physical activity).

Statistical Analyses

All data were analyzed using Statistical Package for the Social Sciences version 25.0 (IBM, Chicago, IL) and reported as mean ± *SD*, including individual responses. For all analyses, normal distribution (Shapiro–Wilk test) and homogeneity of variance (Levene's test) were determined before parametric tests. All outcome measures were then analyzed using separate 2-way mixed-model analysis of variance (ANOVA) to determine the within-subject effects of time (×2 [pre vs. post]) and between-subject effect of group (×2 [treatment vs. control]). Where appropriate, Bonferroni post-hoc analyses were conducted to determine comparisons that were statistically significant. Effect sizes are reported as partial eta-squared value (η_p^2) for ANOVA, and where appropriate, Cohen's *d* is reported for pairwise comparisons and were interpreted as trivial (0–0.19), small (0.20–0.49), moderate (0.50–0.79), and large (>0.80). The alpha value was a priori set at $p < 0.05$.

Reliability

Test-retest reliability was calculated for all outcomes to ensure that any observed differences after training represent a real physiological change, rather than random or systematic error in the measurement procedure. Within-session reliability was examined using ICCs and coefficients of variation (CV) during pretraining experimental session between the second and third trials. No significant differences ($p > 0.05$) were detected in TUG time, or any measure of postural sway, muscle thickness, or muscle quality. High ICCs and low-to-moderate CV were calculated for TUG (ICC = 0.97, CV = 2.0%), postural sway (ICC = 0.84 to 0.97, CV = 4.9–11.1%), muscle quality (ICC = 0.96–0.97, CV = 1.30–1.99%), and muscle thickness (ICC = 0.98–1.00, CV = 1.19–1.83%). Given that subjects completed only one STS test before training (because of the fatigue), within-session reliability could not be reported for this outcome.

Results

Muscle Thickness

The 2-way mixed model ANOVA revealed a significant group × time interaction for RGM ($F_{(1,17)} = 19.268$, $p < 0.001$, $\eta_p^2 = 0.531$) and LGM ($F_{(1,17)} = 8.108$, $p = 0.011$, $\eta_p^2 = 0.323$) muscle thickness, and a main effect of time for RVL ($F_{(1,17)} = 6.073$, $p = 0.025$, $\eta_p^2 = 0.263$) and LVL ($F_{(1,17)} = 5.602$, $p = 0.030$, $\eta_p^2 = 0.248$) thickness. Post-hoc within-subject analyses revealed compared with pretraining, significant ($p < 0.001$) increases in RVL (7.6 ± 7.7% [1.36 ± 1.38 mm], *d* = 0.39), LVL (9.6 ± 9.8% [1.39 ± 1.43 mm], *d* = 0.39), RGM (8.6 ± 6.4% [1.38 ± 0.95 mm], *d* = 0.75), and LGM (8.7 ± 11.5% [1.36 ± 1.69 mm], *d* = 0.70) thickness after flywheel training (Figure 1). There were no changes in muscle thickness in the control group ($p > 0.05$). There were no differences in pretraining muscle thickness between the control and the training group ($p > 0.05$).

Muscle Quality

The 2-way mixed-model ANOVA revealed a significant group × time interaction for RVL ($F_{(1,17)} = 11.761$, $p = 0.003$, $\eta_p^2 = 0.409$), LVL ($F_{(1,17)} = 25.945$, $p < 0.001$, $\eta_p^2 = 0.604$), RGM ($F_{(1,17)} = 31.886$, $p < 0.001$, $\eta_p^2 = 0.652$), and LGM ($F_{(1,17)} = 9.270$, $p = 0.007$, $\eta_p^2 = 0.353$) muscle quality. Post-hoc within-subject analyses revealed a significant ($p < 0.001$) reduction in RVL (−10.2 ± 7.9% [9.2 ± 7.0], *d* = 1.34), LVL (−11.3 ± 5.9% [9.8 ± 5.3], *d* = 1.65), RGM (−11.7 ± 5.6% [9.7 ± 5.0], *d* = 1.06), and LGM (−11.9 ± 9.6% [9.8 ± 7.9], *d* = 1.03) echogenicity after flywheel training (Figure 2). There were no changes in muscle quality in the control group ($p > 0.05$). There were no differences in pretraining muscle quality between the control and the training group ($p > 0.05$).

