Muscle Size Responses to Strength Training in Young and Older Men and Women

Stephen M. Roth, PhD,*† Fred M. Ivey, PhD,*‡ Greg F. Martel, PhD,*§ Jeff T. Lemmer, PhD,*∥ Diane E. Hurlbut, MS,* Eliot L. Siegel, MD,* E. Jeffrey Metter, MD,* Jerome L. Fleg, MD,* James L. Fozard, PhD,** Matthew C. Kostek, MS,* David M. Wernick, MS,* and Ben F. Hurley, PhD*

OBJECTIVES: To examine the possible influences of age and gender on muscle volume responses to strength training (ST).

DESIGN: Prospective intervention study.

SETTING: University of Maryland Exercise Science and Wellness Research Laboratories.

PARTICIPANTS: Eight young men (age 20–30 years), six young women (age 20–30 years), nine older men (age 65–75 years), and ten older women (age 65–75 years).

INTERVENTION: A 6-month whole-body ST program that exercised all major muscle groups of the upper and lower body 3 days/week.

MEASUREMENTS: Thigh and quadriceps muscle volumes and mid-thigh muscle cross-sectional area (CSA) were assessed by magnetic resonance imaging before and after the ST program.

RESULTS: Thigh and quadriceps muscle volume increased significantly in all age and gender groups as a result of ST (P < .001), with no significant differences between the groups. Modest correlations were observed between both the change in quadriceps versus the change in total thigh muscle volume (r = 0.65; P < .001) and the change in thigh muscle volume versus the change in mid-thigh CSA (r = 0.76, P < .001).


Key words: aging; MRI; muscle mass; resistance training; sarcopenia

The loss of muscle mass with advancing age (sarcopenia)1 is associated with a decline in functional abilities and health status.2 Strength training (ST) can reverse this process in older men and women.3–5 However, direct comparisons of young and older subjects’ muscle mass response to ST are limited,4,6,7 and some investigators have concluded that older individuals have an impaired hypertrophic response to ST.4,7 For example, Welle et al.7 reported that older (age 62–72) men and women exhibited significantly lower increases in muscle cross-sectional area (CSA) in response to 3 months of ST than did young (age 22–31) men and women. Moreover, reduced hypertrophy has been observed in older animals in response to muscle overload.8,9 In addition, the loss of skeletal muscle mass with age may be most detrimental to women,10–12 and recent evidence in humans has indicated potential gender differences in the muscle mass response to ST.4,6,13

Existing ST studies involving human subjects are associated with various limitations, which include the lack of a simultaneous gender and age comparison or the use of muscle CSA rather than muscle volume measures,14,15 thus limiting the ability to determine conclusively whether age and gender influence muscle mass response to ST. Thus, the purpose of the present investigation was to assess the possible influence of age and gender on muscle volume response to a 6-month total-body ST program. Based on a previous study in these same subjects,8 we hypothesized that men would demonstrate a significantly greater muscle volume response to ST than women but that age would not significantly alter the hypertrophic response to ST.

From the *Department of Kinesiology, University of Maryland, College Park, Maryland; †Department of Human Genetics, University of Pittsburgh, Pittsburgh, Pennsylvania; ‡Division of Gerontology, University of Maryland, School of Medicine, Baltimore, Maryland; §Department of Physical Therapy, University of Maryland Eastern Shore, Princess Anne, Maryland; ¶The Jean Mayer USDA HNRC on Aging at Tufts University, Boston, Massachusetts; /Department of Radiology, Baltimore VA Medical Center, Baltimore, Maryland; ∥Gerontology Research Center, National Institute on Aging, Baltimore, Maryland; and **Florida Gerontological Research and Training Services, Palm Harbor, Florida.

