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Title: COMPARATIVE EFFECTS OF RESISTANCE TRAINING ON PEAK ISOMETRIC TORQUE, MUSCLE HYPERTROPHY, VOLUNTARY ACTIVATION AND SURFACE EMG BETWEEN YOUNG AND ELDERLY WOMEN

Short Title: Resistance training in young and elderly women

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Summary

We compared the effect of a 10-week resistance training program on peak isometric torque, muscle hypertrophy, voluntary activation, and electromyogram signal amplitude (EMG) of the knee extensors between young and elderly women. Nine young women (YW; range 20-30 years) and 8 elderly women (EW; 64-78 years) performed 3 sets of 10 repetitions at 75% 1 repetition maximum for the bilateral leg extension and bilateral leg curl 3 days per week. Peak isometric torque, EMG, and voluntary activation were assessed before, during, and after the training period, while knee extensor lean muscle cross-sectional area (LCSA) and lean muscle volume (LMV) were assessed before and after the training period only. Similar increases in peak isometric torque (16 % and 18%), LCSA (13% and 12 %), LMV (10% and 9%), and EMG (19% and 21%) were observed between YW and EW at the completion of training (p< 0.05), while the increase in voluntary activation in YW (1.9%) and EW (2.1%) was not significant (p> 0.05). These findings provide evidence to indicate that participation in regular resistance exercise can have significant neuromuscular benefits in women independent of age. The lack of change in voluntary activation following resistance training in both age groups despite the increase in EMG may be related to differences between measurements in their ability to detect resistance training-induced changes in motor unit activity. However, it is possible that neural adaptation did not occur and that the increase in EMG was due to peripheral adaptations.

Keywords: Ageing, Strength training, Knee extensors, MVC, Muscle growth, Electromyography, Twitch Interpolation, Neural adaptation
INTRODUCTION

Ageing in humans is associated with a progressive loss of strength that becomes significant during the seventh decade and accelerates thereafter (Akima et al., 2001). The reduction in strength with age reduces the ability to perform activities of daily living (Skelton et al., 1994; Alexander et al., 2000), which ultimately results in greater reliance on primary care givers and a loss of independence. This is particularly relevant for women who have a greater life expectancy than men but have a reduced functional reserve (Kwon et al., 2001), which places them at greater risk of frailty and more years of functional dependence (Katz et al., 1983). The age-associated reduction in strength is largely attributable to a decrease in muscle quantity and possibly a decline in muscle quality, which are mediated by the selective loss of Type II fibres and the atrophy of those fibres remaining (Lexell et al., 1988), and the increased proportion of Type I fibres (Andersen, 2003). Such changes in muscle mass are not surprising given that ageing is associated with a decline in the quantity and intensity of habitual physical activity (Mäkiä et al., 1994) and alterations in the concentration of circulating hormones (Häkkinen & Pakarian, 1993). In addition, available evidence suggests that losses in strength with age may also be partially related to neural mechanisms resulting in a decline in the ability to maximally activate agonist muscles (De Serres & Enoka, 1998; Yue et al., 1999). Fortunately, resistance training appears to be a highly successful intervention to age-associated muscle weakness with studies reporting increases of ~10-40% in peak isometric torque in both elderly men and women following 10-24 weeks of training (Häkkinen et al., 1998b; Häkkinen et al., 2001a; Häkkinen et al., 2001b; Ferri et al., 2003). However, despite the strength gains achieved by the elderly through regular participation in resistance exercise, the effect of ageing on the capacity of the neuromuscular system to adapt to such a stimulus requires further clarification.

