MUSCLE ARCHITECTURE AND STRENGTH: ADAPTATIONS TO SHORT-TERM RESISTANCE TRAINING IN OLDER ADULTS

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ABSTRACT: *Introduction:* Muscle morphology and architecture changes in response to 6 weeks of progressive resistance training were examined in healthy older adults. *Methods:* In this randomized, controlled design, muscle strength, quality, and architecture were evaluated with knee extension, DEXA, and ultrasound, respectively, in 25 older adults. *Results:* Resistance training resulted in significant increases in strength and muscle quality of 32% and 31%, respectively. Cross-sectional area of the vastus lateralis increased by 7.4% ($p \leq 0.05$). Physiological cross-sectional area (PCSA) of the thigh, a composite measure of muscle architecture, was related significantly to strength ($r = 0.57$; $p \leq 0.01$) and demonstrated a significant interaction after training ($p \leq 0.05$). Change in PCSA of the vastus lateralis was associated with change in strength independent of any other measure. *Conclusions:* Six weeks of resistance training was effective at increasing strength, muscle quality, and muscle morphology in older adult men and women.

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Aging is associated with progressive loss of neuromuscular function that often leads to disability and loss of independence.[1] The term sarcopenia, loosely translated, describes a deficiency of flesh (muscle)[2] and is showcased by decreased total muscle cross-sectional area of approximately 40% between the ages of 20 and 60 years.[1] The current diagnosis of sarcopenia is arbitrary in the sense that an individual who has an appendicular skeletal muscle mass value of ≥2 standard deviations below that of an age-matched population may be classified as sarcopenic. Age-associated loss of muscle mass is often thought to be the cause of strength losses observed with increasing age. Muscle size and strength losses are believed to be associated with metabolic, physiological, and functional impairments.[3] These changes may be attenuated through regular physical activity for the purpose of preserving muscle quality and strength.

Abbreviations: 1RM, predicted 1 repetition maximum; BMI, body mass index; CON, control group; CT, computed tomography; DEXA, dual-energy X-ray absorptiometry; EI, echo intensity; L_f, fascicle length; LTM, lean thigh mass; MQ, muscle quality as relative strength; MT, muscle thickness; PANG, pennation angle; PCSA, physiological cross-sectional area; REI, relative echo intensity; RF, rectus femoris; ROM, range of motion; RPE, ratings of perceived exertion; RT, resistance training group

Key words: echo intensity; exercise; muscle quality; sarcopenia; ultrasonography

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Muscle function is determined by structure and morphology at the architectural level,[4] where the aging process leads to not only changes in muscle quantity, but also quality.[5] Magnetic resonance imaging is considered the "gold standard" for cross-sectional and muscle volume measures. However, due to the limited availability of magnetic resonance imaging (MRI), ultrasonography may be a more cost-efficient alternative that is both valid and reliable for assessing large individual human muscle.[6–9] Decreases in muscle quality that are observed commonly in sarcopenia include enhanced intramuscular adipose and connective tissue in addition to decreased lean muscle mass and contractile units.[10] These changes indicate that both muscle quantity and muscle quality can contribute independently to changes in muscle strength in older adults.[11] Muscle quality can be assessed using many methods, which may include relative strength (strength per unit of mass)[12] and muscle composition (relative measures of connective to contractile tissue).[5] Muscle quality can be assessed as echo intensity using ultrasound scanning, where an increase in the echo intensity of a muscle represents changes caused by increased intramuscular connective and adipose tissues.[11] Moreover, muscle architecture measures of cross-sectional area, fiber pennation angle, and fascicle length allow for calculation of physiological cross-sectional area (PCSA), a composite measure used to describe the structure–function relationship of muscle.[4] However, no consensus currently exists for methods to calculate PCSA. Some computations exclude variables important for description of the muscle structure–function relationship, such as pennation angle and muscle density.[13,14]

Physical exercise is known to result in changes in muscle mass and quality. Resistance training appears to offer greater benefits than aerobic endurance training for gaining muscle mass and improving efficiency of the neuromuscular system.[10] Evidence suggests that up to 20 years of strength and power losses may be attenuated through regular resistance training.[15] In addition, older adults have demonstrated that the neuromuscular system has the ability to respond to resistance training, which may compensate for not only

