Early-phase neuromuscular adaptations to high- and low-volume resistance training in untrained young and older women

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Early-phase neuromuscular adaptations to high- and low-volume resistance training in untrained young and older women

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Abstract
We compared early-phase effects between high- and low-volume moderate-intensity resistance training on lean muscle volume, maximal bilateral leg extension strength, maximal isometric torque, normalized maximal bilateral leg extension strength, normalized maximal isometric torque, and muscle recruitment of the right knee extensors in previously untrained young (23.8 ± 3.7 years, range 20–30 years; n = 16) and older women (67.6 ± 6.3 years, range 60–78 years; n = 15). Participants performed either one set or three sets of 10 repetitions for the bilateral leg extension and bilateral leg curl at an intensity of 50–75% of maximal strength 3 days per week for 10 weeks. Main effects were observed over time for all variables (P < 0.05) with increases ranging from 7.1% to 27.8% and effect sizes (Cohen’s d) ranging from 0.45 to 1.38. No interactions between age and training volume over time were observed for any variable (P > 0.05). Our results provide a novel contribution to the literature demonstrating that additional neuromuscular adaptation during early-phase moderate-intensity resistance training in previously untrained young and older women may not be elicited through higher-volume training when training loads are matched provided that a minimal volume threshold is attained. These findings may have practical applications for the prescription of short-duration resistance training programmes to enhance muscle strength and achieve hypertrophic and non-hypertrophic adaptations in untrained women.

Keywords: Strength training, ageing, training volume, strength, hypertrophy, neuromuscular adaptation

Introduction
Resistance training is recognized as the most effective exercise intervention for increasing muscle mass and strength in young and older individuals (American College of Sports Medicine, 1998a, 1998b; Pollock et al., 2000), and is frequently prescribed for enhancing general health, improving athletic performance, injury prevention, musculoskeletal rehabilitation, reducing falls risk, and increasing functional ability. Adaptations to resistance training are dependent on the interaction between several acute programme variables, including training load (intensity), volume, frequency, exercise selection, exercise order, rest, and repetition velocity (Bird, Tarpenning, & Marino, 2005; Hass, Feigenbaum, & Franklin, 2001). Studies investigating the influence of specific acute training variables on muscle mass and strength gain in young or older individuals have primarily examined training load (Baker, Wilson, & Carlcyon, 1994; Bemben, Fetters, Bemben, Nabavi, & Koh, 2000; Hunter & Treuth, 1995; Taaffe, Pruitt, Pyka, Guido, & Marcus, 1996), while studies examining the effect of training volume are limited.

Training volume is calculated as the product of the number of repetitions completed per set and the number of sets completed per training session (Hass et al., 2001) and directly influences the total work performed during training (where total work performed is the product of training load and training volume). In this regard, it has been suggested that higher-volume resistance training is likely to produce superior adaptations compared with low-volume training due to the greater exercise stimulus (Kraemer et al., 2000; Stone, Johnson, & Carter, 1979). In young individuals, the effect of high- versus low-volume resistance training on muscle mass and strength development remains unresolved. This is because emphasis has been placed on comparing the effects of single- versus multiple-set training (Carpinelli & Otto, 1998; Galvao & Taaffe, 2004; Hass,
Garzarella, De Hoyos, & Pollock, 2000; Rhea, Alvar, Ball, & Burkett, 2002), rather than training volume per se. Although such studies have manipulated training volumes between groups, they frequently fail to equate training load and often require single-set groups to perform repetitions to failure while multiple-set groups do not (Kraemer et al., 2000; Stone et al., 1979). As such, the influence of training volume alone on muscle mass and strength development is difficult to determine.

In older adults, previous studies investigating the influence of the acute programme variables on muscle mass and strength development associated with resistance training have largely examined the effect of training load. These studies indicate that low-intensity resistance training (40% of one-repetition maximum, 1-RM) is equally effective (Bemben et al., 2000; Taaffe et al., 1996), or possibly more effective (Hunter & Treuth, 1995), than high-intensity resistance training (80% of 1-RM) for developing strength in older participants. Such results suggest that older individuals retain a high level of residual neuromuscular plasticity amenable to a resistance training intervention. Furthermore, such results also suggest that the stimulus thresholds required to elicit maximal strength development may be lower for older individuals compared with their young counterparts (Rhea, Alvar, Burkett, & Ball, 2003). Thus, older individuals might respond favourably to low-volume resistance training. However, studies comparing the effects of high- and low-volume resistance training in older adults are limited and the accompanying neuromuscular adaptations are not fully reported (Galvao & Taaffe, 2005). Therefore, the purpose of this study was to compare the early-phase strength gains and neuromuscular adaptations between high- and low-volume resistance training in untrained young and older women.

