Resistance Training Reduces Susceptibility to Eccentric Exercise-Induced Muscle Dysfunction in Older Women

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This study evaluated the effect of age on susceptibility to muscular weakness and damage caused by eccentric (ECC) exercise and determined whether this susceptibility was altered by resistance training. Young and older women performed concentric (CON) and ECC one repetition maximum (1 RM) strength tests of the quadriceps femoris. Older women also performed knee extension training for 12 weeks. An unaccustomed bout of ECC knee extension exercise was performed before and after training, and CON and ECC 1 RM were reassessed for 11 days after the ECC bout. Magnetic resonance imaging was used to evaluate changes in muscle water content associated with muscle damage. Before training, older subjects showed a larger decline in CON (p < 0.008) and ECC (p < 0.03) strength induced by the unaccustomed ECC bout, compared with the young subjects. One day following the ECC bout, the older women showed a 24% reduction in CON and a 27% reduction in ECC 1 RM, compared with only 6% (CON) and 10% (ECC) in the younger women. A magnetic resonance imaging evaluation indicated that edema or damage was significantly greater in the older untrained women than it was in young women (p < 0.05), but the resistance-trained older women showed no greater muscle injury than the young women (p > 0.05). Resistance-trained older women showed no greater decline than sedentary young women in either CON (p > 0.05) or ECC (p > 0.05) strength. In conclusion, sedentary older women are more susceptible to ECC-induced muscle dysfunction, but resistance training reduces this susceptibility.

HUMAN aging is often associated with decreased skeletal muscle function. It has been widely reported that this reduced function is due in part to reductions in physical activity, loss of muscle mass, decreased metabolic capacity, and deteriorations in neuromuscular parameters (1–5). Unaccustomed eccentric (ECC) muscle contractions are known to induce ultrastructural muscle damage, declines in strength, and delayed onset muscle soreness. Because many older individuals have low or inadequate muscle strength, further decrements in strength such as those that occur after ECC exercise are more likely to impair everyday function and mobility. Individuals who are older, weaker, or both may be less able to withstand even a temporary reduction in strength and still maintain their ambulatory ability. Although not widely studied, it has been suggested that older men are more susceptible to ultrastructural muscle damage induced by acute unaccustomed ECC exercise compared with young men (6). Other studies have shown that older men and women are more susceptible to muscle damage even after accustomed ECC contractions compared with their young counterparts (7,8). None of these studies have evaluated muscle performance or function–strength following the ECC exercise. This is an important area to study, because inadequate muscle strength is associated with failure to perform activities of daily living and other everyday tasks (9). The aforementioned studies identified damage by using muscle biopsy techniques and made efforts to quantify the extent of myofibrillar disruption. Recently, magnetic resonance imaging (MRI) has been used to identify muscle that was damaged by ECC contractions (10–12). Increases in signal intensity in T2 (transverse or spin-spin) relaxation time of muscle following ECC exercise correlate well with ultrastructural changes observed in muscle biopsies obtained following novel ECC exercise (13).

Therefore, the purposes of this study were to document the extent of muscle dysfunction (as indicated by strength reduction and MRI changes) in response to acute unaccustomed ECC exercise in young and older women, and to evaluate whether resistance training would have an impact on these responses in older women. The specific hypotheses being tested were (1) older women would demonstrate more muscle dysfunction in response to the same relative ECC challenge compared with young women (6). Other studies have shown that older men and women are more susceptible to muscle damage even after accustomed ECC contractions compared with their young counterparts (7,8). None of these studies have evaluated muscle performance or function–strength following the ECC exercise. This is an important area to study, because inadequate muscle strength is associated with failure to perform activities of daily living and other everyday tasks (9). The aforementioned studies identified damage by using muscle biopsy techniques and made efforts to quantify the extent of myofibrillar disruption. Recently, magnetic resonance imaging (MRI) has been used to identify muscle that was damaged by ECC contractions (10–12). Increases in signal intensity in T2 (transverse or spin-spin) relaxation time of muscle following ECC exercise correlate well with ultrastructural changes observed in muscle biopsies obtained following novel ECC exercise (13).