While a number of studies have compared muscle hypertrophy between the young and elderly following resistance training methodological limitations reduce the validity of the results obtained. Such methodological limitations include the failure to discriminate between contractile and non-contractile tissue within muscle compartment area (Welle et al., 1996; Häkkinen et al.,
1998a; Lemmer et al., 2000; Roth et al., 2001) and the examination of hypertrophy based on changes in muscle cross-sectional area rather than muscle volume (Welle et al., 1996; Häkkinen et al., 1998b; Häkkinen et al., 1998b). Furthermore, available studies comparing the hypertrophic response between the young and elderly to resistance training are equivocal, with some studies (Welle et al., 1996), but not all (Roth et al., 2001), concluding that the elderly have an impaired capacity for muscle hypertrophy. The extent to which the discrepancies between studies represent age- and/or muscle-related differences, as opposed to artefact due to methodological factors, remains unknown. As such, we have attempted to reduce such methodological limitations by examining changes in knee extensor lean muscle volume, which will enhance the validity of the comparison between age groups (Overend et al., 1992) and provide a more accurate estimate of whole muscle hypertrophy (Roth et al., 2000).

A primary factor contributing to strength gain associated with resistance training is neural adaptation; specifically, an increase in agonist muscle activation (Sale, 2003). Previous studies examining agonist muscle activation following resistance training in the elderly have primarily assessed changes in electromyogram signal amplitude (EMG); however, increases in agonist EMG at the completion of the training period are not universally observed (Keen et al., 1994; Ferri et al., 2003). Such discrepancies between studies may be related to the influence of other neuromuscular adaptations, such as changes in muscle fibre excitability or the amplitude of fibre action potentials, on the recorded signal. The influence of such adaptations on EMG may be reduced by normalising data by the peak to peak M-wave amplitude, but available studies comparing changes in EMG between age groups have not used this technique. As such, the extent to which the elderly retain the ability to increase agonist muscle activation with resistance training cannot be determined. Another method to examine agonist muscle activation following resistance training is to assess changes in the amplitude of the interpolated twitch during a maximal voluntary superimposed contraction. However, studies examining changes in interpolated twitch amplitude following resistance training in the elderly are limited and results are equivocal (Harridge et al., 1999; Scaglioni et al., 2002). Furthermore, few investigations
have compared resistance training-related changes in interpolated twitch amplitude between age groups (Knight & Kamen, 2001).

Therefore, the purpose of the present study was to compare the effect of a 10-week resistance training program on peak isometric torque, muscle hypertrophy, voluntary activation, and EMG of the knee extensors between young and elderly women.

METHODS

Subject Sample
Nine young women (YW) and eight elderly women (EW) volunteered to participate in the study. Physical characteristics for YW were as follows; age 20-30 years (mean 25.0 ± 4.0 years), height 167.7 ± 7.6 cm, mass 72.7 ± 10.3kg, and body mass index 26.0 ± 4.5. Physical characteristics for EW were as follows; age 64-78 years (mean 69.8 ± 6.6 years), height 157.8 ± 5.7cm, mass 66.7 ± 13.0kg, and body mass index 26.6 ± 4.2. A significant difference was observed between age groups with respect to height (p< 0.05). None of the subjects had ever been diagnosed with any medical condition thought likely to affect performance, including hypertension, diabetes, or any respiratory, vascular, or neurological disease. All subjects were non-smokers and moderately active; however, none of the participants had any background in regular strength or endurance training prior to the study. Subjects had never taken any prescribed medication thought likely to influence the results of the study, including hormone replacement therapy or Angiotensin Converting Enzyme (ACE) inhibitors. Written consent was obtained prior to the commencement of the study. The present investigation was conducted with the approval of the Ethics in Human Research Committee of Charles Sturt University. There was no conflict of interest with respect to the present study.

Study Design
The investigation consisted of a 13-week study period, which consisted of a 3-week control period followed by 10 weeks of resistance training. Subjects were tested on separate 5
occasions by the same investigator using identical testing procedures. The first 3 weeks of the study (between weeks –3 and 0) served as a control period where no resistance training was performed, after which subjects commenced the 10-week resistance training program. Subjects were instructed to continue participating in normal activities of daily living and recreational activities that they were usually accustomed to and avoid any strenuous physical activity outside of the resistance training program. Subjects were also instructed not to undergo any major dietary modifications (possibly in an attempt to lose weight) or consume any nutritional supplements.