Postural Sway

Significant group × time interactions for postural sway outcomes were observed during EC conditions alone (Table 1). Follow-up post-hoc analyses indicated significant ($p < 0.05$) reductions in mediolateral COP displacement, anteroposterior COP displacement, and mean COP velocity (with the EC after flywheel training). There were no changes in postural sway in the control group ($p > 0.05$). There were no differences in pretraining postural sway metrics between the control and the training group ($p > 0.05$).

Mobility and Physical Function

The 2-way mixed model ANOVA revealed a significant group × time interaction for TUG ($F_{(1,17)} = 20.022$, $p < 0.001$, $\eta_p^2 = 0.541$), 5 times STS ($F_{(1,17)} = 22.546$, $p < 0.001$, $\eta_p^2 = 0.570$), and 30 seconds STS ($F_{(1,17)} = 22.761$, $p < 0.001$, $\eta_p^2 = 0.572$). Post-hoc within-subject analyses revealed a significantly faster TUG (−13.7 ± 7.0% [0.88 ± 0.53 seconds], *d* = 1.27), faster time to reach 5 STS cycles (−17.8 ± 7.5% [2.47 ± 1.45 seconds], *d* = 1.45), and more STS cycles in 30 seconds (23.5 ± 13.4% [3 ± 1 cycles], *d* = 1.27) after 6 weeks of flywheel training (all $p < 0.001$) (Figure 3). There were no differences in pretraining physical function and mobility between the control and the training group ($p > 0.05$).

Training Responses

From the first to the final training session, there were statistically significant mean increases in concentric (183–237%), eccentric (229–236%), and average (233–260%) peak power output ($p < 0.05$) during the squat and calf raise exercises (Figure 4). There was also a significant reduction in repetition time from the first to the final training session for both the squat (−41%) and calf raise (−40%). Overall adherence (number of training sessions/total number of session) was 95%, and all subjects met the 80% exercise program compliance threshold. There were no changes in habitual physical activity levels in either the control or exercise group ($p > 0.05$).

Discussion

Few studies have investigated the effects of a practical, eccentrically biased exercise training program on balance, mobility, physical function, and muscle thickness among older adults, and none have examined muscle quality. Three important findings emerged from the present investigation: (a) the thickness and quality of the VL and GM muscles increased considerably after 6 weeks of flywheel training, (b) the training also provoked a substantial improvement in mobility (i.e., TUG) and physical function (i.e., STS), and (c) there were marked reductions in postural sway with the EC. These findings support the efficacy of using flywheel training with eccentric overload in older adults as a means to enhance physical function, balance, mobility, and muscle mass and muscle quality.

Low muscle mass (1) and poor muscle quality (8) are associated with fall risk, therefore identifying exercise strategies that can