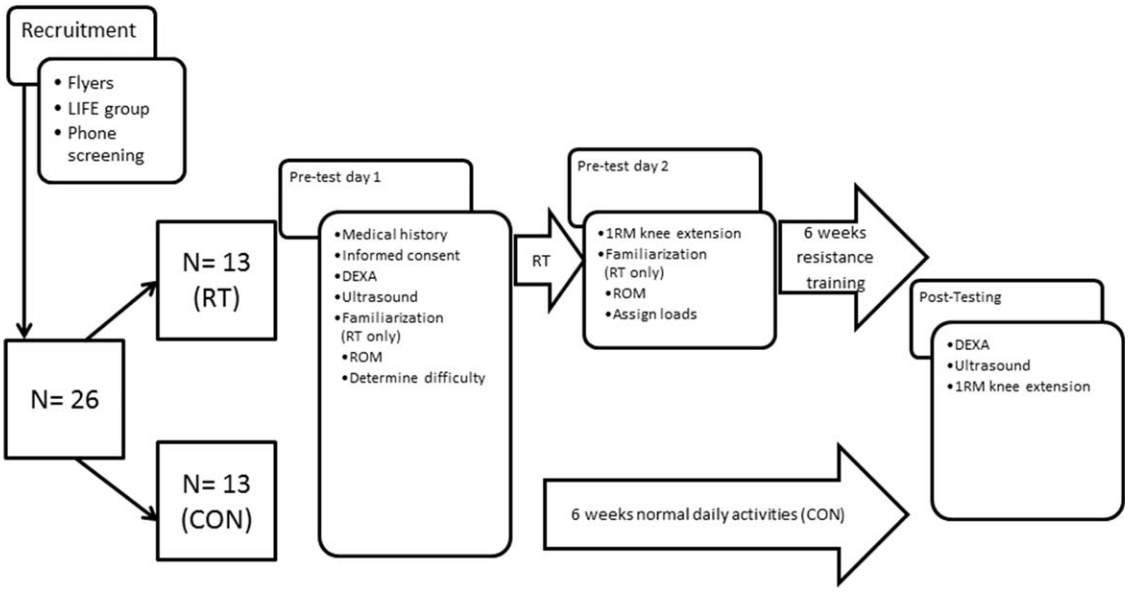

FIGURE 1. Experimental design of the study. Two testing sessions were separated by 6 weeks of resistance training or control. DEXA, dual-energy X-ray absorptiometry; ROM, range of motion; 1RM, predicted 1 repetition maximum.

muscle size and quality changes but also lead to greater functional capacities and a higher quality of life.[10] However, there are limited data regarding the effect of resistance training in older adults on muscle quality at the structural level. Furthermore, to our knowledge, no studies have examined the effects of short-term resistance training on echo intensity, and documented PCSA changes in older adults are limited. Therefore, the purpose of this study was to examine the effect of 6 weeks of progressive resistance training on muscle morphology and architecture in healthy older adults.

METHODS

Experimental Design. In this randomized, controlled design, volunteers were assigned randomly into exercise (RT) or control (CON) groups (Fig. 1). Exercise group participants began 6 weeks of progressive resistance training immediately after baseline pre-testing, during which range of motion (ROM) was assessed, 1RM knee extension was determined, and participants were familiarized with exercises. CON group participants served as non-exercise controls for 6 weeks. All participants were tested on 2 occasions separated by 6 weeks. Each testing session included body composition assessment, and size and architecture assessment of the lower limb musculature. All participants were required to complete an informed consent document approved by the university institutional review board.

Participants. Twenty-six healthy men ($n = 13$) and women ($n = 13$) >60 years of age were recruited to participate in the study on the basis of consent and health status. Participants were assigned randomly to experimental or control groups balanced by gender. Sample size was based on work by Frontera *et al.*,[22] who reported a total of 25 older men in a study of responses to resistance training at 6 and 12 weeks. Initial eligibility was assessed by a scripted phone screening. Participants aged 60–69 years of age were required to have had no positive risk factors on the administered physical activity readiness questionnaire; those ≥70 years of age were required to obtain physician clearance. Body mass index for men must have been >20 but no more than 35, and body mass index for women must have been >18 but no more than 37. Participants had to be ambulatory, agree to maintain current physical activity level, and must have had the ability to visit the university for testing and training. Any individual was excluded from participation for the following: classified as "high risk" by having cardiovascular, pulmonary, or metabolic disease or having 1 or more of the following: undergone major surgery <16 weeks prior to enrollment; stated immunodeficiency disorder; stated presence of partial or artificial limb; known dementia; brain metastases; eating disorder; or history of significant psychiatric or psychological condition that may have interfered with the study. Additional exclusion criteria were for individuals who were: currently taking medications or substances that could modulate metabolism profoundly; participating regularly in any strength or resistance training program in the past 3 months; or considered unfit for participation by the study investigators.

Body Composition. Total and regional body composition was evaluated using dual-energy X-ray absorptiometry (DEXA), providing measures of lean and fat mass. Lean thigh mass (LTM, in kilograms) was obtained by isolating a region of interest that included the thigh and excluded the lower leg and all other tissues of the dominant leg. All DEXA scans were ordered by a licensed physician in the state of Florida and performed at the Faculty Wellness Center by a licensed radiology technician. LTM reliability coefficients (ICCs) were 0.98 (SEM = 0.261 kg) and were determined by measuring 12 participants separated by 6 weeks.

Ultrasonography. Non-invasive skeletal muscle ultrasound images of rectus femoris and vastus lateralis architecture were collected. This technique uses sound waves at fixed frequencies to create real-time images of the limb musculature *in vivo*. Participants reported to the Human Performance Laboratory for ultrasound measurements after 72 hours without any vigorous physical activity. They were instructed to lay supine for 15 minutes to allow fluid shifts to occur before images were collected. A 12-MHz linear probe scanning head (LOGIQ P5; General Electric Wauwatosa, Wisconsin) was used to optimize spatial resolution and was coated with water-soluble transmission gel and positioned on the skin surface to provide acoustic contact without depressing the dermal layer to collect the image. Measures of muscle thickness (MT) and pennation angle (PANG) were taken using B-mode ultrasound. Measures of cross-sectional area (CSA) and fascicle length (L_f) were obtained using a sweep of the muscle in the extended field of view mode with gain set to 50 dB and image depth to 5 cm.[5] All measures were taken in both the rectus femoris and vastus lateralis of the dominant leg. Subsequent measures were taken using the same limb positioning and anatomical site and were performed by the same examiner. After scanning, all images were analyzed offline with image analysis software (ImageJ, version 1.45s) available from the National Institutes of Health (NIH, Bethesda, Maryland), which quantifies muscle quality in the form of echo intensity (EI). A known distance of 1 cm as shown in the image was used to calibrate the software program.[16] For measures of rectus femoris, the participant was placed supine on an examination table, according to the American Institute of Ultrasound in Medicine, with the legs extended but relaxed and with a rolled towel beneath the popliteal fossa allowing for a 10° bend in the knee as measured by a goniometer.[17] For measures of the vastus lateralis, participants were placed on their non-dominant leg side with the legs together and relaxed to allow a 10° bend in the knee as measured by a goniometer. ICCs for ultrasound measures were determined from 10 participants separated by at least 24 hours unless otherwise noted.