**Muscle Characteristics**

Lean knee extensor muscle cross-sectional area (LCSA) and lean knee extensor muscle volume (LMV) were determined using magnetic resonance imaging. Multislice images were obtained using a T1-weighted scanner with a 50cm diameter body coil in a 1.5-T whole body magnet (Magnetom Symphony Maestro, Siemens AG Ltd, Bayswater, Australia). Data were obtained with the subject in a supine position with padding placed under the right knee and buttocks to minimise any tissue compression during the scan. After the subject was positioned, an oil bead was attached to the anterior surface of the thigh equidistant between the superior border of the patella and the anterior superior iliac crest. This bead was subsequently used as a reference point for image acquisition. With the subject positioned on the scanner bed a sagittal scout image of the thigh was taken and the oil bead was located. Following this, 11 axial slices of the thigh were taken perpendicular to the longitudinal axis of the femur with slice 6 taken at the level of the oil bead (Figure 1). Each image was obtained with the following parameters; field of view 300 × 300mm; pixel matrix 256 × 256; slice thickness 10mm; interslice distance of 30mm; spin echo time 20ms; repetition time 452ms; and a flip angle of 90°. One acquisition for each image was performed with a total acquisition time of ~3-minutes.

Image analysis was performed using Scion image analysis software (Scion Corporation, Frederick, Maryland, USA) where contractile and non-contractile tissues were quantified using a
pixel intensity histogram technique, which is described in detail elsewhere (Kent-Braun et al., 2000). Briefly, for each subject the image from axial slice 6 was magnified by a factor of 2 and a region of interest that contained approximately 50% muscle and 50% fat was manually outlined. Imaging software then calculated the pixel intensity histogram for this region, which typically contained two distinct peaks separated by a section of low pixel intensity. The region composed of lower pixel intensity reflects non-contractile tissue (such as fat, vascular, and connective tissue), whereas the peak composed of higher pixel intensity reflects contractile tissue. The pixel intensity histogram was subsequently exported into spreadsheet software where a threshold for contractile tissue was visually determined (Figure 2). Next, the knee extensor muscle compartment was manually outlined in each of the 11 axial slices and the pixel intensity histograms were exported into spreadsheet software. The contractile tissue component within the knee extensor muscle compartment area in pixels for each of the 11 slices was then calculated as the sum of all pixels above the threshold intensity for contractile tissue as previously determined from the region of interest containing 50% muscle and 50% fat (Figure 3).

The scale for each image was determined by scanning an oil phantom with a known cross-sectional area using the parameters previously described. Imaging software determined the area of the oil phantom in square pixels, which was divided by the known cross-sectional area in cm². Subsequent to this, knee extensor contractile tissue area in cm² for each of the 11 axial slices was calculated by dividing the number of pixels occupying this area by the number of pixels per cm² as determined from the oil phantom. Finally, knee extensor contractile tissue volume in cm³ was calculated by summing all 11 knee extensor contractile tissue areas in cm² and multiplying by the interslice distance of 30mm. The reliability of the scanner system and imaging software was determined by scanning the oil phantom on two separate occasions then calculating the coefficient of variation in the number pixels within the cross-sectional image between trials, which was observed to be 0.9%. Furthermore, the reproducibility of contractile tissue volume measurements was determined by randomly reassessing knee extensor

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contractile tissue volume in five young women and five elderly women on a second occasion then calculating the coefficient of variation between measurements, which was observed to be <1.6%.

Peak Isometric Torque Testing

Peak isometric torque testing was performed using Kin-Com isokinetic dynamometer (Chattanooga Group Inc, Hixon, TN) linked to an AMLab system (AMLab Technologies, Lewisham, Australia). Subjects were seated upright on the dynamometer and were secured via waist and shoulder straps. During all tests subjects 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 1cm above the lateral malleolus of the ankle. Prior to testing, subjects performed a standardised warm-up involving six, 5-second submaximal isometric knee extension actions at an angle of 65° knee flexion (0° being full extension); two at ~50% of maximal voluntary effort, two at ~70% maximal voluntary effort, and two at ~90% maximal voluntary effort. A rest period of 30 seconds separated each of the six submaximal exercises. Following the warm-up, a 2-minute period elapsed prior to the commencement of testing.