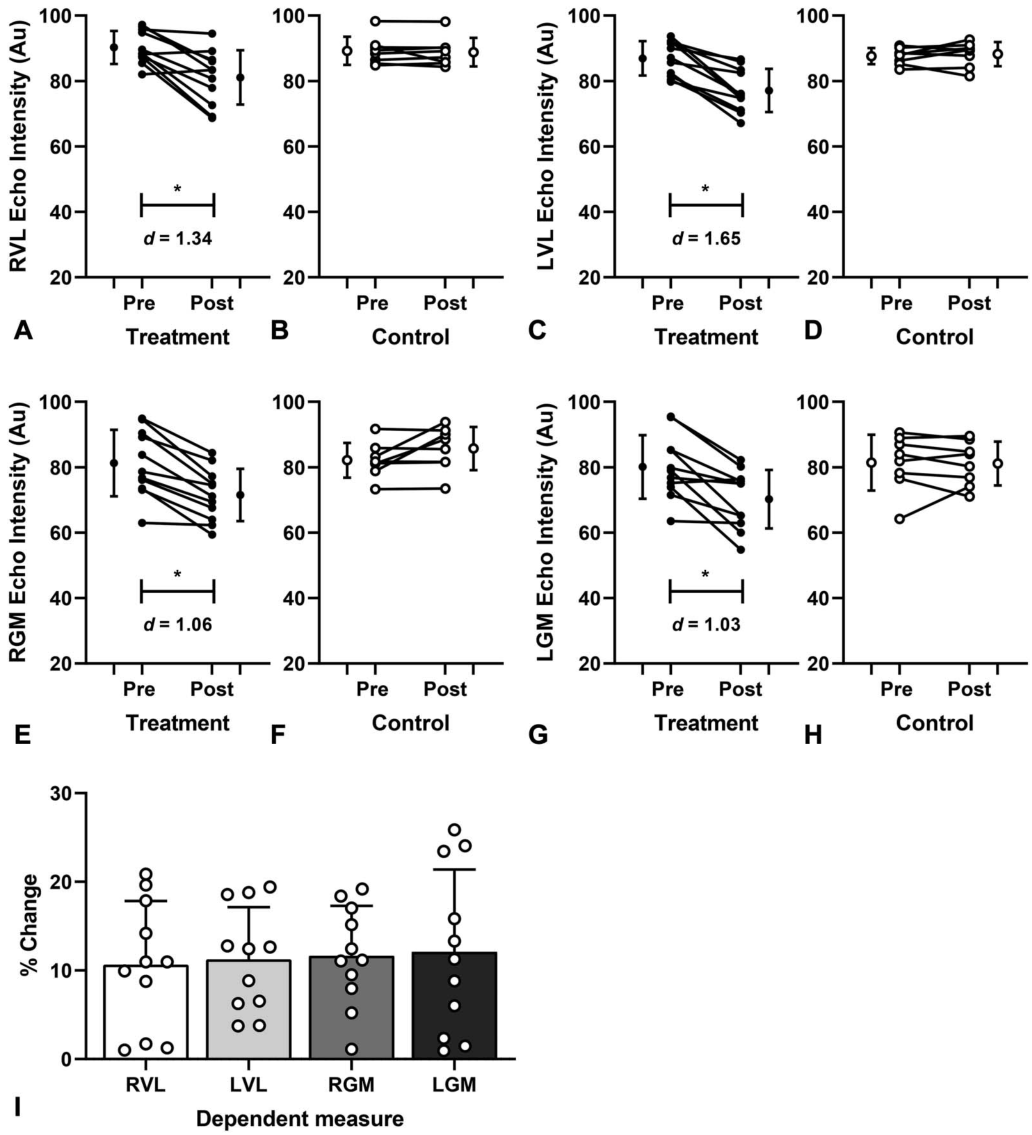

Figure 2. Mean ± *SD* and individual pretraining and post-training absolute values in echogenicity (muscle quality) of the (A and B) right vastus lateralis (VL) (RVL), (C and D) left VL (LVL), (E and F) right gastrocnemius medialis (RGM), and (G and H) left gastrocnemius medialis (LGM) in the training and control groups, and (I) training group percentage change data. *Significantly different to pretraining ($p < 0.05$).

limit or even reverse these losses is a priority in aging research. In accordance with our hypothesis, considerable gains in muscle thickness (~7–10%) were detected after 6 weeks of flywheel training with eccentric overload. These findings are consistent with the increases in VL muscle thickness previously observed in older adults after 14 weeks of eccentric resistance training (~12% (36)). More recently, Bruseghini et al. (3) found that 8 weeks of seated knee extension flywheel training elicited significant