Cross-Sectional Area. The measurement of rectus femoris CSA was taken in the sagittal plane parallel to the long axis of the femur, and scanning occurred in the axial plane perpendicular to the tissue interface at 50% of thigh length. Fifty percent of thigh length was determined as halfway from the anteroinferior iliac spine to the proximal border of the patella. Vastus lateralis CSA was measured at 50% of the distance from the most prominent point of the greater trochanter to the lateral condyle. For both muscles, 3 consecutive CSA images were analyzed and averaged using the polygon tracking tool in the ImageJ software to obtain as much lean muscle as possible without any surrounding bone or fascia (Fig. 2A and B). The ICCs for rectus femoris and vastus lateralis CSA were 0.99 (SEM = 0.46 cm^2) and 0.99 (SEM = 1.26 cm^2), respectively.

Muscle Thickness. Measures of MT were taken at the same site described for CSA but with the probe oriented longitudinal to the muscle tissue interface for both the rectus femoris and vastus lateralis. Within each muscle, MT was measured perpendicularly from the superficial aponeurosis to the deep aponeurosis (Fig. 2D). Three consecutive images were analyzed and averaged offline.[8] ICCs for rectus femoris and vastus lateralis MT were 0.96 (SEM = 0.11 cm) and 0.89 (SEM = 0.12 cm), respectively.

Fascicle Length. Fascicle length was measured using the extended field-of-view mode. A longitudinal sweep began near the distal insertion along the muscle and continued toward the proximal head of the muscle. Fascicle length was determined by identifying a clear fascicle that extended continuously from the superficial aponeurosis to the deep aponeurosis. Three consecutive images were analyzed and averaged offline. ICCs for this measure in rectus femoris and vastus lateralis were 0.75 (SEM = 1.13 cm) and 0.66 (SEM = 1.23 cm), respectively.

Pennation Angle. Pennation angle of the rectus femoris and vastus lateralis were measured using B-mode ultrasound at the same site as MT and CSA.[18] The transducer was placed longitudinal to the muscle tissue interface, and 3 consecutive images were analyzed and averaged offline. Muscle fiber PANG was determined as the intersection of the fascicles with the deep aponeurosis (Fig. 2C). ICCs for rectus femoris and vastus lateralis PANG