Testing consisted of a minimum of six trials under isometric conditions with the knee at 65° flexion (0° being full extension). During testing, subjects were instructed to produce maximal effort as fast as possible and continue exerting maximal effort for a period of 5 seconds. A minimum rest period of 30 seconds separated each trial and testing continued until the final 3 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 voluntary efforts and subjects received continuous visual feedback of performance from the computer monitor. Force data were captured using the AMLab system at a rate of 2500Hz (AMLab Technologies,
Lewisham, Australia). Data from the trial where the highest peak force occurred were exported into spreadsheet software and corrected the effect of gravity on the lower leg and lever arm length. Peak torque was then determined as the single highest torque value attained.

**Voluntary Activation**

Voluntary activation of the right knee extensors were assessed using the twitch interpolation technique (Allen *et al.*, 1995). Force data were obtained using a Kin-Com isokinetic dynamometer (Chattanooga Group Inc, Hixon, TN) linked to an AMLab system (AMLab Technologies, Lewisham, Australia) with the subject positioned identical to that previously described for peak isometric torque testing. Following the warm-up protocol, prior to peak isometric testing, 6 resting control twitches were obtained with the subject at complete rest. This was determined based on the absence of electromyographic activity from the vastus lateralis or vastus medialis and the absence of any load placed on the force transducer other than that due to the effect of gravity on the lower limb. Muscle activation was achieved by stimulating the femoral nerve using a felt pad bar electrode with a tip spacing of 30mm (Nicolet Biomedical, Madison, WI) positioned about the medio-anterior aspect of the upper thigh, directly below the inguinal fold. The current applied to the nerve was delivered by a Digitimer DS7 stimulator (Digitimer Ltd, Welwyn Garden City, Hertfordshire, England) using a single square-wave pulse with a width of 200μsec (400V with a current of 1500-8000 mAm) that was driven by a custom designed instrument using AMLab software (AMLab Technologies, Lewisham, Australia). Initially, the current was manually applied in incremental steps until a twitch of moderate amplitude was observed on the computer monitor. Following this, the position of the stimulating electrode was adjusted until the site most responsive to the stimulation was located. The electrode was then secured in position using a Velcro strap and the stimulus intensity was gradually increased until a plateau in twitch amplitude was achieved. The stimulus intensity at which twitch amplitude plateaued was increased by a further 25% to ensure that supramaximal
stimulation was applied to the nerve. Six pulses, 4 seconds apart, were delivered to the nerve. Force data were captured correct to 4 decimal places at a sampling rate of 2500Hz and exported into spreadsheet software where the data were corrected for the effect of gravity on the lower leg and lever arm length. Subsequently, peak twitch torque data were averaged over the six trials with the mean correct to 4 decimal places used as the resting control twitch amplitude for the calculation of voluntary activation.

Following the assessment of peak isometric torque, six maximal voluntary superimposed isometric contractions were performed, which involved the delivery of two square-wave pulses during a maximal voluntary isometric contraction at a rate of 50Hz using identical stimulation parameters to that used for the assessment of resting peak twitch torque. Subjects were instructed to ramp maximal effort over a 2 second period and to maintain maximal effort until they were instructed to relax. Subjects were intentionally directed to ignore the sensation associated with the stimuli and focus on exerting maximal effort in all tests. The investigator manually triggered the stimuli when it appeared that voluntary isometric torque plateaued on the oscilloscope. The total duration of each superimposed contraction was typically less than 5 seconds. A rest period of at least 30 seconds separated each of the six trials. Force and stimuli onset were captured using AMLab software at a sampling rate of 2500Hz. Data were exported into spreadsheet software where force was corrected for the effect of gravity on the lower leg and lever arm length. Peak voluntary isometric torque during the superimposed contractions was determined as the mean torque value produced during the 25ms prior to the delivery of the stimuli. Superimposed torque following the delivery of the stimuli was then determined as peak isometric torque value produced during the 50-100ms period subsequent to the delivery of the stimuli. Interpolated twitch torque was then calculated correct to 4 decimal places as superimposed isometric torque minus peak voluntary isometric torque (Figure 4). All six trials were assessed with the trial yielding the lowest interpolated twitch amplitude used for analysis. Voluntary activation was finally calculated by expressing the interpolated twitch torque as a
percentage of resting control twitch torque using the following equation: Voluntary Activation (\%) = [1-(Interpolated Twitch Torque / Resting Control Twitch Torque)] x 100.