Materials and methods

Participants

Sixteen young women and 15 older women responded to advertisements to participate in the study. Participants were considered asymptomatic and screened for significant musculoskeletal, cardiovascular, and neurological disorders that might have influenced the results using a health history questionnaire. None of the older participants had ever taken hormone replacement therapy or angiotensin-converting enzyme inhibitors. All participants were non-smokers and performed intermittent, moderate-intensity physical activity (equivalent to brisk walking at 3–6 km · h⁻¹) (American College of Sports Medicine, 1998b) for 30–60 min on 3–5 days a week. None of the women had any background in regular resistance or aerobic training prior to the study. Written consent was obtained from all participants before starting the study, which was approved by the Institutional Ethics in Human Research Committee. Physical characteristics of the participants were obtained using standard procedures and are presented in Table I.

Research design

The present investigation consisted of a 13-week study period. Testing occurred on five separate occasions (weeks −3, 0, 3, 6, and 10) and was performed by the same investigator using identical test procedures. Weeks −3 to 0 served as a non-training period during which no resistance training was performed. This period was used to establish the reproducibility of the neuromuscular assessments. From weeks 0 to 10, participants performed a 10-week resistance training programme. During this period, participants were instructed to avoid any changes in diet and to continue participating in habitual activities they were accustomed to. All participants were briefly interviewed after the final training session of each week when they confirmed they complied with these instructions.

Resistance training protocol

Before data collection, participants were assigned to either a high-volume (three sets) or low-volume (one set) resistance training group that were balanced for age. The exercise intervention consisted of a fully supervised resistance training programme for the knee.

Table I. Physical characteristics of the young women and older women in the high-volume and low-volume resistance training groups (mean ± SD).

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Body mass index (kg · m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young women (n = 16)</td>
<td>23.8 ± 2.7</td>
<td>1.69 ± 0.07</td>
<td>68.7 ± 9.5</td>
<td>24.3 ± 3.9</td>
</tr>
<tr>
<td>Older women (n = 15)</td>
<td>67.6 ± 0.3*</td>
<td>1.60 ± 0.06</td>
<td>67.1 ± 10.6</td>
<td>26.1 ± 3.5</td>
</tr>
<tr>
<td>Three sets (n = 17)</td>
<td>45.6 ± 23.3</td>
<td>1.64 ± 0.08</td>
<td>69.5 ± 11.7</td>
<td>26.0 ± 4.1</td>
</tr>
<tr>
<td>One set (n = 14)</td>
<td>44.1 ± 23.1</td>
<td>1.66 ± 0.06</td>
<td>66.1 ± 7.2</td>
<td>24.2 ± 3.1</td>
</tr>
</tbody>
</table>

*Significantly different from young women (P < 0.01).
extensors and knee flexors 3 days per week with a minimum of 24 h rest between sessions for a period of 10 weeks. Training involved either one set or three sets of 10 repetitions for the bilateral leg extension and the bilateral knee flexion exercises, which were performed using a plate-loaded leg extension and leg curl bench (York Barbell Co., Toronto, ON, Canada). Participants performed a familiarization session prior to training, which involved three sets of the bilateral leg extension and leg curl. Verbal instructions and feedback were provided during this session to ensure that all participants could perform the training exercises correctly. Training intensity was 50% of maximal strength during week 1 and 75% of maximal strength for weeks 2–10. The lower training intensity during week 1 was used to familiarize the participants and enhance motor learning of the task before exposing them to the higher training intensity. Both exercises were performed throughout the full range of motion with participants instructed to perform the movements in a smooth, continuous motion. The velocity of each repetition was closely monitored and participants were given concurrent verbal feedback to ensure each repetition was performed with a 2-s shortening phase, 1-s pause, and a 2-s lengthening phase. Sets were separated by a rest period of 90–120 s, and 3 min rest was allowed between exercises. Each training session began with a warm-up, which consisted of one set of 10 repetitions for each exercise at an intensity of 40% of maximal strength. Although data collection was only performed on the knee extensors, the knee flexors were also trained to minimize the likelihood of developing any muscular imbalance. Before training began and at 2-week intervals throughout the training period, maximal strength for the bilateral knee extension and bilateral knee flexion exercises was determined on the training apparatus using the maximal-repetition method described by Charette et al. (1991). These data were used to adjust training loads as necessary throughout the training period to ensure that all participants continued to train at the required intensity. All maximal strength assessments were performed following the warm-up. After maximal strength testing, participants were given a 10-min rest and then performed the required training session. The number of exercise sessions completed over the 10-week training period (30 sessions in total) was 27.2 ± 1.1 for young women, 27.8 ± 1.3 for older women, 27.2 ± 1.4 for the three-set group, and 28.9 ± 0.9 for one-set group, which were not significantly different ($P > 0.05$).