Table 1

Mean (*SD*) postural sway outcomes measured pretraining and post-training in the treatment and control group.*

	Training group			Control group		Group × time ANOVA		
Outcome	Pretraining	Post-training	*d*	Pretraining	Post-training	F	*p*	η_p^2
EO ML sway (cm)	2.86 ± 0.65	2.26 ± 0.58†	0.97	2.90 ± 0.58	3.02 ± 0.80	3.747	0.070	0.181
EC ML sway (cm)	3.04 ± 0.70	1.92 ± 0.44†	1.93	3.11 ± 0.34	2.97 ± 0.58	7.380	0.015	0.303
EO AP sway (cm)	2.28 ± 0.52	2.24 ± 0.46	0.08	2.39 ± 0.40	2.54 ± 0.60	0.233	0.636	0.013
EC AP sway (cm)	3.34 ± 0.75	1.86 ± 0.36†	2.50	3.38 ± 1.19	3.38 ± 1.36	23.955	0.001	0.585
EO velocity ($cm \cdot s^{-1}$)	2.55 ± 0.38	2.75 ± 0.37	0.54	2.55 ± 0.08	2.62 ± 0.14	0.268	0.611	0.016
EC velocity ($cm \cdot s^{-1}$)	2.85 ± 0.78	1.95 ± 0.44†	1.42	2.29 ± 0.50	2.20 ± 0.28	7.340	0.015	0.302

*ANOVA = analysis of variance; EO = eyes open; EC = eyes closed; ML = mediolateral; AP = anteroposterior.
†Significantly different to pretraining ($p < 0.001$).

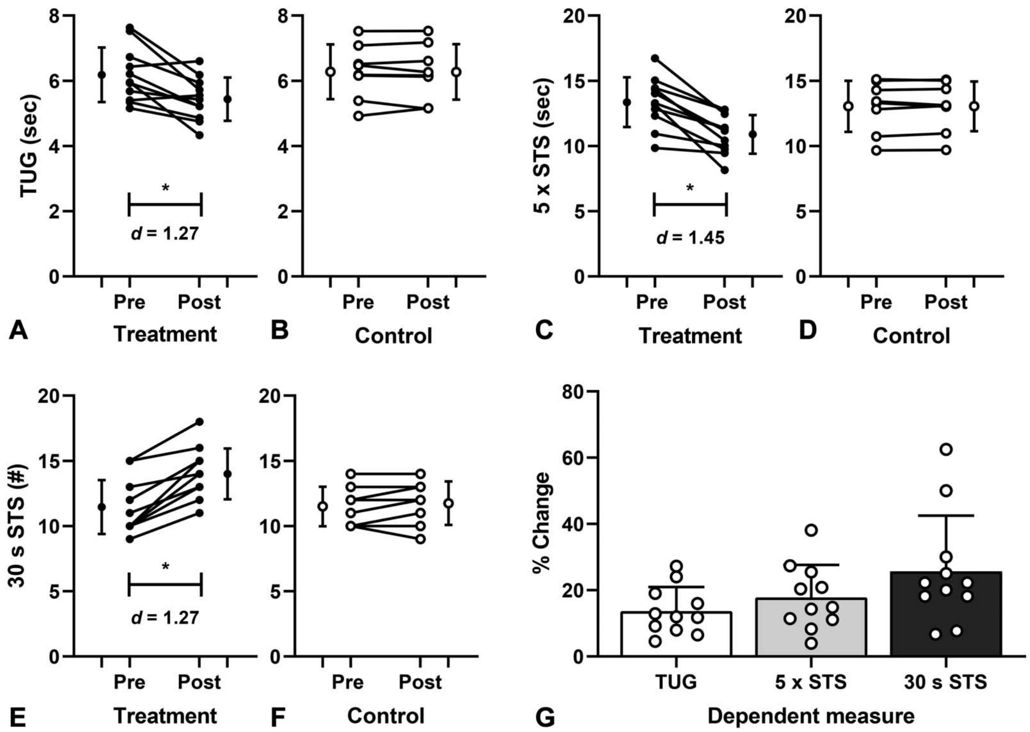

Figure 3. Mean ± *SD* and individual pretraining and post-training absolute values in (A and B) Timed Up and Go (TUG), (C & D) 5 × sit-to-stand (sit to stand [STS]), (E and F) 30 seconds STS and (G) percentage changes for each outcome in the treatment group. *Statistically significant difference to pretraining ($p < 0.05$).