**EMG**

Surface electromyographic signals were sampled from the vastus lateralis and vastus medialis using pairs of 8mm Ag/AgCl surface electrodes (BioPac Systems Inc, Santa Barbara, CA, USA) attached over the vastus lateralis and vastus medialis muscles of the right thigh. For the vastus lateralis, the electrodes were attached to the lateral surface of the thigh, approximately 10cm 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, the electrodes were attached approximately 5cm 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 8mm Ag/AgCl electrode was attached to the patella of the opposing limb to ground the signals. Skin where the recording and ground electrodes were attached 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 20mm was employed for the recording electrodes in all tests using a moulded plastic housing.

M-waves were captured during the assessment of the resting control twitches with a custom designed instrument using AMLab software (AMLab Technologies, Lewisham, Australia) where signals were obtained with a gain of 200V/V and a common mode rejection ratio >120dB at a sampling rate of 2500Hz. M-wave data from all six resting control twitches were subsequently exported into spreadsheet software with the mean used to determine peak to peak amplitude. Voluntary electromyographic signals obtained during peak isometric torque testing were captured with a custom designed instrument using AMLab software (AMLab Technologies, Lewisham, Australia) where signals were obtained with a gain of 1000V/V and a common mode rejection ratio >120dB at a sampling rate of 2500Hz. For processing, voluntary electromyographic data were normalised against the peak to peak M-wave amplitude, bandpass...
filtered with cut-off frequencies of 10Hz and 460Hz, then quantified using the root-mean-square with a sliding window of 50ms (125 data points) using AMLab software (AMLab Technologies, Lewisham, Australia). The processed electromyographic data were exported into spreadsheet software where the mean signal amplitude during the 500ms interval subsequent to the attainment of peak isometric torque was calculated. Electromyogram signal amplitude was then averaged between vasti muscles to provide a global indication of total knee extensor motor unit activity and is referred to herein as EMG.

**Resistance Training Protocol**

Subjects participated in a fully supervised resistance training program for the knee extensors and knee flexors three days per week (Monday, Wednesday, and Friday) for a period of 10 weeks. Training involved three sets of 10 repetitions for a bilateral leg extension and the bilateral knee flexion exercise, which were performed using a plate-loaded leg extension and leg curl bench (York Barbell Co., Toronto, ON, Canada). Training intensity was 50% 1 RM during week 1 and 75% 1 RM for weeks 2-10. The lower training intensity during week 1 was used to familiarise the subjects and enhance motor learning of the task prior to exposing them to the higher training intensity. Both exercises were performed throughout the full range of motion with a shortening muscle action to raise the load, followed by a lengthening phase to return the load to the original position. A single repetition of each exercise consisted of both a shortening and lengthening phase. For each exercise, subjects were instructed to perform the movements in a smooth, continuous motion without pausing. Each repetition was approximately 5 seconds in duration. The shortening phase of the movement lasted approximately 2 seconds, where a 1 second pause occurred when the load reached the end of range of motion, followed by the lengthening phase, which was also approximately 2 seconds in duration. Minimal assistance was provided during if subjects become too fatigued to move the load through a full range of motion at the required duty cycle. A rest period of 90-120 seconds separated each of
the 3 sets for each exercise and a 3-minute rest period elapsed between exercises. Each exercise commenced with a warm-up, which consisted of one set of 10 repetitions for each exercise at an intensity of 40% 1 RM followed by stretching. Although data collection was only performed on the knee extensors, the knee flexors were also trained in an attempt to minimise the likelihood of developing any muscular imbalance about the knee joint.

