



Research Article

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Muscle strength and size gains in older women after four and eight weeks of high-intensity resistance training

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Abstract

The purpose of this study was to examine skeletal muscle strength and size gains that may occur during 4 and 8wk of high-intensity resistance training in physically-active older women. Fifteen regularly aerobic-exercising women (age 63-77 y) were randomly placed into a weight-training group (WTG) (n=8) or control group (CG) (n=7). Weight training consisted of bilateral knee extension (BLE), knee flexion (BKF) and leg press (BLP) (3 d•wk⁻¹, 3 sets, 80% 1-RM). Subjects exercised to full-range failure (6-10 repetitions) and then attempted 2 additional partial reps on each set. When 10 full reps were completed, resistance was increased to allow for only 6 full reps on the subsequent set. Assessments of skeletal muscle strength and size were made in WTG and CG at 0, 4 and 8wk. All measures of strength (1-RM) increased (p<0.001) in WTG after 4wk and 8wk of training. BLE increased 78 and 125%, BKF increased 99 and 156% and BLP increased 42% and 60% after 4wk and 8wk, respectively. Thigh muscle volume (cm³) was measured by obtaining 10 contiguous 10mm thick images of both thighs using T1 weighted magnetic resonance imaging. Muscle volume increased 2.4% (p=0.01) after 4wk and 6.7% (p<0.001) after 8wk in WTG. Muscle strength and size of CG did not change. This study confirms that older women can increase strength dramatically with training. This study also demonstrates that physically-active older muscles are capable of significant hypertrophy after as few as 4wk of high-intensity training.

Keywords: Aging, Strength Training, Hypertrophy, Muscle Volume.

INTRODUCTION

Deterioration of physiological systems is an unavoidable consequence of the aging process^[1]. However, declines in muscle size and function may not be due primarily to the aging process. Other factors including physical inactivity may contribute to this phenomenon.

In young adults, muscle strength has been shown to increase in response to training between 60 and 100% of the 1RM^[2]. Early studies concluded that weight training did not induce strength gains in older adults^[3,4]. However, low exercise intensities similar to those used in early studies promote only modest increases in strength in older subjects^[5,6]. Several studies have since demonstrated that, given an adequate training stimulus, resistance training provides similar or greater strength gains in older men and women compared to younger individuals^[7-9].

Few studies have focused on the adaptive responses of women to strength training. On average men are stronger than women and strength deficits in older women are very common. Data from the Framingham Disability Study indicate that 40% of women aged 55 to 64, 45% of women 65 to 74, and 65% of women aged 75 to 84 were unable to lift 4.5 kg^[10]. Given that muscle mass is related to falling and that older women have higher incidences of osteoporosis and risk of fracture from falling^[11], the paucity of data in this area is unfortunate.

In many studies, the significant increases in strength could be expected because most researchers recruited previously sedentary subjects. Morgan *et al.*^[12] investigated the effect of strength training on muscle size in active 61-71-year-old women. Unlike sedentary older persons used in previous studies, these women had been participating in an aerobic exercise program for the previous several months. During the study, normal exercise activity was supplemented with heavy resistance training.

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Training intensity was set at 80% of maximal strength for three sets of 8 to 12 repetitions. Results showed that physically active post-menopausal women can significantly increase the strength of the knee extensors by 42% and the knee flexors by 89% after eight weeks of training. Although strength increased, significant differences were not observed in muscle mass as measured by limb volume water displacement.

Volume displacement and anthropometric measures of limb musculature are gross estimates of muscle size area that are subject to considerable variability. Changes in subcutaneous or intramuscular fat and water content which may occur in conjunction with muscle alterations may affect these measures of muscle size. As a result, changes in muscle size may occur but remain undetected. Techniques used to assess muscle mass in older individuals must be capable of differentiating tissue within the anatomical compartment because the intra- and intermuscular fat stores of older adults are significant^[13, 14]. Techniques such as computed tomography (CT) provide accurate measurements of skeletal muscle mass *in vivo* by providing high resolution cross-sectional images of muscle that differentiate adipose and bone as distinct components^[15]. In a study performed by Frontera *et al.*^[16], sedentary older men responded to a 12-week progressive resistance exercise program that more than doubled knee-extensor strength and more than tripled knee-flexor strength with total muscle area estimated by CT increasing by 11.4%. In addition, measurements made at the six-week point also revealed significant increases in muscle size. Also using CT, Brown *et al.*^[17] showed statistically significant cross-sectional increases for 60-70-year-old males in the knee flexors (4%) and knee extensors (10%) after 12 weeks of weight training.