increases in quadriceps muscle volume (using magnetic resonance imaging) in older adults. This study extends these findings in 2 important ways. First, changes in muscle thickness of the GM, an important muscle for balance control were also examined, and a second was the examination of muscle quality. A significant improvement in muscle quality (~10–12%) was observed after

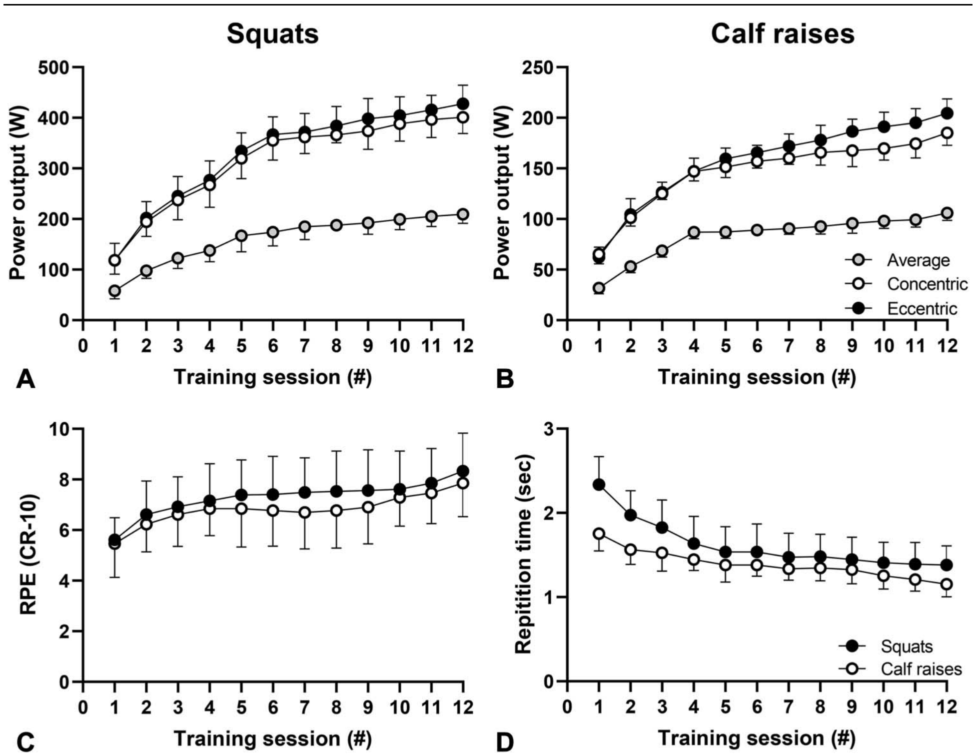

Figure 4. Mean ± *SD* training session data for (A) squat power output, (B) calf raise power output, (C) rating of perceived exertion (RPE), and (D) repetition time.