Muscle strength for the bilateral knee extension and bilateral knee flexion exercises were performed under shortening conditions using the resistance training equipment by means of the 1 RM method (Charette et al., 1991) prior to training and at 2-week intervals during the training period. This strength data was used to adjust the training loads as necessary to ensure that all subjects continued to train at the required intensity for the entire training period. All 1 RM assessments were performed during the Monday training session after the warm-up. Following this, subjects were given a 10-minute rest period before completing the required training session as usual. Exercise adherence over the 10-week training period were 89 ± 3% for the young women and 92 ± 5% for the elderly women, which were not significantly different based on the results of an unpaired t-test (p= 0.12).

Statistics
Within subject and between group differences were determined using a multivariate analysis of variance (MANOVA) with repeated measures with Tukey’s post-test used to identify statistical differences between means. Percentage changes between week 0 and week 10 for all variables were calculated as; Percentage Change (%)= [(Week 10 Value – Week 0 Value) / Week 0 Value] x 100. Probability-adjusted t-tests were performed for pairwise comparisons where appropriate. The critical level of significance was set at p< 0.05. These procedures were performed using Statistical Package for the Social Sciences for Windows (SPSS, Chicago II, version 11.5). Data are presented as the mean ± SD.

RESULTS

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Peak Isometric Torque

Peak isometric torque for the knee extensors during the 13-week study period for YW and EW are presented in Figure 5. Peak isometric torque remained statistically unchanged during the 3-week control period in both age groups (p> 0.05). Peak isometric torque was significantly higher for YW compared with the EW for all assessments (p< 0.05). After the 10-week resistance training period, peak isometric torque was significantly higher in both YW and EW (p< 0.05), which equated to an increase of 16 ± 3% and 18 ± 4%, respectively (p< 0.05). The percentage increase in peak isometric torque between week 0 and week 10 was not significantly different between age groups (p> 0.05).

Muscle Hypertrophy

LCSA of the 11 axial slices of the thigh for YW and EW before and after the 10-week resistance training program are presented in Table 1. Mid-thigh LCSA at slice 6 in YW and EW increase by 13 ± 4% and 12 ± 3%, respectively (p< 0.05). LMV in YW was 1628 ± 186cm³ before training and was 1791 ± 203cm³ after training, which equated to an increase of 10 ± 3% (p< 0.05). LMV in EW was 1247 ± 148cm³ before and 1363 ± 157cm³ after training, which equated to an increase of 9 ± 3% (p< 0.05). The hypertrophic response to the resistance training between weeks 0 and 10 were not significantly different between age groups for either LCSA or LMV (p> 0.05).

Voluntary Activation

Voluntary activation remained statistically unchanged during the 3-week control period in both the young and elderly women (p= 0.52) and was not significantly different between age groups (p> 0.05). The level of voluntary activation at week 0 appeared to be complete in both age groups with values of 95.1 ± 1.7% and 96.2 ± 1.8% for YW and EW, respectively. After the 10-
week training period voluntary activation increased in YW and EW by 1.9 ± 0.9% and 2.1 ± 1.2%, respectively, but did not reach statistical significance in either age group (p> 0.05).

**EMG**

Knee extensor EMG throughout the 13-week study period for the young and elderly women is presented in Figure 6. EMG remained statistically unchanged during the 3-week control period in both age groups (p> 0.05). After the 10-week training period EMG was significantly greater in the young and elderly women, which equated to an increase of 19 ± 4% and 21 ± 4%, respectively (p< 0.05). The percentage increase in EMG between week 0 and week 10 was not significantly different between age groups (p> 0.05).
DISCUSSION

Our study has shown that both YW and EW demonstrated significant increases in peak isometric torque, LMV, and EMG at the conclusion of the 10-week resistance training program; however, the level of voluntary activation remained statistically unchanged in both age groups. Furthermore, the relative increases observed in peak isometric torque, LMV, and EMG between weeks 0 and 10 were comparable between age groups.