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evaluated responses to ECC resistance exercise in older women.

**METHODS**

**Overall Design**

Young and older subjects were strength tested for the unilateral concentric (CON) and ECC knee extension one repetition maximum (1 RM). Then they performed a bout of unaccustomed ECC knee extension exercise consisting of 100 repetitions of a moderate load (75% of 1 RM). Muscle dysfunction was evaluated based on strength loss over 11 days following the ECC bout and changes in signal intensity and cross-sectional area on magnetic resonance images (MRI) obtained 3 days after the ECC bout. Older subjects then participated in 12 weeks of bilateral knee extension resistance training. After training, unilateral CON and ECC 1 RM were retested. The unaccustomed ECC bout was performed again at the same relative load but using the contralateral leg. Muscle dysfunction was again assessed by strength loss and MRI changes. A flow chart summarizing the experimental design is shown in Figure 1.

**Subjects**

Six young (23 ± 4 years) and six older (66 ± 5 years) women participated in the study. None of the women had ever participated in resistance exercise training, and none had been involved in aerobic exercise training for at least 2 years. Although relatively sedentary, all women lived independently in the community and had normal body weights (mean ± SD; young = 61.8 ± 8.2; older = 61.4 ± 4.5; p > .05). Potential participants were excluded if they had ferrous metal implants, uncontrolled cardiovascular disease, or orthopedic limitations that prohibited maximal knee extension exercise. Physician approval was required prior to participation for the older women. The study was approved by the Institutional Review Boards of Syracuse University and the State University of New York Upstate Medical University.

**Strength Testing**

Following two orientation sessions, unilateral 1 RM isometric knee extension strength tests were performed on a knee extension dynamometer (MedX, Ocala, FL). The orientation sessions consisted of an evaluation of knee extension range of motion, adjustment of the dynamometer seat, and practice lifts. CON and ECC unilateral strength were separately evaluated. Ninety percent or more of a subject’s predetermined range of motion was required for a successful lift. The bilateral 1 RM had the same procedure and completion criteria. For the unilateral ECC 1 RM, the weight was lifted and supported at full extension by the investigator. The subject supported the weight with the test leg and slowly lowered it through the ECC range of motion. For a successful attempt the subject was required to catch the weight with the test leg by 75% of their predetermined range of motion and lower it in a controlled manner without dropping the weight at the end of the range of motion. Bilateral CON and ECC strength tests were performed by using the same procedures and evaluation criteria. Prior to the study, subjects were tested over the course of several days, but they were given at least 48 hours rest between testing sessions. If a subject’s 1 RM strength exceeded the previous test by more than 1 kg, she was required to return to the laboratory on another day to be tested again. When consecutive strength tests either decreased or increased by less than 1 kg, the highest value achieved was recorded as the 1 RM. This process was used to ensure that subjects were well familiarized with the activity and that strength tests were repeatable (15). The postexercise and posttraining strength tests were performed only once because subjects were already familiarized. The pretraining value was obtained after the initial ECC testing; the posttraining value was obtained on the last day of training.

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Figure 1. Flow chart of experimental design. The bold text indicates that both younger and older subjects participated in testing; plain text indicates tests in which only the older subjects participated. CON = concentric; ECC = eccentric; 1 RM = one repetition maximum; MRI = magnetic resonance imaging.
**Unaccustomed Eccentric Exercise**

All subjects performed a unilateral ECC knee extension exercise bout consisting of 10 sets of 10 repetitions at 75% of the ECC 1 RM for the test leg. Two minutes of rest were allowed between sets. Initially the test leg was randomly selected. Subjects returned on days 1, 3, 4, 7, 9, and 11 following the unaccustomed ECC exercise. The unilateral CON and ECC 1 RM were tested on each day to document the decrease in strength associated with the ECC bout.