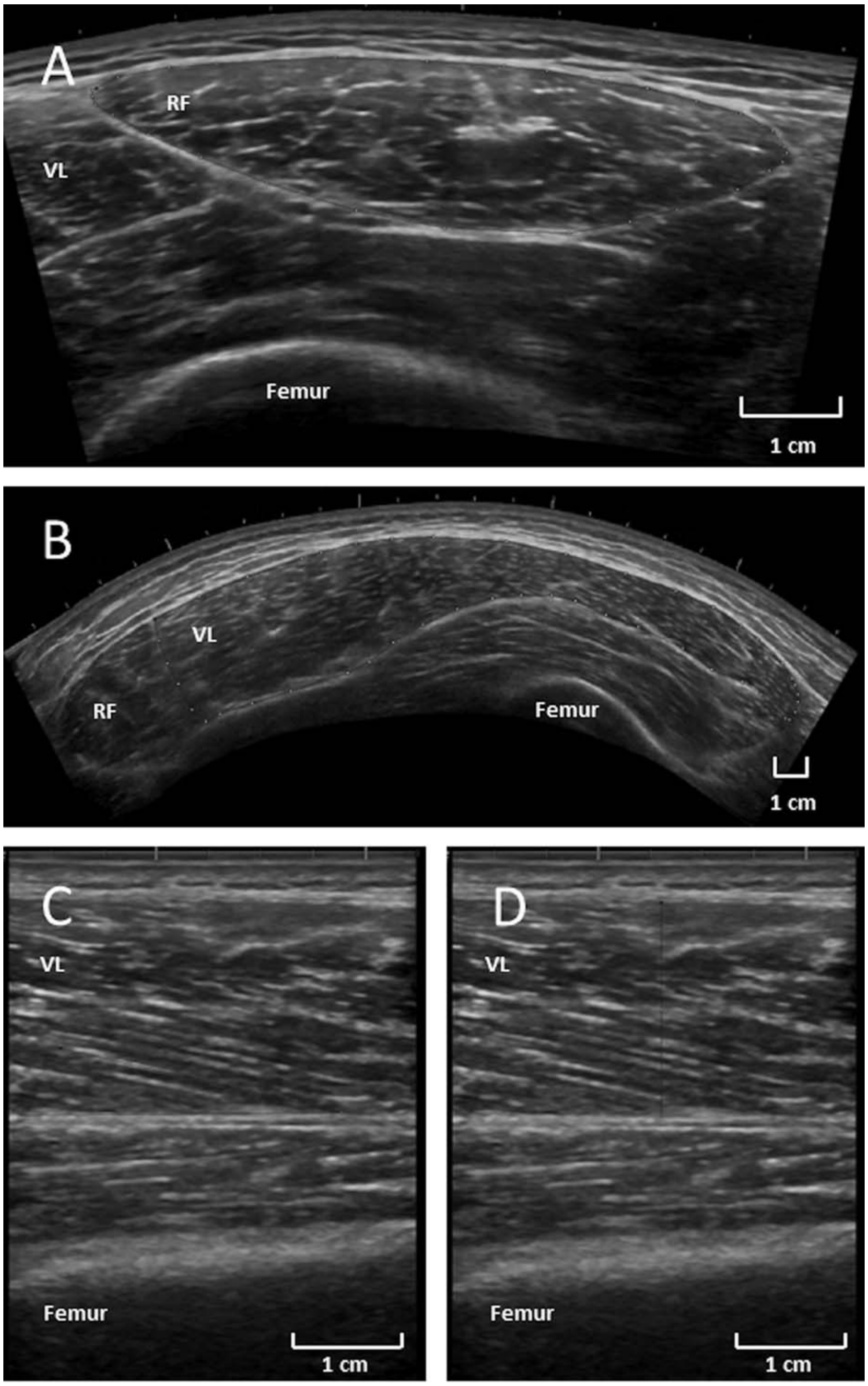

FIGURE 2. Example of ultrasound measurements of rectus femoris (RF) cross-sectional area **(A)**, vastus lateralis (VL) cross-sectional area **(B)**, VL pennation angle **(C)**, and VL muscle thickness **(D)**. A known distance of 1 cm was used for calibration of the image analysis software. For all scans, gain was set constant at 50 dB and depth to 5 cm.

were 0.73 (SEM = 2.8°) and 0.86 (SEM = 1.44°), respectively.

Echo Intensity. Echo Intensity of the rectus femoris and vastus lateralis were obtained using the same images as for CSA (Fig. 2A), and were the average of 3 consecutive images measured. EI was determined by gray-scale analysis using the standard histogram function in ImageJ.[5] A region of interest within each muscle was selected by obtaining as much muscle as possible without including any surrounding bone or fascia using the polygon tracking tool.[5] EI in the region of interest was expressed as arbitrary unit (AU) values of between

0 and 255 (0 = black, 255 = white); an increase in EI reflected an increase in intramuscular connective tissue and adipose relative to lean skeletal muscle. ICCs were 0.91 (SEM = 3.47 AU) for rectus femoris, and 0.93 (SEM = 5.1 AU) for vastus lateralis. A relative measure of EI was determined by dividing LTM by EI to calculate mass per unit of EI.

Physiological Cross-Sectional Area. Physiological cross-sectional area (PCSA) values of the rectus femoris, vastus lateralis, and thigh (rectus femoris + vastus lateralis) were calculated based on the relationship between muscle architectural variables using a modified version of the structure–function relationship proposed as follows[4]:

$$\text{PCSA} = \frac{\text{mass (g)} \times \cos\theta}{\text{density (g/cm}^3) \times \text{fascicle ength}} \quad (1)$$

All muscle architectural variables were measured by ultrasound where mass was substituted as the CSA (in cm^2), PANG was entered as cos θ, density was entered as inverse of EI (in AU), and L_f was also entered (in cm).[4] Reliability for the rectus femoris, vastus lateralis, and total thigh PCSA was determined from 12 participants measured 6 weeks apart and yielded ICCs of 0.94 (SEM = 0.26 cm^2), 0.95 (SEM = 0.29 cm^2), and 0.96 (SEM = 0.43 cm^2), respectively.

Resistance Training Protocol. The RT group participants completed a 6-week total body progressive resistance training program consisting of 2 workouts per week. The program was an individualized, periodized program including exercises of varying progressions of all major muscle groups. At least 48 hours were allowed between sessions for full recovery. Acute program variables were manipulated throughout the 6 weeks but generally consisted of 2–4 sets of 8–12 repetitions of 6–10 exercises at submaximal intensity (perceived exertion was not to exceed 5–6 on a 10-point scale, which is ∽70–85% of repetition maximum), according to the OMNI scale.[19] Each workout session began with a dynamic warm-up consisting of body weight squats, high knee walking, and limb rotations and terminated with an appropriate cool down. The exercise program followed the recommended guidelines for older adults by the American College of Sports Medicine[20] and was overseen by a certified strength and conditioning specialist.

Knee Extensor Strength. Maximal voluntary isotonic strength of the lower body was assessed with a knee extension machine (Conner Athletic Products, Inc., Jefferson, Iowa). Participants were seated within the machine so that the shin pad was just proximal to the lateral malleolus, and the beginning and terminating position of the leg was at 90° of knee flexion. Participants performed an initial set of 10 repetitions to assess comfort. After a 3-minute rest period, a load was estimated that participants believed they could complete for 10 repetitions. If more than 10 repetitions were performed, they were stopped and the participant rested for an additional 3 minutes. Level of perceived exertion was monitored constantly using the OMNI scale for all resistance training sessions. When required, this process was repeated until a load was achieved that the participant could perform for a maximum of 10 repetitions or less. Participants performed up to 3 attempts to reach the goal. After repetition maximum evaluation, the Brzycki prediction equation [load in kg/(1.0278 − 0.0278 × repetitions)] was used to predict maximal knee extensor strength (1RM). This method has been validated previously in clinical populations, yielding a typical error of 4% (±3.4 kg).[21]

Muscle Quality as Relative Strength Measures. Muscle quality as relative strength (MQ) was assessed by dividing 1RM by LTM. Muscle quality as strength relative to echo intensity (REI) was assessed by dividing 1RM by EI of the thigh (rectus femoris + vastus lateralis) in arbitrary units, as assessed by ultrasound.

Statistical Analysis. Results are expressed as mean ± standard deviation unless otherwise noted. A 2-way repeated-measures analysis of variance [group (exercise vs. control) × time (pre vs. post)] was used to identify group differences and group × time interactions. Analyses were conducted on the following variables: CSA, MT, L_f, PANG, EI, MQ, REI, and PCSA. Independent *t*-tests were performed to detect differences between groups at baseline. An alpha level of $p \leq 0.05$ was used to determine statistical significance. Data analysis was performed using statistical software (SPSS, version 20.0.0; SPSS, Inc., Chicago, Illinois).

RESULTS

Participants. Anthropometrics did not differ between groups at baseline for any measure (Table 1). No significant changes in any anthropometric measure were seen in either group after the 6-week resistance training protocol. Twenty-five participants completed the study (RT = 13, CON = 12). One participant dropped out for reasons unrelated to the study.