The comparable increase in peak isometric torque associated with resistance training between YW and EW is similar to previous studies examining men and women (Häkkinen et al., 1998a; Häkkinen et al., 1998b; Häkkinen et al., 2000; Lemmer et al., 2000; Knight & Kamen, 2001; Häkkinen et al., 2001a; Häkkinen et al., 2001b; Newton et al., 2002). These results demonstrate that the elderly have the same relative capacity for isometric strength gain associated with resistance training as young individuals. The comparable increase in peak isometric torque in YW and EW likely reflects the similar increases observed in LMV and EMG between age groups.

We observed comparable increases in LCSA of 12% and 13% in YW and EW, respectively, which is in agreement with previous data demonstrating increases of 5-20% in total knee-extensor muscle cross-sectional area in young and elderly men and women following 10-24 weeks of resistance training (Häkkinen et al., 1998a; Häkkinen et al., 1998b; Häkkinen et al., 2001b). In contrast, Welle et al. (1996) examining changes in total muscle cross-sectional area reported an attenuated hypertrophic response of the elbow flexors and knee flexors in elderly men and women compared with young individuals. Interestingly, however, Welle et al. (1996) observed that the relative increase in total knee extensor muscle cross-sectional area was similar between young (4%) and elderly (6%) subjects. The degree to which the results of Welle et al. (1996) represent intramuscular differences regarding the effect of age on the hypertrophic response to resistance training or methodological limitations associated with the assessment
muscle hypertrophy and/or the application of the training intervention remains unknown and warrants investigation.

More recent studies have used muscle volume to compare resistance training-induced muscle hypertrophy between age groups. Roth et al. (2001) reported a similar increase in total knee-extensor muscle volume in young and elderly men and women following 9 weeks of heavy resistance training. Additionally, Ivey et al. (2000) reported a 5-12% increase in total knee extensor muscle volume in young and elderly men and women following 9 weeks of resistance training. These results are highly comparable to the 9% and 10% increases in LMV we observed in YW and EW, respectively. However, a limitation of our investigation is that as YW were significantly taller than EW, it is possible that the more proximal and distal portions of the thigh in YW may not have been included in the MRI assessment. This may have caused muscle hypertrophy in YW to be overestimated relative to that observed in EW. Despite this, we argue that the possible overestimation of LMV in YW relative to EW does not detract from the overall findings reported here as no significant difference in hypertrophy was observed between age groups.

We failed to observe a significant training-related increase in interpolated twitch amplitude relative to the resting control twitch amplitude in the young and elderly women. Our inability to identify such changes in both age groups may be related to methodological and/or performance issues, rather than a lack of neural adaptation. It is possible that the interpolated twitch technique may be insensitive to small increases in motor unit activation at near-maximal muscle forces and may be more sensitive to increases in motor unit recruitment than increased motor unit firing frequency (Herbert & Gandevia, 1999). Additionally, young individuals are somewhat inconsistent in achieving maximal activation during interpolated twitch testing (Allen et al., 1995) and this performance variability has been reported to increase with age (Jakobi & Rice, 2002). Knight & Kamen (2001) assessed the central activation ratio and reported a 3% increase in voluntary activation of the trained knee-extensors in both young and elderly individuals following
6 weeks of resistance training. The contrasting findings between the present study and those of Knight & Kamen (2001) are not entirely unexpected as studies examining changes in the level of voluntary activation following resistance training in young (Yue & Cole, 1992; Herbert et al., 1998) and elderly individuals (Harridge et al., 1999; Scaglioni et al., 2002) independently also provide contradictory results.