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Address correspondence to Ben F. Hurley, PhD, Department of Kinesiology, University of Maryland, College Park, MD 20742.
METHODS

Subjects

Eight young men (age 20–30), six young women (age 20–30), nine older men (age 65–75), and 10 older women (age 65–75) volunteered to participate in this 6-month whole-body ST program. A physician, who performed a medical history, physical examination, and maximal graded exercise test, screened subjects. All subjects were nonsmokers and were free of significant cardiovascular, metabolic, or musculoskeletal disorders. Only inactive persons who had not exercised regularly (more than once every 2 weeks) during the 6 months before the study were allowed to participate. These same subjects had volunteered for a previous 9-week ST investigation described elsewhere. However, all subjects completed a detraining period of approximately 8 months before participation in the current study. During this detraining period, the subjects resumed their previously inactive lifestyle. Only the young men maintained quadriceps muscle volume values that were significantly higher than their baseline values following the detraining period, but even in this group the values started at 158 cm³ below the level that they were after the initial training program. Thus, a substantial amount of muscle volume was lost during the detraining period. Before participation in the current study, the purpose and procedures of the research were explained in detail, and the subjects gave their written informed consent to participate. The human subjects institutional review boards of the University of Maryland College Park, the Baltimore Veterans Affairs Medical Center, and the Johns Hopkins Bayview Medical Center in Baltimore approved the procedures used in this study.

Body Composition

Using a Lunar DPXL dual energy x-ray absorptiometer (Lunar DPXL, 1994), body composition was assessed before and after 6 months of ST, as described previously. Subjects were instructed not to eat or drink anything after midnight before their morning scan. A calibration standard was scanned daily, and measurement accuracy was assured by scanning a water/oil phantom of known proportions (41% fat) monthly. The coefficient of variation of repeated measurements was less than 1.0%.

Muscle Volume and CSA Measurement

The dominant thigh for each subject was scanned using magnetic resonance imaging (MRI) before and at least 48 hours after the last ST session. A Picker Edge 1.5 Tesla MRI scanner was used to obtain a series of axial slices extending from the superior border of the patella to the anterior superior iliac spine, encompassing the entire thigh musculature, including the quadriceps and hamstring muscle groups. The images were produced using 9-mm-thick (1-mm gap) T1-weighted axial scans, with an echo time of 14 ms and a relaxation time of 700 ms. Subjects were instructed not to eat or drink anything after midnight before the scans to perform any vigorous activity before the scans, which were performed between 8 a.m. and 10 a.m. The images were stored on magnetic disk for subsequent analysis on a personal computer. The MRI scanner calibration was checked daily and adjusted if needed. MRI accuracy and precision of volume determination were assessed by repeat scanning and analysis of a lean beef phantom with dimensions approximating the knee extensor group. Repeat MRI volume measurements on the beef phantom yielded a 0.12% difference between measurements.

The images were imported into NIH Image version 1.61 imaging software for analysis. For every fifth axial slice, the CSA (cm²) of both the entire thigh and the quadriceps-only musculature was manually outlined and measured. The thigh muscle CSA was outlined in axial images extending from the superior border of the head of the femur to the superior border of the patella. The gluteal muscles were not included in the analysis. The quadriceps CSA was outlined in every axial image from the superior border of the patella to a point where the quadriceps muscle group is no longer reliably distinguishable from the adductor and hip flexor groups. The same number of slices proximal from the patella was measured for a particular subject before and after training, to ensure within-subject measurement replication. In addition, the CSA of the mid-thigh slice, as defined by the slice half the distance between the head of the femur and the distal end of the medial condyle, was also measured for each subject. Investigators were blinded to both subject identification and training condition during all image analyses. Variability of total thigh muscle volume assessed by repeat determination of the same set of axial scans on different days by the same investigator was <2%.

Muscle Volume Calculation

We have reported a significant correlation (r = 0.96, P < .01) between the direct measurement of quadriceps muscle volume, as assessed by the CSA of all axial muscle slices, and estimated muscle volume using every fifth axial slice. Therefore, the CSA of every fifth axial slice was measured, multiplied by the distance between slices (5 cm), and summed across slices as an estimate of muscle volume expressed in cubic centimeters (cm³).