Detailed, serial investigations of body structures in healthy subjects have not been performed with CT due to significant X-ray exposure. Unlike CT, magnetic resonance (MR) imaging can be performed without exposing the subject to ionizing radiation. With CT, the use of a single CSA introduces the potential for greater test-retest error and therefore the accuracy of repeated CT scans depends on the precise localization of the measures. However, MR minimizes this potential error by using imaged bony landmarks as references. Additionally, with MR, a series of images can be taken at specific sites and a computerized integration procedure used to measure CSA and calculate total muscle volume from the images.

As in young adults^[2], heavy-resistance training can be used to increase muscle size in older adults. Previously it was thought that muscle strength improvements in this population were solely the result of neurological factors (i.e., motor unit recruitment patterns) because hypertrophy was not detectable using anthropomorphic measures^[18]. Recently, studies using more sensitive techniques (CT and/or muscle biopsies) have demonstrated significant increases in muscle mass accompany strength improvements, even in nonagenarians. The purpose of this study was to utilize MR to determine if and when any changes in skeletal muscle size occur in active, older women who participate in an 8-week heavy resistance training program.

METHODS

Subjects

Seventeen healthy women between the ages of 63 and 77 years volunteered to participate in the study. All women had been post-menopausal (i.e., no menstrual bleeding) for at least 5 years. Subjects were recruited from the community and a university-based exercise program for older adults, as well as from advertisements in local newspapers. No one was currently involved in any type of resistance training. Subjects had no history, signs or symptoms of any disabilities or neuromuscular illness that could preclude participation in a strength training program. Approval was given by the university's Institutional

Review Board. All subjects, as well as their physicians, signed informed consent documents.

All subjects were physically active having participated in an aerobic exercise program for ≥ 2 months (at least 15 min on 3 d \cdot wk⁻¹). Ten of the subjects were enrolled in the university-based exercise program. This program was conducted three times per week and consisted of stretching and calisthenics (10 min), walking/jogging/bicycling/rowing (20-30 minutes), and relaxation/recovery (5 min). Four others participated in swimming programs that consisted of approximately 30 min of swimming surrounded by 15-min warm-up and cool-down sessions. Three others participated in walking programs of their own.

Study Design

The study was a randomized 8-wk controlled investigation. After acceptance into the study, subjects were randomly assigned to strength training (n=9) or control (n=8) groups. All subjects continued to participate in their aerobic exercise programs during the study. Unless otherwise stated, all evaluations were made at baseline and four and eight wk thereafter.

Body mass was measured to the nearest 0.1 kg using a balance beam scale and stature was measured to the nearest 1.0 mm using a stadiometer. Although subjects were asked to maintain their normal dietary patterns, food records were not obtained.

Strength Testing

All strength testing was performed at each of the evaluations times. The one repetition maximum (1RM) was recorded as the measure of dynamic concentric strength for bilateral knee extension (BKE), bilateral knee flexion (BKF), and bilateral leg press (BLP). All measurements were made with identical equipment positioning and technique at each time point. The same weight machines used in the strength training program were used to determine 1RM. The best of two 1RM measurements (obtained 2-3 days apart for the strength trainers and 2-8 days apart for the control subjects) was used as the baseline, mid-study, and final measurement of strength for the strength trainers and controls.

The BKE strength was assessed on a weight bench (Task Ind., Chino, CA) utilizing weight plates for the resistance. Subjects were seated upright with both ankles resting behind a padded ankle bar. Each subject was instructed to slowly extend the knees from the resting position (90° - 100° of flexion) to full extension over 3 sec and then returned to the starting position over 2 sec.