**Lean knee extensor muscle volume**

Lean knee extensor muscle volume of the right extensors was determined using magnetic resonance imaging as previously described in detail (Cannon, Kay, Tarpenning, & Marino, 2007). Briefly, 11 axial images were obtained using a T1-weighted scanner with a 50-cm diameter body coil in a 1.5-T whole-body magnet (Magnetom Symphony Maestro, Siemens AG Ltd., Bayswater, Australia). Contractile and non-contractile tissues within each axial slice were quantified using the pixel intensity histogram technique using image analysis software (Scion Image for MS-Windows, Scion Corporation, Frederick, MD, USA). The scale for each image was determined by scanning an oil phantom with a known cross-sectional area using identical scanning parameters. Imaging software determined the area of the oil phantom in pixels, which was divided by the known cross-sectional area in cm² of the phantom. Following this, lean knee extensor muscle volume in cm³ was calculated by summing the 11 lean knee extensor muscle areas in cm² and multiplying by the inter-slice distance of 30 mm. The reproducibility of the lean knee extensor muscle volume measures was observed to be <1.6%.

**Maximal isometric torque**

Maximal isometric torque testing was performed using a Kin-Com isokinetic dynamometer (model 125H, Chattanooga Group Inc., Hixon, TN) with data captured using an AMLab data acquisition system (AMLab Technologies, Lewisham, Australia) at a sampling rate of 2500 Hz as described in detail elsewhere (Cannon, Kay, Tarpenning, & Marino, 2008). Briefly, participants were seated upright on the dynamometer with the hip flexed at 75° (0° being full extension) and were secured via waist and shoulder straps. During all tests, participants crossed their arms against their chest to ensure that additional forces did not contribute to performance. The axis of rotation of the dynamometer was aligned with the lateral epicondyle of the femur with the lower leg attached to the lever arm 1 cm above the lateral malleolus of the ankle. Testing was performed at 65° knee flexion and consisted of a minimum of six trials in which participants were instructed to exert maximal effort for 5 s. A minimum rest period of 1 min separated trials and testing continued until the final three trials had values within approximately ± 5% of each other, which typically required 6–8 trials for each participant. Strong verbal encouragement was provided during all trials and participants received continuous visual feedback of performance from a graphic display.

Force data were exported into spreadsheet software for Windows (Excel 1997–2003; Microsoft Corp., Redmond, WA) for analysis. Gravity correction was achieved by determining the average force applied to the transducer during the 1-s period immediately before contraction while the participant...
was at complete rest. The average load applied to the transducer during this period for each contraction was used to offset the force data recorded during testing. Following this, force data were multiplied by lever arm length to express data in units of torque (N · m). Maximal voluntary isometric torque was identified as the single highest torque value attained across all trials.

Normalized muscle strength

To provide an index of the neuromuscular contribution to performance, bilateral leg extension muscle strength (1-RM) and maximal isometric torque (MVC) per unit of lean muscle volume were calculated as: normalized 1-RM strength (kg · m⁻³) = [1-RM (kg)/muscle volume (m³)], and normalized MVC (N · m⁻³) = [MVC (N · m)/lean muscle volume (m³)].