Strength Training (ST) Program

Before beginning the 6-month, 3-day/week ST program, subjects underwent six familiarization sessions during which they completed the training program exercises with little or no resistance and were instructed on proper warm-up, stretching, and exercise techniques. To determine the initial level of resistance for each exercise, one- and five-repetition maximum (1 RM and 5 RM, respectively) strength tests were performed following the familiarization sessions, as described previously. Using the same Keiser K-300 air-powered resistance machines and free weight dumbbells that were used for training, strength was measured for each of the following nine exercises: unilateral leg press, unilateral leg curl, unilateral leg extension, chest press, lat pulldown, overhead shoulder press, upper back rowing, triceps pushdown, and unilateral biceps curls. Subjects performed all leg exercises unilaterally to better isolate the targeted muscle groups, to help stabilize other nontargeted muscle groups, and, in some cases, to individualize the load for each contralateral limb. Both limbs were strength tested and exercised, with resulting strength values reported as the combined total of each limb. The 1 RM and 5 RM tests were defined as the maximal resistance that could be moved through the full range of motion with proper form.
once and five times, respectively. These tests were performed after the familiarization sessions to help control for early strength gains due to motor learning effects and to reduce the risk of injury.

As described in detail previously, the ST program consisted of the same nine exercises listed above plus abdominal crunches performed to fatigue during each training session. All other exercises during the first 3-month period consisted of four to five repetitions of each exercise at a 5 RM resistance and then, in the same set of exercise, reducing the resistance just enough to perform one or two additional repetitions. This process was repeated for all subsequent repetitions without altering the cadence of the repetitions, until 15 continuous repetitions were completed. This procedure allowed subjects to exert a near-maximal level of effort on all repetitions and has led to substantial increases in strength and muscle hypertrophy when similar training regimens were used. The concentric phase of each repetition was performed in 1 to 2 seconds and the eccentric in 2 to 3 seconds. The training resistance (5 RM) was monitored during each session and was increased as strength improved. Subjects were allowed 2 to 3 minutes of rest between sets throughout the entire ST program. Two sets were performed on the leg exercises and one set for the upper body and trunk exercises during each training session. To help maintain high subject compliance and reduce boredom, the ST protocol for the second 3-month period of training was altered such that each subject gradually increased the resistance of each repetition starting from an initial level of 50% of his or her 1 RM until failure to complete another repetition resulted. Subjects learned to increase the resistance just enough after each repetition so that failure occurred on or before the 15th repetition. Thus, the first portion (~5 repetitions) of the 15 repetitions served as warm-up repetitions and each repetition thereafter used slightly greater resistance until a maximum was reached at the end of each set.

Subjects were asked to maintain their current dietary intake and activity habits throughout the 6-month training period, and body weight was recorded once a week throughout the duration of the study to verify compliance. At least two exercise specialists supervised training sessions at all times.

Statistical Analysis
Changes in muscle volume with ST were assessed using a repeated-measures analysis of variance (ANOVA) model (age and gender as explanatory variables) with before-ST muscle volume used as a covariate. Differences in baseline muscle volume between groups were assessed using a one-way ANOVA model with each age and gender group separated, with a Tukey post hoc procedure used to determine specific group differences, when necessary. These analyses were repeated for muscle CSA values and subject characteristics (e.g., body mass). Data are presented as means ± standard error, with statistical significance accepted at \( P < .05 \).

RESULTS
Subject Characteristics
Subject characteristics before and after the ST program are outlined in Table 1. Fat free mass (FFM) increased in all groups \((P < .001)\), whereas percentage of body fat did not change significantly \((P = .076)\), as a result of the ST program. Both upper- and lower-body strength (1 RM) increased significantly \((P < .001)\) in all groups in response to ST (Table 1), as reported previously for the older subjects.