Bilateral knee flexion was performed on a custom-made weight bench that also used weight plates. Subjects were placed in a prone position with the knees in an extended position just overhanging the end of the bench. A padded ankle bar that held the weights was placed behind the ankles. From the fully extended position, subjects flexed the knees to 90° of flexion over 3 sec and then returned to the starting position.

Bilateral leg press strength was measured using a standard weight-and-pulley system (Pacific Fitness, Santa Fe Springs, CA). Subjects were seated erect with both feet resting against a foot-plate directly in front of them. The seat was adjusted to place the hip in approximately 45° of flexion. The knees were placed at 90° of flexion and subjects placed the heels of the feet 10-12 cm apart on the foot-plate. Subjects were instructed to focus on pushing with the heels and not the toes during lifting. The hips and knees were extended over 3 sec until the knees were approximately 5° short of full extension (to prevent knee joint locking) and then returned to the starting position in over a 3 sec period.

Prior to each strength testing session, subjects performed a general warm-up for 5-10 min that included walking and stretching. After instruction in the use of weight-training equipment, subjects performed each exercise several times at a low resistance to ensure proper warm-up and familiarization. The order of testing was: 1) BKE, 2) BKF, and 3) BLP. All exercises were repeated with weight increments of 0.25 to 25.00 pounds until failure occurred despite verbal encouragement. All weight plates had been previously weighed for accuracy. Failure was reached when the subject failed to lift the weight through the entire range of motion on at least two attempts spaced 45-60 sec apart. Lifts were discounted if the subject utilized momentum or changed body position in a manner not directly related to the movement of the weight during the exercise motion. To stabilize the body, subjects were allowed to grasp handles that were attached to each machine. To minimize fatigue resulting from repetition, each test began at a weight near a predicted maximum. Most subjects required fewer than six repetitions to determine the 1RM. The highest successfully lifted weight was used as the 1RM for that muscle group. There was 45-60 sec between repetitions with five minutes of rest between the three exercises.

Exercise Training

Subjects in the strength-training group participated in a high-intensity resistance training program of dynamic exercise that included both concentric and eccentric work. Training took place 3 d•wk⁻¹ for 8 wk. Each subject participated in a total of 24 training sessions during the study. Subjects were forced to miss an occasional exercise session (e.g., holidays, bad weather, family care) so 100% compliance was set at 24 training sessions within 9 wk. Sessions were carried out in groups of 2-3 subjects under the constant supervision by the study investigators.

Three exercises were used to specifically increase the strength and mass of the thigh muscles: BKE, BKF, and BLP. The same machines and subject positioning as described above were used during training. Initial starting weights were determined using 80% of the individual's initial 1RM. To maintain intensity, subjects were asked to repeatedly lift the weight until they failed to complete a full repetition and then to attempt two more partial repetitions. When a subject could complete 10 full repetitions the weight was increased (0.25-5.0 pounds) to allow for only 6 full repetitions to be completed on the subsequent set. If less than 10 repetitions were completed during the third set, the final weight lifted was used to begin the following session. Resistances were evaluated daily and attempts were made to increase the resistance each session. All weights were placed on the machines by study investigators.

Each training session included 3 sets of 6-10 full repetitions for each exercise with 3-5 min of rest between sets. Subjects were allowed to stand and walk about the room between sets. Concentric and eccentric phases lasted 2-3 seconds each without rest between repetitions. Subjects completed all sets for a given exercise before moving to the next exercise. The order in which exercises were performed was rotated for each subject on a daily basis. Strength training sessions lasted approximately 45 min and were completed on alternate days to allow for adequate rest and recovery.

Subjects in both groups were instructed to continue their current aerobic fitness programs. Half of the strength group performed their aerobic program before strength training and half performed their aerobic exercise later in the day. Concurrent strength and endurance training does not interfere with the development of strength or endurance when compared to either type of training completed alone^[19,20]. Controls were instructed to not initiate any resistance training during the 8-week study and were offered the opportunity to participate in a strength training program after the completion of the study. While making, confirming, and performing follow-up

evaluations, frequent contact was maintained with controls that sustained their level of interest.

Magnetic Resonance Imaging

Magnetic resonance (MR) images of the thighs were obtained at baseline and after four and eight weeks of training. The subject was positioned on the imaging table and the feet secured with adhesive tape. All subjects entered the magnet feet-first with the arms placed along the body. Subject placement was standardized by the technician.