Surface electromyography

Surface electromyographic signals (EMG) from the vastus lateralis and vastus medialis of the right thigh were captured during maximal isometric torque testing using two 8-mm diameter Ag/AgCl cup bipolar electrodes (EL258S, BioPac Systems Inc., Santa Barbara, CA) linked to an AMLab measurement acquisition system (AMLab Technologies, Lewisham, Australia) where data were sampled with a gain of 1000 V/V and a common mode rejection ratio > 120 dB at a sampling rate of 2500 Hz. For the vastus lateralis, electrodes were attached to the lateral surface of the thigh, approximately 10 cm above the top of the lateral border of the patella and orientated laterally 15° from vertical with the knee at full extension (Cram & Kasman, 1998). For the vastus medialis, electrodes were attached approximately 5 cm above the medial border of the patella and orientated medially at 55° from vertical with the leg at full extension (Cram & Kasman, 1998). In addition, an 8-mm Ag/AgCl cup electrode (EL258H, BioPac Systems Inc., Santa Barbara, CA) was attached to the patella of the opposing limb to ground the signals. Skin under the electrodes was shaved and the outer layer of epidermal cells was abraded. Oil and dirt on the skin was removed using a 70% isopropyl solution. A constant inter-electrode distance of 20 mm was employed for the recording electrodes for all tests.

For processing, EMG data were bandpass-filtered with cut-off frequencies of 10 Hz and 460 Hz, full-wave rectified, then smoothed using the root-mean-square with a sliding window of 50 ms. These procedures were performed using AMLab software (AMLab Technologies, Lewisham, Australia). The EMG data were then exported into spreadsheet software for Windows (Excel 1997–2003, Microsoft Corp., Redmond, WA) and averaged between vasti muscles to provide a global indication of knee extensor muscle activity. Subsequently, the average EMG value during the 500-ms period beginning at the attainment of maximal isometric torque was determined and used for analysis.

Statistics

A priori sample size calculations for a mixed-factorial analysis of variance (ANOVA) were performed using the following input parameters: effect size $F = 0.25$, type I error probability = 0.05, power = 0.80, number of groups = 2, number of repeated observations = 5, correlations among observations = 0.80, and nonsphericity correction = 1. Results indicated that 10 participants in each group would provide a statistical power of 87%. These procedures were performed using G*Power version 3.1.2 (Faul, Erdfelder, Lang, & Buchner, 2007).

Before analysis, data were log transformed (Portney & Watkins, 2000). Exploratory analyses revealed that all training-related data for the young women, older women, three-set group, and one-set group had a normal distribution (Kolmogrov-Smirnov statistic > 0.05). A mixed factorial ANOVA was applied to identify between-group and within-participant differences. Where Mauchy’s test of sphericity was significant, a Greenhouse-Geisser correction was applied to the within-participant analyses. Levene’s test of equality of error variance between participants did not show statistical significance for any of the analyses ($P > 0.3$). Where a significant main effect and/or interaction was observed between groups, a univariate ANOVA was used to identify the source of significance. A Bonferroni adjustment for pairwise comparisons was applied where appropriate and statistical significance was set at $P < 0.05$.

Data obtained between weeks −3 and 0 for maximal strength, maximal isometric torque, and EMG were used to establish measurement reproducibility and the threshold change within participants required to identify a meaningful training effect. Measurement reproducibility was assessed using a one-way ANOVA with repeated measures and the technical error of the measurement. All statistical procedures were performed using SPSS™ for MS-Windows version 16.0 (Statistical Package for the Social Sciences, Chicago, IL). Technical error of the measurement was calculated as the square root of the sum of the squared differences between corresponding test scores divided by twice the sample size, and is expressed as a percentage of grand mean across both tests (Dahlberg, 1940).

Data obtained between weeks 0 and 10 were assessed for the magnitude of change within participants over time, which was quantified as: $\Delta (\%) = (week 10 − 0) / ((week 10 + 0) / 2)$.
The effect size (ES) was also calculated for within-participant changes over time to determine the practical significance of the training-related adaptations and was calculated as: Cohen’s $d = [(week 10 mean – week 0 mean)/pooled standard deviation for weeks 0 and 10]$. An effect size of $<0.20$ was considered trivial, $0.20–0.49$ small, $0.50–0.79$ moderate, and $>0.80$ large (Cohen, 1988). Descriptive statistics are presented as means ± standard deviations ($\bar{s}$).

Results

Muscle hypertrophy

Lean knee extensor muscle volume before and after resistance training is presented in Figure 1. A significant main effect was observed for lean knee extensor muscle volume over time ($P < 0.01$); however, no interactions between age or training volume and time were apparent ($P > 0.05$). The magnitude of change within participants and the accompanying effect sizes for lean knee extensor muscle volume are presented in Table II.