The older women performed a second bout of ECC exercise following the resistance training period. The same relative load was used (75% of the posttraining ECC 1 RM), because of training-induced strength increases this was a higher absolute load. The contralateral leg was tested posttraining because of the well known “repeated bouts effect” of ECC exercise (11,16–18). Therefore, in the older subjects the test leg was randomly selected for the first ECC bout (pretraining). The contralateral leg was tested for the second ECC bout (posttraining) so that each leg performed the unaccustomed ECC exercise only one time because it is known that a single bout of high-intensity ECC exercise protects against dysfunction resulting from similar ECC exercise. Strength tests were repeated in the same manner and with the same time course following this second bout.

**MRI Scans**

MRIs were obtained before the study began and again 3 days after each ECC bout and analyzed for muscle cross-sectional area (CSA) and increases in signal intensity (T2), which correlates highly with ultrastructural changes associated with muscle damage observed in muscle biopsies. Subjects were required to lie supine for 30 minutes to allow any venous pooling or accumulation of body fluids to equilibrate before imaging (19). Transaxial images (1.5T; TR 2000; TE 30,60; 256 × 256 matrix; 40-cm field of view; 1-cm slices; 0 spacing; 1 nsec; scan time 4:40) were obtained between the knee joint and the femoral head. The CSA of the quadriceps femoris (QF) was determined by manually tracing around the muscle. Total T2 and the area of muscle sectioning CSA in repeat measurements of the same scans.

**Resistance Training**

The older women performed bilateral seated knee extension resistance training twice per week for 12 weeks. Each training session consisted of sets of 8–12 repetitions to failure, using both CON and ECC contractions. When 12 or more repetitions could be completed the load was increased. On average, subjects trained at ~65% of CON 1 RM. Subjects performed three sets during weeks 1–3, four sets during weeks 4–7, and five sets during weeks 8–12. Unilateral and bilateral CON and ECC 1 RM and bilateral 5 × 10 RM strength tests were performed before and after training to document the effectiveness of training. The unaccustomed unilateral ECC bout was performed before and after training, with different legs being used at each time to avoid the confounding effect of the initial ECC bout.

**Specific Tension**

Specific tension was calculated by dividing the concentric 1 RM in kilograms by the CSA in square centimeters. The resting, pre-ECC exercise MRI scan was used for the CSA value. Specific tension was calculated before and after training in the older subjects and only once in the younger subjects. Comparisons between younger and older subjects were made as well as before training and after training comparisons in the older subjects only.

**Statistical Analysis**

A three way analysis of variance (ANOVA) with repeated measures was performed (Group × Time × Side) for each of the variables. When interactions occurred, a series of two-way ANOVAs were performed. Preplanned contrasts were specified for individual means comparisons for post hoc testing. A value of \( p = .05 \) was used to define significance.

**Results**

**Training and Specific Tension**

The training-induced adaptations in bilateral strength and QF CSA have been reported previously (22). Briefly, bilateral 1 RM strength increased by 13% (\( p < .05 \)) and bilateral 5 × 10 RM strength increased by 25% (\( p < .05 \)). There were significant (\( p < .05 \)) increases in QF CSA, with a 5% increase in the right QF and a 9% increase in the left QF. Despite the training-induced improvements in strength and CSA, the younger women had greater 1 RM strength and QF CSA than the older women at all times during the study. The unilateral 1 RM values are shown in Figure 2. As a result of training, older women showed a 13.8% and 14.9% increase in unilateral CON and ECC 1 RM strength, respectively (\( p < .05 \)). Even after training, the older women were still weaker than the sedentary young women (\( p < .05 \)). No changes in specific tension were observed with training in the older subjects (\( p > .05 \)). There were no age-related differences in specific tension (\( p > .05 \)). There was a significant difference between the right and left sides for the older subjects, regardless of training status (\( p < .05 \); see Table 1).