Images were generated on a General Electric Signa MRI system (Milwaukee, WI) equipped with a 1.5 Tesla superconducting magnet, cooled to liquid helium temperatures. Shielded gradient coils allowed spatial localization of the MR signal. To obtain reasonable tissue contrast, T1 images were obtained using a spin-echo sequence with a 500 ms repetition time and 12 ms echo time. Data sets were obtained with a 400x480 mm field of view that consisted of a two-dimensional array of 256 x 256 pixels.

Initially, a series of coronal images were taken to identify the femur. A series 27-30 transaxial, 10-mm-thick slices of both thighs were then acquired beginning at the femoral head for each subject. Images were taken with a 100% gap to eliminate inter-image interference and then sequentially arranged to form a continuous muscle volume. Data were stored on 9-mm reel-to-reel tape using a Data General 7800 computer. The total acquisition time was approximately 10 minutes.

Images were transferred using a UNIX workstation to a stand-alone personal Indigo computer (Silicon Graphics) for analysis. Processing was performed using an image analysis package that allows for the separation and quantitation of muscle and non-muscle tissue. All identifications of tissue were performed by a single operator blinded to the identity of the subject.

Ten sequential images from the right and left thighs of each subject were analyzed. Quantitation of thigh muscle mass without anatomical interference (i.e., buttocks and patella) was possible using this method. Using the femoral head as the anatomical landmark from which the leg images were measured, analysis of images began 120 mm distal to the femoral head. At each slice level, images of both thighs were treated together and data combined during analysis.

Subcutaneous and interstitial adipose tissue (AT), muscle, and bone were differentiated based on MR image pixel intensity within the gray level histograms. Each tissue was assigned a different color code (subcutaneous AT, beige; interstitial AT, green; muscle, blue; bone, red). Each slice was reviewed using an interactive slice editor program that allowed the operator to identify, verify, and edit the classification of individual pixels. Identification of tissue was facilitated by superimposing the original gray level image on the segmented image using a transparency mode controlled by a toggle switch.

The areas of respective tissues in each slice were computed automatically by summing respective pixels and multiplying by the pixel surface area (2.93 mm²). Volumes (mm³) of respective tissues within each image were calculated by multiplying the tissue area (mm²) by the slice thickness (10 mm). Total muscle volume for individual tissues within 10 slices was calculated by adding individual slice volumes. Intra-observer and inter-observer reliability coefficients were 0.99. Previous work has verified that the error in the spatial dimensions of images using this system ranges from 0.1 to 1.5%^[21]. Total analysis time for each image was approximately 3 minutes.

Statistical Analysis

Data analysis was completed using the statistical software program SPSS for Windows V.18.0 (SPSS Inc., Chicago, IL). Data were screened for outliers, and assumptions of normality and homoscedasticity. To

reduce the potential influence of outliers on the statistical analysis, box-and-whiskers plots were used to identify outliers, which were subsequently eliminated prior to analysis. Each variable was examined for normality using the Kolomogorov-Smirnov test. Assumptions of homogeneity of variance and sphericity were evaluated. Baseline group mean comparisons were performed using a one-way ANOVA. Repeated measures ANOVA procedures were conducted to evaluate the effects of the interventions and post-hoc analysis was performed to identify the nature of any differences. A probability value of less than 0.05 will be considered statistically significant.

RESULTS

Of the original sample of 17 women, 15 successfully completed the study. Two declined further participation following initial testing. For the remaining women, protocol compliance was excellent. All weight-trainers completed 24 training sessions within 9 weeks. Subjects in both groups completed all strength testing sessions. No training-related injuries were reported. No significant differences were found in age, body stature, or mass between weight-training and control groups (Table 1).

Table 1: Subject characteristics

Group	n	Age (yr)	Stature (m)	Mass (kg)
Strength Training	8	67.9 \pm 5.4	1.63 \pm 0.06	78.2 \pm 15.5
Control	7	68.9 \pm 3.7	1.60 \pm 0.10	75.7 \pm 19.2

Values are means + standard deviation; n: number of subjects.