Maximal strength

Maximal strength during the 3-week non-training phase and the 10-week resistance training period is presented in Figure 2. No significant differences were observed within participants between weeks $-3$ and $0$ ($P > 0.05$). The technical error of the measurement for maximal isometric torque between weeks $-3$ and $0$ ranged from 4.0% to 7.1%. A significant main effect was observed for maximal isometric torque over time ($P < 0.01$); however, no significant interactions between age or training volume and time were apparent ($P > 0.05$). The magnitude of change within participants and the accompanying effect sizes for maximal isometric torque are presented in Table II.

Surface electromyography

Electromyography during the maximal voluntary isometric contraction during the 3-week non-training phase and the 10-week resistance training period is presented in Figure 4. No significant differences were observed within participants between weeks $-3$ and $0$ ($P > 0.05$). The technical error of the measurement for EMG between weeks $-3$ and $0$ ranged from 3.2% to 5.0%. A significant main effect was observed for EMG over time ($P < 0.01$); however, no significant interactions between age or training volume and time were apparent ($P > 0.05$). The magnitude of change within participants and the accompanying effect sizes for EMG are presented in Table II.

Normalized maximal strength and normalized maximal isometric torque

Normalized maximal strength and normalized maximal isometric torque before and after the resistance training period are presented in Figure 5. A significant main effect was observed for normalized maximal strength and normalized maximal isometric torque over time ($P < 0.01$); however, no interactions between age or training volume and time were apparent ($P > 0.05$). The magnitude of change within participants and the accompanying effect sizes for normalized maximal strength and normalized maximal isometric torque are presented in Table II.

Discussion

To our knowledge, this is the first study to compare short-term strength gains and hypertrophic and non-hypertrophic adaptations between high- and
Table II. Magnitude of change within participants and accompanying effect size for lean muscle volume, strength performance, and muscle recruitment following the 10-week resistance training period (mean ± s).

<table>
<thead>
<tr>
<th>Group</th>
<th>Lean muscle volume</th>
<th>Normalized 1-RM</th>
<th>Normalized MVC</th>
<th>Normalized EMG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δ%</td>
<td>ES</td>
<td>Δ%</td>
<td>ES</td>
</tr>
<tr>
<td>Young women (n = 16)</td>
<td>8.9 ± 2.5</td>
<td>0.75</td>
<td>25.5 ± 4.4</td>
<td>1.25</td>
</tr>
<tr>
<td>Older women (n = 15)</td>
<td>8.7 ± 2.7</td>
<td>0.71</td>
<td>26.8 ± 5.0</td>
<td>1.37</td>
</tr>
<tr>
<td>Three sets (n = 17)</td>
<td>9.6 ± 2.8</td>
<td>0.51</td>
<td>24.7 ± 5.0</td>
<td>0.95</td>
</tr>
<tr>
<td>One set (n = 14)</td>
<td>7.8 ± 2.0</td>
<td>0.45</td>
<td>27.8 ± 3.7</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Note: 1-RM = bilateral knee extension repetition maximum, MVC = peak isometric torque, EMG = electromyography, ES = effect size, Δ% = within-participant change.

Figure 2. Bilateral leg extension maximal strength (1-RM) during the 3-week non-training phase and the 10-week resistance training period. YW = young women, OW = older women, 3S = three-set group, 1S = one-set group. aSignificantly different from week 0 within all training groups (P < 0.01). bSignificantly different from week 2 within all training groups (P < 0.03). Values are presented as means ± standard deviations.

Figure 3. Maximal isometric torque (MVC) of the right knee extensors during the 3-week non-training phase and the 10-week resistance training period. YW = young women, OW = older women, 3S = three-set group, 1S = one-set group. aSignificantly different from week 0 within all training groups (P < 0.01). bSignificantly different from week 2 within all training groups (P < 0.03). Values are presented as means ± standard deviations.

Figure 4. Right knee extensor electromyography amplitude (EMG) during the maximal isometric torque contraction during the 3-week non-training phase and the 10-week resistance training period. YW = young women, OW = older women, 3S = three-set group, 1S = one-set group. aSignificantly different from week 0 within all training groups (P < 0.01). bSignificantly different from week 3 within all training groups (P < 0.01). Values are presented as means ± standard deviations.