**Muscle Performance Following ECC Exercise**

Untrained older women showed a larger decline in CON and ECC 1 RM strength 24 hours after the unaccustomed ECC exercise as compared with sedentary young subjects (\( p < .05 \); Figure 3). The older women showed a 24% reduction in CON and a 27% reduction in ECC 1 RM strength compared with only a 6% (CON) and 10% (ECC) reduction.
in the younger women. The 6% and 10% reduction in strength in the younger women did represent a statistically significant decrement in strength \( (p < 0.05) \). Following 12 weeks of resistance training the older women had an attenuated response to the ECC exercise bout, losing only 14% (CON) and 12% (ECC) of 1 RM strength. Following training the strength loss associated with ECC exercise was similar between sedentary young and trained older women \( (p > 0.05) \). There were no significant strength changes in the control limbs, which did not perform ECC exercise \( (p > 0.05) \). Data are presented as relative changes; absolute differences shared the same statistical significance.

**Time Course of Recovery of Muscle Function**

Prior to training the time required to recover the strength lost as a result of the ECC exercise bout was also different between groups, with untrained older women requiring a longer time to recover compared with young women. The time course of recovery was similar between groups following training, indicating that training caused the older women to be able to recover faster than they had pretraining (Figures 4A and 4B). For untrained older women, CON 1 RM strength was significantly lower than baseline for 7 days following the ECC exercise bout (Figure 4A; \( p < 0.05 \)), and ECC 1 RM strength was depressed for 3 days afterward (Figure 4B; \( p < 0.05 \)). Following training, both CON and ECC 1 RM strength returned to normal baseline values by day 3. Sedentary young women showed a return of CON and ECC strength by day 4. There were no significant changes in the control limb on any of the 11 days \( (p > 0.05) \); data not shown.

**MRI Assessment of Muscle Dysfunction**

Muscle dysfunction was assessed by MRI 3 days after the unaccustomed ECC exercise. Total area of QF was increased 3 days following the ECC exercise in the untrained older women \( (p < 0.05) \), but not in any other group (Table 2). Untrained older women showed a significant increase in average muscle T2 \( (p < 0.05) \); Table 3). More detailed analyses showed that 15% of the QF CSA showed elevated T2, compared with only 1% in the control QF of untrained older women \( (p < 0.05) \); Table 4). After training, only 3% of the QF CSA demonstrated elevated T2 in response to ECC exercise in the older women. This is comparable with the 1% of QF CSA showing elevated T2 in sedentary young women \( (p > 0.05) \).

**DISCUSSION**

The major findings of this study were (1) that sedentary older women are more susceptible to ECC-induced muscle dysfunction than sedentary young women and (2) that resistance training alleviates this susceptibility so that trained older women have similar responses to ECC exercise compared with sedentary young women. T2 elevation in MRI images was used as an indirect assessment of muscle damage. Elevated T2 correlates well with ultrastructural changes observed in muscle biopsies following ECC exercise (13),

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**Table 1. Specific Tension Significantly Different From Left Side**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Right Side (kg/cm²)</th>
<th>Left Side (kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young</td>
<td>1.06 ± 0.04</td>
<td>1.04 ± 0.04</td>
</tr>
<tr>
<td>Older untrained</td>
<td>0.93 ± 0.09</td>
<td>0.88 ± 0.09*</td>
</tr>
<tr>
<td>Older trained</td>
<td>0.99 ± 0.08</td>
<td>0.92 ± 0.71*</td>
</tr>
</tbody>
</table>

*Note: Values are mean ± SE.* Significant difference from right side; there were no differences related to age or training status.
Figure 4. Time course of recovery for quadriceps femoris one repetition maximum (1 RM) concentric (A) and eccentric (B) strength for 11 days following unaccustomed eccentric exercise. Values are mean ± SE. *Indicates significant difference within groups compared with day 0.