Knee Extensor Strength and Muscle Quality. Measures of strength and relative muscle quality before and after training are presented in Table 2. Muscle strength (1RM) increased 31.9% and corresponded to an increase in MQ of 31.5%

Table 1. Anthropometric measures for participants before and after training.

Group/variable	Pre	Post
Training (n = 13)		
Height (cm)	171.1 ± 10.1	—
Weight (kg)	84.2 ± 19.9	84.3 ± 20.3
Body fat (%)	40.0 ± 9.0	40.0 ± 8.0
Age (y)	71.1 ± 6.7	—
BMI (m/kg^2)	28.5 ± 5.2	28.5 ± 5.4
LBM (kg)	47.6 ± 10.6	47.9 ± 10.5
LTM (kg)	5.4 ± 1.3	5.4 ± 1.3
Control (n = 12)		
Height (cm)	166.5 ± 7.9	—
Weight (kg)	76.5 ± 18.2	76.8 ± 18.4
Body fat (%)	35.0 ± 9.0	35.0 ± 9.0
Age (y)	70.1 ± 5.5	—
BMI (m/kg^2)	27.5 ± 5.6	27.6 ± 5.5
LBM (kg)	49.5 ± 13.4	49.5 ± 13.2
LTM (kg)	5.7 ± 2.2	5.8 ± 2.4

Values presented as mean ± standard deviation; BMI, body mass index; LBM, lean body mass; LTM, lean thigh mass of dominant leg.

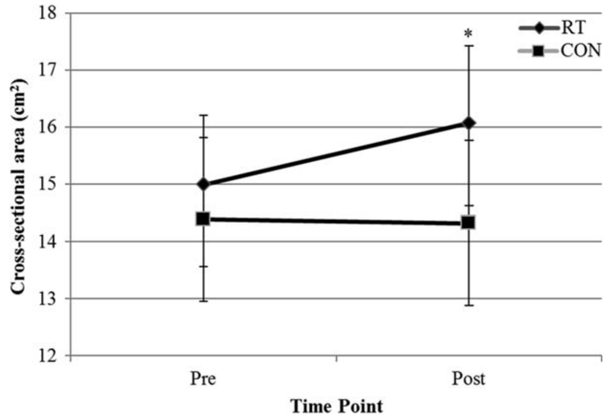

FIGURE 3. CSA (cm^2) of vastus lateralis before and after training in the RT (–◆–) and CON (–■–) groups. *Significant group × time interaction after training ($p < 0.05$).

and an increase in REI of 33.3% in the RT group. Muscle strength (1RM), MQ, and REI did not change in CON. Lean thigh mass relative to EI did not change significantly in either group after training.

Cross-Sectional Area. All measures of muscle morphology, architecture, and size before and after training are presented in Table 3. In the RT group, CSA of the rectus femoris did not change significantly, which was consistent with LTM assessed by DEXA; however, there was a significant group × time interaction for the RT group in the vastus lateralis, which was accompanied by a significant CSA increase of 7.4% (Fig. 3), as compared with no changes observed in CSA of either muscle for CON.

Muscle Thickness. Mean MT did not change significantly in the rectus femoris or vastus lateralis for either group, and no significant interactions were observed (Table 3).

Fascicle Length. No significant changes in L_f were seen in the rectus femoris or vastus lateralis in either group. Rectus femoris and vastus lateralis L_f did not demonstrate group × time interactions (Table 3).

Pennation Angle. No changes in PANG were observed in the rectus femoris or vastus lateralis in either group. PANG of rectus femoris and vastus lateralis did not demonstrate a significant group × time interaction (Table 3).

Echo Intensity. Mean baseline EI values were 81.3 ± 12.6 AU and 89.1 ± 10.0 AU for the rectus femoris and vastus lateralis, respectively (Table 3). At baseline, women had significantly higher echo intensity of the rectus femoris than men (EI = 87.6 ± 5.8 AU in women; EI = 78.4 ± 12.9 AU in men). There were no significant group mean changes in EI of rectus femoris or vastus lateralis for the RT group. However, *post hoc* analysis revealed a gender interaction ($p = 0.014$), as EI of vastus lateralis decreased in women after training. EI for the CON group did not change significantly in vastus lateralis; however, a main effect for time was observed for rectus femoris. There was no significant group × time interaction for rectus

Table 2. Measures of strength and muscle quality before and after training.

Measure	RT Pre	RT Post	CON Pre	CON Post
1RM (kg)*	39.20 ± 15.90	51.70 ± 17.60†	31.10 ± 11.80	33.30 ± 14.70
MQ (kg)*	7.14 ± 1.74	9.38 ± 1.65†	6.04 ± 2.11	6.29 ± 2.21
REI (kg/AU)*	0.54 ± 0.27	0.72 ± 0.32†	0.40 ± 0.16	0.44 ± 0.22
LTM (kg) / thigh EI	0.032 ± 0.012	0.033 ± 0.013	0.034 ± 0.013	0.035 ± 0.017

Values presented as mean ± standard deviation; 1RM, predicted 1-repetition maximum; MQ, muscle quality as relative strength; REI, muscle quality as strength relative to echo intensity; LTM, lean thigh mass; EI, echo intensity.

*Significant group × time interaction, $p \leq 0.01$.

†Significantly different than before training, $p \leq 0.01$.

Table 3. Measures of muscle architecture and size before and after training.