Figure 5. Normalized bilateral leg extension maximal strength (1-RM) and normalized maximal isometric torque (MVC) before and after the 10-week resistance training period. YW = young women, OW = older women, 3S = three-set group, 1S = one-set group. aSignificantly different from before training within all training groups (P < 0.01). Values are presented as means ± standard deviations.
low-volume, moderate-intensity resistance training in previously untrained young and older women. The main findings of this study were that significant changes over time were observed in all variables examined; however, no interactions between age or training volume and time were apparent. Thus, our results lend further support to work reporting that previously untrained older individuals retain a similar relative capacity for short-term strength development and neuromuscular adaptation to resistance training as untrained young individuals. Moreover, our results provide a novel contribution to the literature by also demonstrating that additional strength gains and neuromuscular adaptations during the early phase of moderate-intensity resistance training in untrained young and older women may not be achieved by performing multiple sets when training loads are matched provided that a minimum threshold volume is achieved. These results may have practical applications for professionals responsible for prescribing short-duration, moderate-intensity resistance training programmes for untrained women.

**Muscle hypertrophy**

Previous studies comparing the hypertrophic response between high- and low-volume resistance training in the young are limited and data pertaining to older adults are not currently available. Starkey et al. (1996) examined untrained young men performing either one set or three sets of 10- to 12-RM for a bilateral leg extension and bilateral leg curl and reported an increase in lateral thigh muscle thickness of 4.0% when assessed at 60% thigh length following 14 weeks of training. Similar findings were reported by Ostrowski and colleagues (Ostrowski, Wilson, Weatherby, Murphy, & Lyttle, 1997), who examined young men with 1–4 years of weightlifting experience who performed one set, two sets, and four sets of 7-RM load for 20 exercises. Ostrowski et al. reported increases in rectus femoris cross-sectional area ranging from 5.0% to 13.1% after 10 weeks of training. Furthermore, no interactions between training volume and hypertrophy over time were reported. Our findings based on changes in lean knee extensor muscle volume are in agreement with these results and add to the literature by demonstrating that muscle hypertrophy during early-phase resistance training may not be volume dependent in previously untrained young or older women.

Our lack of interaction between resistance training volume and muscle hypertrophy appears to conflict with traditional views that high-volume resistance training is necessary to achieve optimal increases in muscle mass (Fleck & Kraemer, 2004). It is generally believed that the physiological stimulus for muscle hypertrophy associated with resistance training is ultrastructural muscle damage (McDonagh & Davies, 1984), which may be enhanced through higher-volume training. However, available data indicate that the threshold level of ultrastructural damage required to elicit a maximal hypertrophic response in both untrained and trained young men may not require high-volume training provided that the training load is sufficient (Ostrowski et al., 1997). However, such results are yet to be replicated in older men, or young or older women.

**Maximal strength and maximal isometric torque**

Results from available studies comparing the effect of resistance training volume on maximal strength and/or maximal isometric torque are conflicting. In this regard, high-volume training has not been clearly demonstrated in untrained young and/or middle-aged adults to produce additional gains in maximal strength for the bench press (Paulsen, Myklestad, & Raastad, 2003; Stowers et al., 1983), squat (Stowers et al., 1983), leg extension or leg flexion (Starkey et al., 1996), shoulder press or lat pulldown (Paulsen et al., 2003), or maximal isometric torque of the knee extensors or knee flexors (Starkey et al., 1996) following 6–14 weeks of training. In contrast, Borst et al. (2001) reported that, in untrained young men and women, summed maximal strength for the bench press and leg extension following 13 weeks of training was significantly higher in a three-set group (~24%) than a single-set group (~37%) who used equated training loads. Furthermore, Paulsen et al. (2003) reported that, in untrained young men, the average increases in maximal strength for the squat, leg extension, and leg curl exercises were greater for a three-set group (~21%) than a single-set group (~14%). Such discrepancies between studies suggest that high-volume resistance training may not always promote additional strength gains during early-phase resistance training. However, interpreting the results between such studies is difficult due to differences in participant characteristics (Borst et al., 2001; Paulsen et al., 2003; Starkey et al., 1996), exercise selection (Ostrowski et al., 1997; Paulsen et al., 2003; Schlumberger, Stec, & Schmidtbleicher, 2001), length of rest periods between sets (Hass et al., 2000; Rhea et al., 2002), and repetition velocity (Ostrowski et al., 1997; Rhea et al., 2002). All of these factors have been demonstrated to influence the neuromuscular response to resistance training (Bird et al., 2005) and therefore confound the results obtained.