Muscle Volume
At baseline, men had greater thigh (Table 2) and quadriceps (data not shown) muscle volumes than did women, and young subjects had greater muscle volumes than did older subjects (both \( P < .002 \)). Thigh (Table 2) and quadriceps (data not shown) muscle volumes increased significantly as a result of ST in all age and gender groups \((P < .001)\), with no significant differences between the groups \((P > .229)\). Although older men demonstrated significantly greater baseline thigh muscle volume than did young women \((P < .048)\), this difference was not significant for baseline quadriceps muscle volume \((P = .969)\). The change in thigh

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Table 1. Physical Characteristics Before and After 6 Months of Strength Training (ST)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Young Men (n = 8)</th>
<th>Young Women (n = 6)</th>
<th>Older Men (n = 9)</th>
<th>Older Women (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before ST</td>
<td>After ST</td>
<td>Before ST</td>
<td>After ST</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>25 ± 1</td>
<td>—</td>
<td>26 ± 1</td>
<td>—</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180 ± 2</td>
<td>—</td>
<td>169 ± 2</td>
<td>—</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>84.4 ± 5.5</td>
<td>84.6 ± 5.3</td>
<td>64.7 ± 4.6</td>
<td>67.2 ± 4.9</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>24.2 ± 2.8</td>
<td>22.3 ± 2.4</td>
<td>32.0 ± 2.0</td>
<td>32.4 ± 1.9</td>
</tr>
<tr>
<td>Fat free mass (kg)</td>
<td>62.9 ± 2.4</td>
<td>64.9 ± 2.4*</td>
<td>42.9 ± 1.9</td>
<td>44.8 ± 2.1*</td>
</tr>
<tr>
<td>Leg press strength (kg)*</td>
<td>695 ± 33</td>
<td>865 ± 44*</td>
<td>433 ± 42</td>
<td>577 ± 58*</td>
</tr>
<tr>
<td>Chest press strength (kg)*</td>
<td>69.6 ± 6.0</td>
<td>86.6 ± 8.6*</td>
<td>34.1 ± 1.9</td>
<td>45.5 ± 3.4*</td>
</tr>
</tbody>
</table>