and this measure has been used in previous studies to indirectly evaluate ECC-induced muscle damage (10–12,23,24). MRI offers some advantages over conventional biopsy techniques because it allows for evaluation of the entire cross-sectional area of the muscle over a long length, in this case allowing for evaluation of all of the muscles of the QF group; MRI is also noninvasive, thus eliminating the possibility that the evaluation by procedure itself induces dam-

age. Muscle dysfunction was evaluated by using dynamic strength tests (1 RM). Dynamic functional (CON and ECC strength) differences between young and older women in response to ECC exercise were observed.

Fortunately, resistance training can alleviate vulnerability to ECC dysfunction in older women. These results are supported by other studies. Dedrick and Clarkson have shown that older women have a greater loss of isometric forearm strength and slower recovery from a single novel bout of ECC exercise compared with young women (25). Manfredi and colleagues (6) have shown that older men exhibit greater muscle damage, assessed by biopsy, compared with young men. It is not so clear why older muscle suffers more dynamic strength loss when exposed to the same relative load as younger muscle, but this might be related to age differences in the integrity of the muscle cytoskeleton or age-related declines in the number of motor units resulting in greater force per motor unit in older subjects. The fact that older muscle recovers from ECC-induced dysfunction more slowly than young muscle implies a reduced growth or healing capability. There are several possible explanations, such as decreased myofibrillar protein synthesis in older subjects (26), or a neural limitation of force output in older but not younger subjects. This last possibility seems less likely because the intrinsic ability of muscle to generate force has been shown to be lower following ECC exercise, at least in young subjects (27,28).

Another major finding of the present study was that resistance training reduced susceptibility to unaccustomed ECC-induced muscle dysfunction. Roth and colleagues (6) have shown that older men exhibit greater force loss when exposed to the same relative load as younger muscle, but this might be related to age differences in the number of motor units resulting in greater force per motor unit in older subjects. The damage was not severe enough to compromise muscle strength and function. The age-related disparity was not evi-

Table 3. T2 Values of the QF Obtained 3 Days After Unaccustomed ECC Exercise

<table>
<thead>
<tr>
<th>Subject</th>
<th>Treatment Leg (ms)</th>
<th>Control Leg (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-ECC</td>
<td>Post-ECC</td>
</tr>
<tr>
<td></td>
<td>Pre-ECC</td>
<td>Post-ECC</td>
</tr>
<tr>
<td>Young</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.4 ± 1.5</td>
<td>30.9 ± 1.8</td>
<td>30.5 ± 0.7</td>
</tr>
<tr>
<td>Older Untrained</td>
<td>33.1 ± 1.8</td>
<td>34.4 ± 1.2</td>
</tr>
<tr>
<td>33.0 ± 2.3</td>
<td>33.2 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>Older Trained</td>
<td>33.4 ± 2.2</td>
<td>33.4 ± 0.09</td>
</tr>
</tbody>
</table>

Notes: Values are mean ± SD. QF = quadriceps femoris; ECC = eccentric.

*Significant difference from pre-ECC.

Table 4. Percentage of QF CSA Showing Elevated T2 Values 3 Days After Unaccustomed ECC Exercise

<table>
<thead>
<tr>
<th>Subject</th>
<th>Treatment Leg (%)</th>
<th>Control Leg (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young</td>
<td>1.0 ± 0.5</td>
<td>0.3 ± 0.5</td>
</tr>
<tr>
<td>Older Untrained</td>
<td>15.0 ± 4.0*</td>
<td>1.2 ± 1.7</td>
</tr>
<tr>
<td>Older Trained</td>
<td>2.8 ± 4.1</td>
<td>1.7 ± 1.8</td>
</tr>
</tbody>
</table>

Notes: Values are mean ± SD. QF = quadriceps femoris; CSA = cross-sectional area; ECC = eccentric.

*Significant difference from control for all other conditions.