Available data pertaining to the effect of resistance training volume on strength development in older adults is limited. Galvao and Taaffe (2005) reported that older adults performing three sets of 8-RM loads
demonstrated greater increases in the seated row (9.7 vs. 4.1%), tricep (6.7 vs. 3.2%) and leg extension (17.4 vs. 9.4%) maximal strength compared with a matched group performing one set of each exercise at the same training intensity; while the changes in chest press (9.1 vs. 5.7%), leg press (14.6 vs. 10.5%), and leg curl (12.5 vs. 10.3%) maximal strength and isometric (24.5 vs. 8.7%) and isokinetic (13.8 vs. 15.3%) maximal knee extensor torque were not different between the two groups after 20 weeks of training. Our results for leg extension maximal strength contrast with those of Galvao and Taaffe (2005) in so much as we observed comparable strength gains between training volume groups. The discrepancy between results may possibly be explained by differences in training loads and duration. As such, further studies are need before any conclusions can be drawn.

Surface electromyography

We observed significant increases in EMG in the both the young and older women and the high- and low-volume training groups over the 10-week resistance training period. No previous studies have compared changes in muscle recruitment between high- and low-volume resistance training in untrained young or older individuals. Hass et al. (2000) suggest that because complex training actions, such as the back squat, involve considerable skill and movement coordination, high-volume resistance training may be necessary to promote maximal neural adaptation for these tasks. Such a statement would also imply that less complex training actions, such as the leg extension task performed in the present study, may not require high-volume training to induce maximal neural adaptation. Our results partially support this theory, as no interaction between training volume and time was observed for EMG. As such, maximal neural adaptation during the early phase of resistance training may be obtained with low-volume training for this relatively simple exercise. However, it remains to be determined if similar findings are observed when the training stimulus involves more complex training actions.

Normalized maximal strength and normalized maximal isometric torque

No previous studies have examined the effect of resistance training volume on maximal strength and/or maximal isometric torque per unit of muscle volume in young and/or older adults. As such, our results provide a unique contribution to the literature by reporting comparable increases in these measurements among all training groups. These results indicate that the non-hypertrophic contributions to strength development in the present study were not dependent on age or training volume. Non-hypertrophic adaptations associated with resistance training that may contribute to strength development include: (1) greater agonist muscle activity and/or a decrease in antagonist muscle co-activation (Häkkinen, 2003), and/or (2) greater intrinsic force production capacity of the muscle, possibly due to changes in muscle architecture (Aagaard et al., 2001), and/or greater specific force from the contractile apparatus (Trappe et al., 2000, 2001). As previously discussed, all training groups exhibited comparable increases in agonist EMG after the resistance training period. However, it cannot be determined from the present study if changes in antagonist muscle recruitment, muscle architecture, and/or fibre-specific force also contributed to the training-induced strength gains. Despite this, as the contribution of non-hypertrophic adaptations to strength development were similar between all groups, it appears that high-volume resistance training may not be necessary to elicit maximal adaptation in some, or possibly all, of these mechanisms.

Conclusion

Our results suggest that performing three sets of resistance training may not facilitate additional strength development or neuromuscular adaptation compared with performing one set during the early phase of training in previously untrained young and older women provided that training loads are equated. These findings may have practical applications for designing short-term resistance training programmes or the initial phase of long-duration resistance training programmes in untrained young and older women. However, these data should be interpreted with care. As specific training stimuli induce specific adaptations, it is likely that the manipulation of other acute training variables in addition to training volume, such as exercise selection and the muscle group trained, exercise order, intensity, frequency, repetition velocity and rest between sets, will also influence strength gains and neuromuscular adaptations (Fleck & Kraemer, 2004; Kramer et al., 1997; McDonagh & Davies, 1984; Paulsen et al., 2003). Accordingly, our results may only be valid with respect to performing a bilateral leg extension and leg curl programme involving one set of 10, slow- to moderate-velocity repetitions performed at 75% of maximal strength over a period of 10 weeks. Fleck and Kraemer (2004) suggest that after the neuromuscular system adapts to a resistance training stimulus, an increase in volume is necessary for further adaptation to occur. Such a statement implies that low-volume training may be sufficient to elicit maximal adaptation in untrained individuals.
during the early phase of training, but higher-volume training may be necessary during later phases to induce further adaptation. Thus, it is possible that an effect of training volume may be observed with training of longer duration. In this context, our results are meaningful but should be followed up with further studies examining the effect of training volume across various applications of the acute training variables, such as exercise selection and the muscle group trained.

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