Muscle Strength

Absolute values of 1RM measures were corrected for total body mass at each time-point for BKE (Figure 1), BKF (Figure 2), and BLP (Figure 3). Strength did not differ between groups at baseline. Relative strength increased ($p < 0.001$) in the weight-training group after only 4 wk of training. Gains of 78% (± 6.4) in BKE, 99% (± 12.1) in BKF, and 42%

(± 6.9) in BLP were observed in the weight-training group (Table 6). After 8 wk of training there were further increases ($p < 0.001$) in muscular strength for the weight-training group as indicated by increases of 125% (± 12.6) in BKE, 156% (± 21.3) in BKF, and 60% (± 8.7) in BLP as compared to baseline measures. Significant changes in 1RM strength in the control group were not observed during any 4 wk period of the study but BLP did increase after eight weeks ($p = 0.02$).

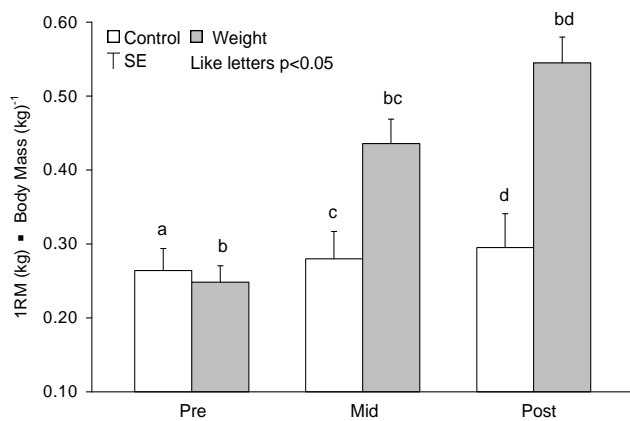


Figure 1: Bilateral Knee Extension 1RM (kg) • Body Mass (kg)⁻¹

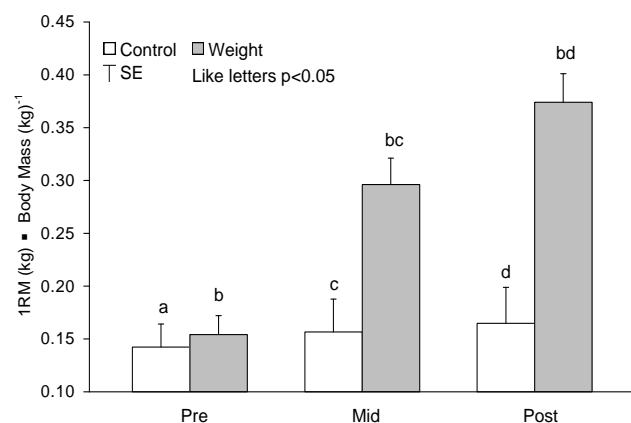


Figure 2: Bilateral Knee Extension 1RM (kg) • Body Mass (kg)⁻¹

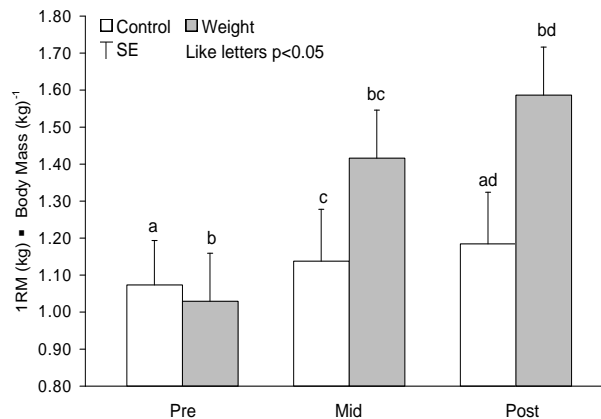


Figure 3: Bilateral Knee Extension 1RM (kg) • Body Mass (kg)⁻¹

Muscle Volume

Due to technical errors, the baseline magnetic resonance (MR) images of one weight-training subject and the 4-wk MR images of one control subject were lost. During baseline measures, an additional weight-training subject had to be removed from the MR unit after becoming claustrophobic before imaging was completed. However, this subject was able to successfully complete the final two MR analyses. In the analysis of tissue volume, images obtained at four-weeks were also used at baseline for the two training subjects with missing baseline data. Images obtained at eight-weeks were used for the missing four-

week measure of the control subject. This conservative approach was used for the missing data as it decreased the probability of observing any significant differences over time.