Measure	RT			CON		
	Pre	Post	Change	Pre	Post	Change
RF MT	1.84 ± 0.37	1.90 ± 0.41	3.30%	1.75 ± 0.37	1.70 ± 0.40	−2.90%
RF PANG	13.52 ± 3.48	12.90 ± 2.78	−4.60%	11.58 ± 3.97	10.50 ± 2.90	−9.30%
RF FL	7.92 ± 1.57	8.20 ± 1.68	3.50%	7.45 ± 1.96	7.31 ± 1.78	−1.90%
RF CSA	7.89 ± 2.43	8.20 ± 2.78	3.90%	7.59 ± 2.76	7.64 ± 2.58	0.70%
RF EI	81.57 ± 13.94	80.10 ± 16.02	−1.80%	83.66 ± 7.91	79.94 ± 7.87*	−4.40%
VL MT	1.51 ± 0.34	1.40 ± 0.34	−7.30%	1.34 ± 0.43	1.27 ± 0.44	−5.20%
VL PANG	9.87 ± 1.40	10.20 ± 1.54	3.30%	10.98 ± 2.80	10.13 ± 2.61	−7.70%
VL FL	7.45 ± 1.15	7.90 ± 1.40	6.00%	7.27 ± 1.28	7.33 ± 1.12	0.80%
VL CSA†	14.99 ± 4.36	16.10 ± 4.87*	7.40%*	14.39 ± 4.59	14.33 ± 5.01	−0.40%
VL EI	91.80 ± 10.79	90.10 ± 8.10	−1.90%	86.49 ± 9.22	86.33 ± 9.83	−0.20%
LTM (kg)	5.42 ± 1.33	5.46 ± 1.39	0.70%	5.75 ± 2.25	5.80 ± 2.42	0.90%
Thigh PCSA†	3.12 ± 1.44	3.39 ± 1.64	8.7%	3.05 ± 1.54	2.84 ± 1.48	−6.90%
VL PCSA†	1.68 ± 0.68	1.92 ± 0.82	14.30%	1.90 ± 0.93	1.75 ± 0.96	−7.90%
RF PCSA	1.44 ± 0.82	1.47 ± 0.86	2.10%	1.15 ± 0.79	1.08 ± 0.65	−6.10%

Values presented as mean ± standard deviation; RF, rectus femoris; VL, vastus lateralis; MT, muscle thickness; PANG, pennation angle; FL, fascicle length; CSA, cross-sectional area; EI, echo intensity; LTM, lean thigh mass; PCSA, physiological cross-sectional area.

*Significantly vs. before training, $p < 0.05$.

†Significant group × time interaction, $p < 0.05$.

femoris or vastus lateralis EI. Similarly, LTM per unit of EI did not change significantly for either group after training (Table 2).

Physiological Cross-Sectional Area. A significant group × time interaction was observed after training for PCSA of the thigh and vastus lateralis (Table 3); the training group tended to increase, whereas the control group tended to decrease. The PCSA of rectus femoris remained unchanged after the intervention.

DISCUSSION

We have examined the effects of resistance training on muscle morphology and architecture inclusive of EI in a model of PCSA of the lower body musculature in older adults. The main findings of this study suggest that 6 weeks of progressive resistance training may be sufficient to increase specific measures of muscle morphology and architecture. Interestingly, muscular adaptations observed as muscle quality (as relative strength) were not similar to changes in EI. Results suggest that 6 weeks of resistance training may increase strength as well as muscle architecture and morphology in older adults.

The focus of this study was to evaluate early muscular adaptations (within 6 weeks) of progressive resistance training. This duration of training elicited significant gains in 1RM as well as strength relative to LTM and relative to EI. The results show that strength gains may occur as early as 6 weeks in an older population and are supported by previous studies in which training durations ranged from 4 to 22 weeks.[13,14,22–24] Moreover, Tracy and colleagues reported absolute strength gains of 29% in knee extensors in just 9 weeks, which supports our results, although the gains they observed were slightly less.[12] Testing modality is a possible explanation for differences observed in strength gains between studies, as our study used the Brzycki prediction equation to estimate maximal isotonic knee extensor strength, whereas Tracy *et al.* tested maximal isometric contraction strength using an isokinetic device. In addition, it is possible that, after training, the participants in our study may have felt more comfortable testing at a lower repetition maximum, which could have influenced strength assessment.

No gains were observed in LTM when assessed by DEXA; however, ultrasound revealed a significant increase in CSA of vastus lateralis. This may indicate that the ultrasound device is more sensitive than DEXA for detection of small gains in lean muscle mass in response to short-term resistance training. Similarly, when performing computed tomography (CT) scans of quadriceps femoris in response to 12 weeks of knee extension and flexion training in older men, Frontera *et al.* reported significant gains in total quadriceps area of 9.3%.[22] These gains were attributed to significant muscle hypertrophy and myofibrillar protein turnover. It is possible that, with a longer training duration, the hypertrophic gains in our study would have approached those reported by Frontera and colleagues. Regarding the vastus lateralis, similar results have been reported in response to resistance training ranging from 12 to 16 weeks.[22,25] In addition, Frontera *et al.* reported that 16 weeks of leg press training resulted in knee extensor CSA increases of 7.4%, similar to our findings. Differential observations for rectus femoris may be explained by distinct functional anatomy and may indicate a form of selective hypertrophy in the early stages of lower body resistance training programs. It is possible that lower body resistance training may not demonstrate significant increases in CSA of rectus femoris until after 6 weeks of training. However, structurally, rectus femoris is the only muscle in the quadriceps that crosses 2 joints. When the hip is flexed, it may not be identified as a significant contributor to knee extension; however, with the hip extended, rectus femoris is activated more fully.[26] Häkkinen *et al.* also reported differential quadriceps muscle hypertrophy in response to 21 weeks of lower body training in older women.[27]