*Significantly different from before training \((P < .035)\).
†The sum of both unilateral 1-repetition maximum values.
Leg and chest press strength values are included to demonstrate the effectiveness of the ST program only. Complete results of the muscle strength responses to the ST program have been reported previously for the older subjects.
Table 2. Whole Thigh Magnetic Resonance Imaging (MRI) Muscle Volume (cm³) and Mid-Thigh MRI Muscle Cross Sectional Area (cm²) Measurements Before and After Strength Training (ST)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Older Men</th>
<th>Older Women</th>
<th>Young Men</th>
<th>Young Women</th>
<th>All Men</th>
<th>All Women</th>
<th>All Older</th>
<th>All Young</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole thigh muscle volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before ST (cm³)</td>
<td>3,896 ± 118†</td>
<td>2,562 ± 99</td>
<td>4,825 ± 350‡</td>
<td>2,916 ± 273</td>
<td>4,333 ± 206†</td>
<td>2,695 ± 122</td>
<td>3,194 ± 174</td>
<td>4,007 ± 345‡</td>
</tr>
<tr>
<td>After ST (cm³)</td>
<td>4,057 ± 129†</td>
<td>2,705 ± 95</td>
<td>5,010 ± 338‡</td>
<td>3,156 ± 306</td>
<td>4,506 ± 205‡</td>
<td>2,874 ± 135</td>
<td>3,345 ± 177</td>
<td>4,216 ± 340‡</td>
</tr>
<tr>
<td>Change (cm³)</td>
<td>161.5 ± 32.7*</td>
<td>142.7 ± 30.2*</td>
<td>185.4 ± 56.0*</td>
<td>240.4 ± 90.4*</td>
<td>172.7 ± 30.6*</td>
<td>179.4 ± 38.9*</td>
<td>151.6 ± 21.7*</td>
<td>209.0 ± 48.7*</td>
</tr>
<tr>
<td>Percentage change</td>
<td>4.1 ± 0.8</td>
<td>5.8 ± 1.2</td>
<td>4.2 ± 1.5</td>
<td>8.1 ± 2.8</td>
<td>4.2 ± 0.8</td>
<td>6.6 ± 1.3</td>
<td>5.0 ± 0.7</td>
<td>5.9 ± 1.5</td>
</tr>
<tr>
<td>Whole mid-thigh muscle cross sectional area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before ST (cm²)</td>
<td>146.5 ± 5.2†</td>
<td>104.0 ± 4.8</td>
<td>174.6 ± 11.7‡</td>
<td>113.6 ± 9.5</td>
<td>159.7 ± 6.9‡</td>
<td>107.6 ± 4.6</td>
<td>124.1 ± 6.1</td>
<td>148.5 ± 11.3‡</td>
</tr>
<tr>
<td>After ST (cm²)</td>
<td>148.6 ± 4.7*</td>
<td>109.4 ± 4.3</td>
<td>177.5 ± 11.4‡</td>
<td>123.5 ± 10.2</td>
<td>162.2 ± 6.8‡</td>
<td>114.7 ± 4.8</td>
<td>128.0 ± 5.6</td>
<td>154.3 ± 10.6‡</td>
</tr>
<tr>
<td>Change (cm²)</td>
<td>2.1 ± 1.9*</td>
<td>5.4 ± 1.6*</td>
<td>2.8 ± 3.3*</td>
<td>10.0 ± 3.1*</td>
<td>2.4 ± 1.8*</td>
<td>7.1 ± 1.6‡</td>
<td>3.8 ± 1.3*</td>
<td>5.9 ± 2.5*</td>
</tr>
<tr>
<td>Percentage change</td>
<td>1.6 ± 1.3</td>
<td>5.6 ± 1.8</td>
<td>2.0 ± 2.3</td>
<td>8.9 ± 2.5‖</td>
<td>1.8 ± 1.2</td>
<td>6.8 ± 1.5‖</td>
<td>3.7 ± 1.2</td>
<td>5.0 ± 1.9</td>
</tr>
</tbody>
</table>

*Significant increase in from before training \( P < .001 \).
†Significantly greater than young and older women \( P < .048 \).
‡Significantly greater than young and older women, and older men \( P < .050 \).
§Significantly greater than women \( P < .001 \).
¶Significantly greater than older subjects \( P < .050 \).
‖Significantly greater than older women \( P = .003 \).
**Significantly greater than men \( P < .013 \).
††\( P = .083 \) versus older men.
‡‡\( P = .061 \) versus men.
muscle volume with ST was modestly correlated with the change in quadriceps muscle volume ($r = 0.65; P < .001$).

**Muscle CSA**

A comparison between ST-induced changes in thigh muscle volume and mid-thigh muscle CSA (Table 2) revealed that both measures increased significantly in each group ($P = .001$). Changes in mid-thigh muscle CSA with ST correlated moderately ($r = 0.76$) with changes in mid-thigh muscle volume ($P < .001$). When age and gender groups were compared at baseline, mid-thigh muscle CSA was significantly greater in men than in women ($P < .001$) and greater in young than in older subjects ($P < .050$). In addition, women demonstrated a significantly higher percentage increase in mid-thigh muscle CSA than men in response to ST ($P < .013$) and a trend for a greater absolute increase in CSA ($P = .061$).