Muscle volumes were significantly different ($p < 0.001$) between the groups throughout the study. Strength training resulted in significant increases in mid-thigh muscle volume after 4 wk ($p = 0.01$) and 8 wk ($p < 0.001$) (Figure 4). The increase in muscle volume after 4 wk of training was 2.4% (± 0.9) and 6.7% (± 0.8) after 8 wk. Mid-thigh muscle volume in the control group did not change significantly over the course of the study.

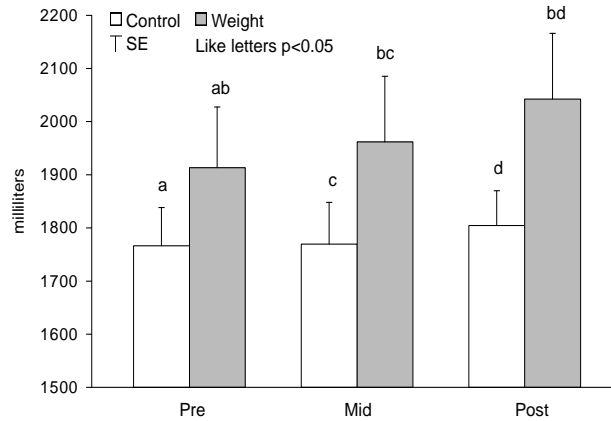


Figure 4: Muscle Volume (ml)

DISCUSSION

The major finding of this study is that significant increases in muscle volume are possible after as little as 4 weeks of progressive, heavy resistance training in women aged 63-77 years. These results suggest that neurological adjustments within older muscle are not solely responsible for the strength gains observed during the early phases of a weight training program. The data of this study support the findings of other studies that indicate weight-training is capable of producing rapid and dramatic increases of muscle strength in older women. Furthermore, the present investigation indicates that the muscles of older individuals who have remained physically active retain the capacity to undergo rapid strength accretion along with significant changes in hypertrophy.

Earlier studies had concluded that weight training did not induce strength gains in older adults^[3,4]. However, low exercise intensities similar to those used in such studies promote only modest increases in strength in elderly subjects^[5,6]. More recent studies have utilized higher workloads that have demonstrated rapid strength gains as a consequence of weight training, even at very advanced ages.

The results of the current study are in agreement with the findings of Frontera *et al.*^[16] who conducted a slightly longer training protocol in older males. They used a dynamic weight training program to train a group of 12 previously sedentary men aged 60-72 years. Subjects trained the knee extensors and flexors with weights three times per week performing three sets of eight repetitions, using 80% of the 1RM throughout the 12-week program. Subjects significantly increased the strength of the knee flexors (227%) and extensors (107%).

Strength gains in the present investigation were greater than those reported by Charette *et al.*^[22] in women, aged 64 to 86 years, after 12 weeks of moderate- to high-intensity isotonic resistance training. In that study, subjects exercised at 65% of 1RM during the first five weeks, 70% for four weeks, and 75% for the final 3 weeks. Training sessions were conducted three days a week and three sets of six repetitions of each exercise were performed during each training session. Strength increased 93% for knee extension, 115% for knee

flexion, and 28% for leg press. The control group did not demonstrate significant strength changes. Although the current study was of shorter duration, the higher training intensity may explain the greater gains in strength.

In many studies the significant increases in strength could be expected as previously sedentary subjects were recruited. However, the aging process may not be the sole cause of the decline in muscle function. Other factors, including physical inactivity, likely contribute to this phenomenon. Morgan *et al.*^[12] have shown that physically active post-menopausal women can significantly increase the strength of the knee extensors by 42% and the knee flexors by 89% after eight weeks of training in a study designed similarly to the current study. However, the results of the present investigation show strength gains of almost twice the magnitude of the previous study^[12].