We observed significant increases in CSA of vastus lateralis that did not correspond to changes in MT. However, when reporting MT changes after longer training durations, Suetta and colleagues found vastus lateralis MT to increase in older men and women by 14.8% in response to 12 weeks of unilateral knee extension and leg press training.[28] It is possible that training durations of >6 weeks may be necessary to cause significant changes that are isolated to thickness of the lower limb musculature. In addition, CSA may provide a more sensitive assessment of total muscle hypertrophy, as it has been reported to better relate to the hypertrophic and force-producing characteristics associated with muscle size.[17]

Fascicle length did not change significantly in the rectus femoris or vastus lateralis; however, in response to training durations of 14 weeks, significant increases have been reported in older adults.[29] In 2009, Reeves *et al.*[29] examined the effects of 14 weeks of resistance training, comparing eccentric training with conventional training modalities in older adults. They found significant increases in both groups, although significantly greater gains were reported in the eccentric training group than in the conventional training group.[30] It is likely that architectural changes in L_f may require training durations of >6 weeks.

The short duration of the training program employed in our study resulted in no significant changes in PANG for either rectus femoris or vastus lateralis. In previous studies of longer duration (12–14 weeks), increases in PANG of vastus lateralis were reported to range from 13% to 22%,[13,28,29] whereas others indicated that similar durations of training may increase PANG up to 35%.[30] Our findings may suggest that a longer duration of training is needed to exhibit changes in fiber orientation relative to the force-generating axis. There is limited research available regarding changes in PANG of rectus femoris.

Muscle quality, as defined by EI of rectus femoris and vastus lateralis, did not change in the RT group after training. Surprisingly, our results indicate a main effect of time for rectus femoris EI in controls, although the study protocol was designed to minimize the potential acute effects of prior exercise on EI measurements by allowing a minimum of 72 hours between the last bout of exercise and ultrasound measurements. Further studies are required to better understand EI responses to acute exercise. It is likely that changes in EI in older adults in response to resistance training may require training durations of >6 weeks to elicit significant improvements despite significant changes in strength and muscle architecture. Based on changes observed in muscle morphology, primarily in vastus lateralis, changes in muscle size may occur earlier than changes in the composition of muscle that pertain to infiltration of intramuscular connective tissue and/or adipose tissue.

This study has addressed changes in muscle morphology and architecture inclusive of EI in a model of PCSA of the lower body musculature in older adults after resistance training, but the study sample size was not powered statistically *a priori* to describe gender differences. However, in *post hoc* examination of the data by gender, we observed a significant difference at baseline for echo intensity of rectus femoris between men and women. At baseline, women had higher echo intensity of rectus femoris (lower muscle quality) but not vastus lateralis. In addition, we observed significant differences at baseline in vastus lateralis CSA, as well as PCSA of rectus femoris and vastus lateralis, with men having greater values. When we examined gender differences in response to resistance training, EI of vastus lateralis was the only measure to show a significant gender difference; EI of vastus lateralis decreased in women with training. This difference may be due to gender differences in body composition or hormonal influences on muscle quality changes. However, as older men and women in our study showed some preliminary differences in muscle size and architecture, further studies are needed to elucidate gender differences in muscle composition and architecture in response to interventions in older adults.

Echo intensity relative to LTM did not change significantly in the RT or CON groups. Similar to the observations with EI, it may be apparent that, within this time frame, neurological adaptations contribute to a greater degree to the observed changes in strength. This is consistent with what is generally understood regarding initial strength gains in novice trained individuals.[31]

Resistance training in this study was successful in attenuating the decline in PCSA that is generally observed with aging.[32] In contrast to our results, however, resistance training has been reported to have no effect on PCSA in healthy older adults after 14 weeks of training,[13] as well as in older adults after resistance training preceded by an immobilization period.[14] It is important to note the inconsistency in methodologies for the calculation of PCSA. The methods used by Reeves *et al.* were based solely on the ratio of muscle volume to fascicle length, whereas Suetta *et al.* used muscle volume but did not account for muscle density. In our study, muscle CSA was used in addition to EI as a measure of muscle density[33] in an effort to provide a more composite measure of muscle architecture.

We examined changes in muscle morphology and architecture inclusive of EI in a model of PCSA of the lower body musculature in older adults after resistance training. Six weeks of progressive resistance training was sufficient to increase muscle strength, muscle quality (relative strength), and muscle architecture, but not echo intensity. Although previous research has attributed earlier strength gains from acute resistance training to primarily neuromuscular adaptation, results from the present study reveal muscle size changes by ultrasound, but not DEXA, after 6 weeks of training, most likely due to the differences in sensitivity to change between the devices. Our findings also indicate that composite ultrasound measures of PCSA are related to maximal leg extensor strength in older men and women.