flywheel training (deduced from the reduction in echo intensity), data consistent with previous studies using longer durations (13 weeks) of traditional strength training programs (13–14% (34)). This study is the first to report an increase in muscle quality after flywheel exercise with eccentric overload among older adults. Muscle quality is a key determinant of muscle function in later life (26) and is associated with previous falls in older adults (8). Muscle quality is now widely assessed using noninvasive and easily accessible ultrasound-derived measures of muscle echo intensity, whereby a greater echo intensity is associated with increases in intramuscular infiltration of fibrous and adipose tissues (i.e., lower muscle quality) (7). Multiple mechanisms may account for the increase in muscle quality after strength training, including an increase in contractile proteins, cross sectional area, muscular power, resting fascicle length (i.e., addition of sarcomeres in series), and/or a reduction in intramuscular fat deposits (6). It is important to note that an increase in echo intensity (i.e., lower muscle quality) could be related to an accumulation of inflammatory cells between muscle fibers and a decrease in muscle glycogen (45). However, we do not believe this was the case in the current study because we observed a reduction in echo intensity and study outcomes were measured 1 week after the final training session so any residual effects of training would be removed. Our results would align with the general consensus in the literature that a decrease in echo intensity corresponds to an increase in muscle strength per unit of muscle mass. These findings have important implications for exercise prescription as they demonstrate that muscle mass and muscle quality can be substantially improved in older adults with the use of a practical, portable, and relatively low volume of exercise training.

Flywheel training elicited substantial improvements in mobility (TUG; 14%) performance, which is inconsistent with previous research reporting significant improvements in TUG after 6 weeks of flywheel training (~13% (40)) and other studies involving eccentrically-biased exercise training among older adults (5–29% (9,19)). Given that individuals recording TUG times of >13.5 seconds have a 90% probability of being a faller (41), any exercise that reduces TUG time and prevents individuals from entering the high-risk category should be welcomed. Novel to this study was the assessment of STS performance. In agreement with our hypothesis, a reduction in the time taken to complete 5 STS cycles (~18%) and an increase in the number of STS cycles completed in 30 seconds (~24%) was observed after flywheel training. These results are in agreement with previous research that found a significant decrease in the time it took to complete 5 chair rises (~−18% (21)) and the number of STS cycles performed in 30 seconds (~24% (32)) after traditional strength training. Overall, flywheel training composed of concentric and eccentric muscle actions is able to counteract the loss of mobility and physical function (rising from a chair), both of which are major clinical and physiological issues affecting activities of daily living and independence in older adults.

The magnitude of reduction in postural sway in the current investigation (~60–80% with the EC) is of particular interest when compared with previous studies. Previous systematic reviews (31) and meta-analyses (24) have reported strength exercise interventions did not influence postural sway in older adults. A primary criticism of resistance-based training studies is that the exercises are performed in the seated position that does not involve body movements that stress, and therefore improve, standing balance ability. By contrast, previous studies examining the effects of seated (30) and standing (40) flywheel eccentric overload training in older adults, have reported modest reductions (16–27%) in postural sway during quiet standing. The larger reductions in postural sway reported in this study are likely related to the inclusion of plantar/dorsiflexor exercises. Previous studies have adopted squat (40) or seated knee extensions (30) exercise which are likely to target the hip and knee extensors, respectively. In addition to the squat exercise, this study also included calf raises. This is important because humans need to generate appropriate torques at the ankle joint to control postural sway while standing upright. The large magnitude reductions in postural sway reported here (d = 0.97–2.50) are encouraging given that increased postural sway has been shown to be predictive of future falls (15). Overall, flywheel training seems to be effective in constraining postural sway to a smaller displacement (i.e., area) and lower movement velocity (30,40), and the effects seem to be more pronounced than traditional resistance training (24,31). It seems plausible that adding an eccentric overload phase to traditional resistance training and targeting the ankle musculature increases the potential of achieving postural adaptations.