Research has suggested that strength gains are approximately 5% per training session^[16] during a twelve-week program. In the present study, gains of 6% per session were observed in BKE and BKF and 3% for BLP. It is apparent that improvements in strength can be rapid for older persons, occurring within two months. Although older people continue to gain strength with prolonged programs, it appears that as with young individuals the greatest gains for older adults are made during the initial stages of a strength training program. The strength training group continued to gain strength during the final four weeks, however the increase was less than that of the preceding 4 weeks. This possibly reflects a trend for the gains to level off as reported by Hakkinen and Pakarinen^[23]. They observed a plateau in strength gains in older men and women at eight weeks during a 12-week strength training program. Similarly, the strength gains recorded by Moritani and deVries^[16] appeared to level off after 6 weeks. In addition, Pyka *et al.*^[24] strength trained three older men and five older women for 52 wk and demonstrated that three quarters of the strength gains over baseline were obtained in the first eight weeks with the remaining gains seen over the remaining year. In contrast, the present investigation was only eight weeks in duration and therefore, the effects of this training protocol on older muscle after eight weeks remains undetermined.

Few studies have utilized a control group when investigating the effects of training on strength and muscle mass. The control group is of value to separate factors such as strength declines over time, neural learning, psychological motivation, and changes in activity patterns. Although the strength of control subjects in the study of Morgan *et al.* [12] did not change during the study, other control groups in strength studies have shown increases of approximately 5% [21,25,26]. These changes may be attributed to learning effects. In an attempt to minimize these effects, two baseline measures of strength were conducted in this study.

In the control group of this study, there was an approximate 6% improvement in the three bilateral strength measures after 4 wk. However, these changes were not significant. After 8 wk, this increase was approximately 10% for each of the three exercises and did reach statistical significance ($p=0.02$) for BLP. These results are similar to those of Morganti *et al.* [27] in which a control group demonstrated small improvements in knee extension (13%; not significant) and leg press (4%; $p = 0.04$) strength during a study. However, it must be remembered that the control group of the current study was not sedentary. Instead, they were participating in regular aerobic exercise. The significant gain in leg press strength after eight weeks is not surprising because it is an activity often used in daily living (e.g., raising from a chair). In addition, the leg press is a more complex motion than either of the other two exercises (i.e., knee extension/flexion) and may have involved more motor learning that resulted in gains over time. General activity questionnaires indicated that activity did increase for the control group. This change in general activity may have caused the subjects to derive some training effect from simply performing this motion more often throughout the day.

The finding in the present investigation that hypertrophy of older muscles can occur following heavy-resistance training contradicts the early conclusions of Moritani and deVries [18] who failed to observe muscle hypertrophy in old muscle following moderate-intensity resistance training. Groups of young (aged 18 to 26 years) and old (aged 67-72 years) men in the study of Moritani and deVries [18] both had similar and significant relative increases in strength, however only the young group demonstrated any changes in muscle mass. The investigators concluded that neural factors were responsible for the initial strength gains in young people and hypertrophy became the dominant factor after three to five weeks of training. The investigators also concluded that the effects of strength training in older adults were entirely due to neurological factors as hypertrophy was not observed using indirect anthropometric measures.

The increase in muscle tissue due to strength training in this study was within the range of results from other studies using older people. Frontera *et al.* [16] found an 11% increase in the total muscle area of the thigh in elderly men after 12 wk. Fiatarone *et al.* [28] found an increase of 9% in a group of 86- to 96-year-old men and women after eight weeks of strength training.

Again our results are similar to those of Frontera *et al.* [16] in which older men more than doubled knee extension strength and more than tripled knee flexor strength. After 12 weeks of training, total muscle area estimated by CT increased 11.4%. In addition, measurements conducted at the six-week point also revealed significant increases in muscle size. Also using CT, Brown *et al.* [26] showed statistically significant cross-sectional increases for 60-70-year-old males in the knee flexors (4%) and knee extensors (10%) after 12 weeks of weight training.