Notes:
- CSA = cross-sectional area; QF = quadriceps femoris; ECC = eccentric.
- *Significant difference from pre-ECC exercise.
dent in men, suggesting gender differences in response to muscle damage (7). The training stimulus in the Roth studies was much greater than in the current study, both in intensity and frequency. Our results show that one benefit of training in older women is protection against unaccustomed ECC loading. The Roth papers suggest that the training itself induces microscopic muscle damage that is minor enough not to affect strength. Such minor damage has been previously hypothesized to provide some protection against subsequent similar ECC bouts—often called the “repeated bout effect” (18). Our data extend this one step further and suggest that training may provide protection against subsequent unaccustomed ECC loading, including bouts that may be of higher intensity and higher number of repetitions than the original training episodes themselves. One question that our data do not address is the threshold required for protection against repeated ECC bouts. For example, how many training sessions and what minimal training intensity is required to reduce vulnerability to ECC dysfunction? Others who have studied the repeated bout effect have found that the duration of the initial bout has no influence on the responses to a second bout, such that performing a single bout of 10 or 30 maximal repetitions does not provide protection against a second bout of 50 maximal contractions (29). Clearly it must take more than one bout to provide the protection observed in the current study.

There were no differences in specific tension between age groups or related to training status. Both 1 RM and CSA were equally increased with training. This is probably in part due to the comprehensive orientation to strength training that was conducted with all subjects prior to 1 RM testing. All subjects were tested for 1 RM strength until consistent measurements were obtained, at which time 1 RM strength was recorded. This eliminates a substantial “learning effect,” which could confound the results of a specific tension calculation. Furthermore, there were no age-related differences in specific tension. There were side differences in the older subjects before and after training, with the right leg showing higher values of strength/CSA. It is not known what accounted for this difference.

One limitation to the study is that we were not able to assess each subject’s everyday level of physical activity. None of the subjects had ever performed resistance training and none had been involved in aerobic exercise training for the past 2 years; however, it is possible that subjects did differ (both between and within groups) in their everyday tasks.

It is of great practical significance to note that resistance training was able to alleviate the disparity between young and older subjects for both the strength loss and the delayed recovery of strength. The ECC loads used in this study (75% of 1 RM) are not particularly high compared with those of some other studies and as evidenced by the mild reductions in strength observed in the young subjects. However, even these moderate loads were enough to cause significant strength reduction in untrained older women. However, following training, the older women responded in a similar manner to that of the young women. This has practical application to everyday activities. Older individuals face unaccustomed ECC activities on a regular basis, especially associated with seasonal variation in activity. For example, many older people increase their physical activity in the spring when the weather in colder climates improves (30). They find themselves doing more household and yard work, which they are not accustomed to (31) and which may involve an eccentric component such as lowering their body weight in a squatting motion while doing yard work. Older women are more vulnerable to temporary strength loss associated with ECC exercise, and presumably muscle soreness when performing everyday tasks, almost all of which involve some ECC component. Several studies have demonstrated thresholds of leg strength below which ambulatory function is impaired (32–34). Stronger individuals whose strength well exceeds the minimum threshold have a substantial strength reserve, and so transient reductions in strength might have a minimal impact on ambulatory function. However, many older or weaker individuals have leg strength values very close to the minimal threshold. If these individuals experience a transient reduction in strength following ECC exercise, it may affect their ability to perform everyday tasks or render them more vulnerable to falls or other injuries. In addition to the other well-known benefits of resistance training, older women can expect to reduce their susceptibility to ECC dysfunction with training. Furthermore, the training protocol used in this study provided only a moderate training stimulus. Training was conducted only 2 days/week and subjects performed only three to five sets (depending on the week). The entire training program consisted of 24 exercise sessions, each lasting only a few minutes. Even if additional exercises were added, such training might be more easily incorporated into a person’s schedule than the often-prescribed 3–5 days/week.

Acknowledgments

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