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REFERENCES

1. Doherty TJ. Invited review: aging and sarcopenia. J Appl Physiol 2003;95:1717–1727.
2. Rosenberg IH. Summary comments. Am J Clin Nutr 1989;50:1231–1233.
3. Baumgartner RN, Koehler KM, Gallagher D, Romero L, Heymsfield SB, Ross RR, et al. Epidemiology of sarcopenia among the elderly in New Mexico. Am J Epidemiol 1998;147:755–763.
4. Lieber R. Skeletal muscle anatomy. In: Lupash E, editor. Skeletal muscle structure, function, and plasticity: the physiological basis of rehabilitation. Vol.3. Baltimore: Lippincott Williams & Wilkins; 2010. p 1–40.
5. Cadore EL, Izquierdo M, Conceição M, Radaelli R, Pinto RS, Baroni BM, et al. Echo intensity is associated with skeletal muscle power and cardiovascular performance in elderly men. Exp Gerontol 2012;47:473–478.
6. Narici MV, Reeves ND, Morse CI, Maganaris CN. Muscular adaptations to resistance exercise in the elderly. J Musculoskel Neuron Interact 2004;4:161–164.
7. Howe T, Oldham J. The reliability of measuring quadriceps cross-sectional area with compound B ultrasound scanning. Physiother Res Int 1996;1:112.
8. Thomaes T, Thomis M, Onkelinx S, Coudyzer W, Cornelissen V, Vanhees L. Reliability and validity of the ultrasound technique to measure the rectus femoris muscle diameter in older CAD-patients. BMC Med Imaging 2012;12.
9. Noorkoiv M, Stavnsbo A, Aagaard P, Blazevich AJ. In vivo assessment of muscle fascicle length by extended field-of-view ultrasonography. J Appl Physiol 2010;109:1974–1979.
10. Aagaard P, Suetta C, Caserotti P, Magnusson SP, Kjær M. Role of the nervous system in sarcopenia and muscle atrophy with aging: strength training as a countermeasure. Scand J Med Sci Sports 2010;20:49–64.
11. Fukumoto Y, Ikezoe T, Yamada Y, Tsukagoshi R, Nakamura M, Mori N, et al. Skeletal muscle quality assessed from echo intensity is associated with muscle strength of middle-aged and elderly persons. Eur J Appl Physiol 2012;112:1519–1525.
12. Tracy B, Ivey F, Hurlbut D, Martel G, Lemmer J, Siegel E, et al. Muscle quality. II. Effects of strength training in 65-to 75-yr-old men and women. J Appl Physiol 1999;86:195–201.
13. Reeves ND, Narici, MV, Maganaris CN. Effect of resistance training on skeletal muscle-specific force in elderly humans. J Appl Physiol 2004;96:885–892.
14. Suetta C, Hvid LG, Justesen L, Christensen U, Neergaard K, Simonsen L, et al. Effects of aging on human skeletal muscle after immobilization and retraining. J Appl Physiol 2009;107:1172–1180.
15. Pearson SJ, Young A, Macaluso A, Devito G, Nimmo MA, Cobbold M, et al. Muscle function in elite master weightlifters. Med Sci Sports Exerc 2002;34:1199.
16. Chapman DW, Newton M, McGuigan MR, Nosaka K. Comparison between old and young men for responses to fast velocity maximal lengthening contractions of the elbow flexors. Eur J Appl Physiol 2008;104:531–539.
17. Bemben MG. Use of diagnostic ultrasound for assessing muscle size. J Strength Cond Res 2002;16:103–108.
18. Abe T, Brechue WF, Fujita S, Brown JB. Gender differences in FFM accumulation and architectural characteristics of muscle. Med Sci Sports Exerc 1998;30:1066–1070.
19. Gearhart RF, Lagally KM, Riechman SE, Andrews RD, Robertson RJ. Strength tracking using the OMNI resistance exercise scale in older men and women. J Strength Cond Res 2009;23:1011–1015.
20. Chodzko-Zajko WJ, Proctor DN, Fiatarone Singh MA, Minson CT, Nigg CR, Salem GJ, et al. American College of Sports Medicine position stand. Exercise and physical activity for older adults. Med Sci Sports Exerc 2009;41:1510–1530.
21. McNair PJ, Colvin M, Reid D. Predicting maximal strength of quadriceps from submaximal performance in individuals with knee joint osteoarthritis. Arthritis Care Res 2011;63:216–222.
22. Frontera WR, Meredith CN, O'Reilly K, Knuttgen H, Evans W. Strength conditioning in older men: skeletal muscle hypertrophy and improved function. J Appl Physiol 1988;64:1038–1044.
23. Abe T, DeHoyos DV, Pollock ML, Garzarella L. Time course for strength and muscle thickness changes following upper and lower body resistance training in men and women. Eur J Appl Physiol 2000;81:174–180.
24. Candow DG, Chilibeck PD, Abeysekara S, Zello GA. Short-term heavy resistance training eliminates age-related deficits in muscle mass and strength in healthy older males. J Strength Cond Res 2011;25:326.
25. Ferri A, Scaglioni G, Pousson M, Capodaglio P, van Hoecke J, Narici M. Strength and power changes of the human plantar flexors and knee extensors in response to resistance training in old age. Acta Physiol Scand 2003;177:69–78.
26. Hamill J, Knutzen KM. Functional anatomy of the lower extremity. In: Malakoff-Klein E, editor. Biomechanical basis of human movement. Vol.3. Baltimore: Lippincott, Williams & Wilkins; 2009. p 187–257.
27. Häkkinen K, Pakarinen A, Kraemer WJ, Häkkinen A, Valkeinen H, Alen M. Selective muscle hypertrophy, changes in EMG and force, and serum hormones during strength training in older women. J Appl Physiol 2001;91:569–580.
28. Suetta C, Andersen JL, Dalgas U, Berget J, Koskinen S, Aagaard P, et al. Resistance training induces qualitative changes in muscle morphology, muscle architecture, and muscle function in elderly postoperative patients. J Appl Physiol 2008;105:180–186.
29. Reeves ND, Maganaris CN, Narici MV. Ultrasonographic assessment of human skeletal muscle size. Eur J Appl Physiol 2004;91:116–118.
30. Reeves ND, Maganaris CN, Longo S, Narici MV. Differential adaptations to eccentric versus conventional resistance training in older humans. Exp Physiol 2009;94:825–833.
31. Moritani T, Devries HA. Potential for gross muscle hypertrophy in older men. J Gerontol A Biol Sci Med Sci 1980;35:672–682.
32. Narici MV, Maganaris CN, Reeves ND, Capodaglio P. Effect of aging on human muscle architecture. J Appl Physiol 2003;95:2229–2234.
33. Pillen S, van Alfen N. Skeletal muscle ultrasound. Neurol Res 2011;33:1016–1024.