**DISCUSSION**

The few studies that have compared young and older subjects, or men and women, provide conflicting evidence about possible age differences and gender-related differences in muscle mass response to ST. In the present investigation, neither age nor gender differences existed in muscle volume response to a 6-month whole-body ST program, although group differences were noted in the mid-thigh CSA response. The lack of a gender difference was unexpected because the men’s increase in muscle volume was twice that of the women in response to a 9-week unilateral ST program reported previously in these same subjects.$^6$

Although ST has been shown previously to elicit significant increases in muscle mass in older men$^{16}$ and women,$^i$ few direct comparisons of muscle mass response to ST have been completed among young and older men and women simultaneously. Welle et al.$^7$ demonstrated less hypertrophy in older men and women than in young men and women in response to 3 months of ST, and Häkkinen et al.$^4$ reported less hypertrophy in older men than in older women and middle-aged men and women in response to 6 months of high-resistance ST. In contrast, we observed similar increases in muscle mass in young men and women as in older men and women, in response to both single-muscle-group$^e$ and whole-body (present investigation) ST programs. Häkkinen et al.$^18$ reported no differences in quadriceps CSA increases in response to ST in young and older men. Although it is possible that the level of resistance might explain the lower hypertrophy reported in older individuals by Welle et al.,$^7$ Häkkinen et al.$^4$ used a high-resistance ST program that included explosive-type exercises. The use of muscle CSA$^4,7,18$ rather than muscle volume measurements$^6$ may also be an important factor. Given the substantial evidence for reduced hypertrophy$^8,9$ and altered myogenic regulatory factor expression$^{21}$ in response to muscle overload in older animals, further work is needed to explain the conflicting findings regarding age effects on the muscle mass response to ST in humans.

Recent evidence has also indicated possible gender differences in the muscle mass response to ST. Our group demonstrated lower muscle volume increases in women than in men in response to 9 weeks of high-resistance unilateral ST,$^i$ and Häkkinen et al.$^4$ reported significant increases in quadriceps CSA in older women, but not in older men, in response to 6 months of heavy-resistance ST. McCartney et al.$^{22}$ observed no gender differences in muscle hypertrophy after the first 10 months of moderate ST in older men and women, but a trend was noted for a greater increase in quadriceps CSA in men when a further training period was introduced. Joseph et al.$^{11}$ reported increased FFM in men but not in women following a 12-week ST program. In contrast, the present investigation and others$^{19,20,22,24}$ have demonstrated no significant gender differences in the muscle hypertrophic response to ST. An explanation for this discrepancy has not been established, but general experimental variation and differences in the ST programs used in each investigation likely contribute. Although the subjects who participated in the current study were also studied in our previous unilateral knee extension ST study,$^e$ differences between the training programs limited our ability to compare the studies, which was not a purpose of the original investigation. However, differences in the muscle volume response between the studies indicate the need for future investigations designed to determine muscle mass responses to specific ST programs in which only one factor (e.g., number of exercises, training volume, length of detraining) differs between the two training programs. This was not done in our studies, because this comparison of ST programs was not a major focus of our investigation, and the need for this comparison became evident only after we analyzed the data.

Much of the research literature addressing muscle mass response to ST has focused on changes in muscle CSA.$^3,4,18,25$ In the current investigation, only a moderate correlation was observed between training-induced changes in mid-thigh muscle CSA and changes in thigh muscle volume ($r = 0.76; P < .001$). Women exhibited a significantly greater percentage increase in mid-thigh muscle CSA than men, a difference not observed in the thigh or quadriceps muscle volume data, and a trend for a greater absolute change in CSA ($P = .061$), also not seen in the volume data. In addition, young women demonstrated a trend toward a larger relative increase in CSA than did older men ($P = .083$). The differences observed in the CSA data compared with the volume data, when combined with the fact that muscle hypertrophy has been shown to be nonuniform along the muscle belly in response to ST,$^{14}$ provide support for the recommendations$^{26}$ that muscle volume rather than CSA be studied in investigations where muscle mass or hypertrophy are primary variables of interest.

In summary, neither age nor gender influenced the muscle volume response to ST, with similar relative increases in thigh and quadriceps muscle volumes among the groups. Thigh or quadriceps muscle volume determinations, although more time consuming, may be more suitable than mid-thigh CSA for the study of muscle mass and hypertrophy responses to ST.

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