Our study should be interpreted with the recognition that potential limitations exist. First, given the pragmatic and exploratory nature, the current study was a nonrandomized control trial. As noted previously, we acknowledge that nonrandomized designs can lead to biased and overestimations of effects because of unequal distribution of confounding factors. However, it should be noted that baseline characteristics between groups were similar for all the measured variables. In addition, nonrandomized designs are now widely accepted as quasi-experimental design that can contribute important data on the efficacy of exercise interventions (5). Moreover, quasi-experimental designs that use a control group are considered to be the soundest of nonrandomized studies with respect to determining causality (11). Second, this was an exploratory trial involving only a small number of healthy community-dwelling older adults. The homogeneity of our small sample precludes us from generalizing our findings to frail or institutionalized older adults at greater risk of falls. However, it could also be argued that the subjects' homogeneity may have limited the influences of confounding demographic variables. Nonetheless, the effects of flywheel training on the outcomes reported here would be more clearly ascertained with a further definitive trial involving a larger and functionally diverse group. Third, the lack of a parallel training group performing traditional resistance exercise may preclude observations being drawn relating to whether flywheel training adds further value as an exercise intervention, given that traditional resistance exercise is often prescribed to older adults as a safe and appropriate way to exercise. Finally, we did not include any other factors that may have contributed to improvements in functional ability, such as direct measures of muscle strength or power. It is also important to note that one of the main drawbacks of isoinertial devices modality is that the ability to accentuate resistance during the eccentric phase is determined by the effort applied and/or power generated during the concentric contraction. Therefore, the improved balance and mobility outcomes after flywheel training reported here may be a result of the high-intensity nature of exercise on a flywheel device, rather than the eccentric overload component. For example, assuming that effort is maximal, all repetitions produce maximal loading through the full range of motion of the concentric contraction (42). Crucially, previous research (31) has indicated that high-intensity training may best deliver the stimulus required to increase muscle strength and to elicit neuromuscular benefits to enhance balance performance.

Practical Applications

Eccentric exercise training has received a growing interest over the last decade, particularly in light of the substantial improvements in muscle mass and strength. Because of the preservation of maximal eccentric force–generating capacity in older adults, in addition to the low energetic cost attributes, eccentric exercise is ideally suited to older adults (19). However, eccentric exercise training typically used in human studies requires the use of expensive equipment, such as dynamometers or machine-driven ergometers. Although this type of exercise training can be undertaken in the research environment, it is impractical in locations where the general population typically exercises (i.e., fitness centers or in the home). Flywheel training may offer a more practical way of obtaining an eccentric overload stimulus while also providing an accessible form of eccentric training, which may have important implications for exercise prescription targeting the preservation of functional capacity of older adults. Flywheel exercise with eccentric overload presents with several advantages compared with conventional gravity-dependent resistance training. First, flywheel devices offer the possibility of variable resistance. Unlike conventional resistance exercises that yield maximal effort only at the "sticking point" of the final repetitions of each set (17), isoinertial flywheels allow maximal effort from the first repetition and through the entire range of motion of the concentrate phase (42). Second, the use of a flywheel device to accentuate the eccentric contraction avoids many of the difficulties associated with traditional eccentric exercise programs (i.e., partner assistance, costly dynamometers, or machine-drive ergometers, inaccessible/nonportable). Finally, in this study, subjects were able to achieve substantial increases in concentric and eccentric peak power output (~230%), had a 100% completion rate, with those completing the program recording a 95% adherence to sessions. Collectively, these data point toward a well-tolerated exercise modality and are consistent with previous studies observing that eccentric exercise was well-tolerated in older adults and other individuals with cardiorespiratory impairments (19). As with any exercise, flywheel exercises are not without risk. First, given the high muscle forces that can be achieved during the eccentric phase, this exercise may cause temporary muscle damage. Muscle damage resulting from eccentric exercise can lead to muscle weakness, postural instability, and impaired physical function which can persist for several days, endangering older adult's safety during daily activities and potentially increase the risk of falls (13). Second, although coordination and technical demand of flywheel exercise may increase the risk of injury, the use of a harness and holding onto a secure structure for balance, as used in this study, likely reduces the technical skills necessary for proper movement execution. In addition, using a harness and/or hand rail may help to distribute the center of mass within the base of support throughout the movement, reducing the stress and strain on the lower back (i.e., during a squat). Overall, this study shows that flywheel training elicits substantial gains in muscle thickness and muscle quality, in addition to enhanced physical function, balance, and mobility performance among older adults.

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