It is widely believed that differences in the measurement technique used to assess muscle mass may explain the disparity in research results. Several methods have been utilized to document changes in muscle mass following resistance training in the elderly. Observed differences in muscle mass are largely dependent on the method

utilized [29]. The one study [12] that examined strength training in active older women measured muscle volume using water-displacement procedures that are subject to large errors. The 8-week strength gains in that study are similar to those observed after 4 weeks in the present study. The change in muscle mass at that time-point was 2.5%. The sensitive MR imaging techniques utilized in the present investigation are capable of detecting such a small change. In addition, changes in subcutaneous or intramuscular fat and water content that may have occurred in conjunction with muscle alterations could have affected the estimates of muscle size in the study of Morgan *et al.* [12]. Only techniques capable of separating muscle from fat (e.g., MR imaging) would provide information concerning volume changes independent of intramuscular and subcutaneous fat. Therefore, while hypertrophy may have occurred during the previous study performed by Morgan *et al.* [12], the technique used to measure muscle mass did not detect any changes. This could explain the failure of those investigators to observe muscle hypertrophy after 8-weeks of strength training in older women although significant strength changes occurred.

The increases in strength and muscle mass found in the current study are larger than previously reported for older women. The differences may be explained by the training intensity and the sensitivity of the technique used to measure small changes in muscle mass. Two main factors may account for the differences in the results of this study compared to others. First, in this study the training stimulus was greater than that used in other studies of strength in older subjects. Other studies have utilized high workloads but have not overloaded the subjects as rapidly nor included partial repetitions at the end of each set. Second, all subjects in this study were cooperative and highly motivated as evidenced by the low absenteeism.

Many studies have used moderately-high intensities (60-70% of 1RM) during the initial weeks of a study and increased the intensity as the study progressed. In contrast, this study attempted to begin strength-training at a high-intensity and maintain that intensity throughout the entire program. While most studies have adjusted the training-weights on a weekly or bi-weekly basis, the present study adjusted the training load on a session-to-session basis. Prior to the first week of the strength program, strength trainers were given the opportunity to do a "familiarization session" or "practice workout" in which they completed three sets of each exercise at approximately 50% of their 1RM. Starting weights for the first training session were determined using 80% of the individual's initial 1RM. To maintain intensity, subjects were asked to repeatedly lift the weight until they failed to complete a full repetition and then to attempt two more partial repetitions. When a subject could complete 10 full repetitions the weight was increased to allow for only 6 full repetitions to be completed on the subsequent set. The final weight lifted was used to begin the following session. To maintain a constant level of intensity, resistances were evaluated daily, and attempts were made to increase the resistance each session.

In addition, adequate rest (3-5 minutes) was given following each set to allow sufficient recovery before the performance of the subsequent set. These rest periods were used to avoid additional fatigue that would decrease the subjects' ability to lift maximal amounts of weight during each set. The training intensity was also augmented by having the subjects attempt two repetitions after they were unable to lift the weight through the full range-of-motion. The resulting partial repetitions enhanced the challenge to which the muscle was subjected and provided more assurance that each set was sufficiently fatiguing the muscle. This is a technique often used by competitive body-builders to increase workout intensity and the current study is the first to apply this "forced-repetitions" technique to strength-training in older women. It appears that older women are capable of handling training intensities and techniques that are typically used by much younger athletes of competition caliber. This study clearly demonstrates that given an adequate training stimulus, resistance

training can provide greater strength gains in older women than once believed.

CONCLUSION

This study confirms that a progressive heavy-resistance training program can produce dramatic improvements in muscle strength for physically-active older women, aged 63-77 years. Muscle strength increased significantly after four and eight weeks of heavy-resistance training compared to a small increase that occurred in the controls who remained physically active but did not participate in resistance training. Strength increases during the first four weeks accounted for approximately two-thirds of the total strength gain. Significant increases in muscle mass were also observed after four and eight weeks of training. Muscle volume increases during the final four weeks accounted for approximately two-thirds of the total gain in muscle mass. Significant changes in muscle size were not observed in the control group. Thus, this study indicates that the muscles of older women, who have remained physically active, retain the capacity to undergo rapid strength accretion along with significant changes in hypertrophy. This study also supports the safety of strength training performed at very high intensity for older women.

Conflicts of interest

The authors declare no conflicts of interest.

Authors' Contribution

The authors shared responsibility for the study design and data collection. M.E. Rogers analyzed the data and wrote the manuscript.

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