A significant increase in EMG was observed in YW and EW following the 10-week resistance training period. Because we normalised EMG against the M-wave peak to peak amplitude, the increase in EMG observed was most likely related to a resistance training-induced increase in motor unit recruitment and/or firing frequency. As previous studies examining changes in EMG in the young and elderly following resistance training report data in absolute units (Häkkinen et al., 1998a; Häkkinen et al., 1998b), it is difficult compare past findings with our results. The mechanisms contributing to increased motor unit activity following resistance training are not fully known, however we interpret our data as evidence for neural adaptation, which may result from greater drive from descending corticospinal pathways and/or an increase in motor neuron excitability (Aagaard et al., 2002). However, another interpretation of our data is that neural adaptation did not occur and that the increase in EMG was due to peripheral adaptations, such as an increase in muscle fibre excitability, amplitude of fibre action potentials, and/or conduction velocity due to training-induced increases Na⁺-K⁺ pump concentration and/or activity (Hicks et al., 1992; Medbo et al., 2001). Although the influence of any change in muscle fibre excitability and the amplitude of fibre action potentials with training on EMG was minimised in our study by the normalisation procedure employed, the possible influence of an increase in muscle fibre conduction velocity on EMG should be considered.

Despite our failure to observe a significant increase in the level of voluntary activity after resistance training in both age groups, we did observe significant increases in EMG. Although speculative, we suggest this discrepancy may be related to the greater ability of EMG to detect increases in myoelectrical activity compared with the ability of the twitch interpolation technique.
to detect increases in motor output at near-maximal muscle forces. In contrast to our results, Pensini et al. (2002) reported significant increases in both voluntary activation and EMG after a period of eccentric resistance training. The discrepancy between our results and those of Pensini et al. (2002) may be related to differences between studies in the subject’s initial voluntary activation capacity. In our study, all subjects were capable of achieving near-complete muscle activation prior to training (~95%), however those in Pensini et al. (2002) demonstrated evidence of incomplete activation during initial testing (~80%). Consequently, it is possible that the large increase in voluntary activation observed by Pensini et al. (2002) may be partially related to the subject’s greater capacity for neural adaptation, which may have been more readily detected using twitch interpolation. This supported by the ~15% increase in voluntary activation reported by Pensini et al. (2002) after training. In contrast, the capacity for neural adaptation of the knee extensors in our study was comparatively lower, which may not have been detected due to the non-linear relationship between interpolated twitch amplitude and muscle force beyond 65% MVC (Scaglioni et al., 2002).

In summary, we observed that the 10-week resistance training program was associated with comparable increases in peak isometric torque, LMV, and EMG between the young and elderly women. These results demonstrate that the elderly have the same relative capacity to develop isometric strength associated with resistance training as young individuals. The comparable increase in peak isometric torque in YW and EW likely reflects the similar increases observed in LMV and EMG between age groups. An interesting finding in the present study not previously reported was that voluntary activation remained unchanged after resistance training in YW and EW, while EMG was significantly increased in both age groups. Although a precise explanation for this discrepancy cannot be determined, we contend that EMG is more sensitive to detecting neural adaptation compared with the twitch interpolation technique at near-maximal muscle forces. However, an alternative interpretation of these data is that neural adaptation did not occur and that the increase in EMG was related to peripheral adaptations.
Acknowledgments

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TABLE 1- Lean knee extensor muscle cross-sectional area for the 11 axial slices of the thigh for the young women and elderly women before and after the 10-week resistance training program.

<table>
<thead>
<tr>
<th>Knee Extensor Axial Slice</th>
<th>(Proximal)</th>
<th>Knee Extensor Axial Slice</th>
<th>(Distal)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>YW (n= 9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before (cm²)</td>
<td>26 ± 3</td>
<td>40 ± 5</td>
<td>53 ± 6</td>
</tr>
<tr>
<td>After (cm²)</td>
<td>27 ± 4</td>
<td>43 ± 5</td>
<td>58 ± 7</td>
</tr>
<tr>
<td>Increase (%)</td>
<td>6 ± 1†</td>
<td>7 ± 1†</td>
<td>9 ± 2†</td>
</tr>
<tr>
<td>EW (n= 8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before (cm²)</td>
<td>15 ± 2</td>
<td>32 ± 4</td>
<td>42 ± 5</td>
</tr>
<tr>
<td>After (cm²)</td>
<td>16 ± 3</td>
<td>34 ± 4</td>
<td>45 ± 4</td>
</tr>
<tr>
<td>Increase (%)</td>
<td>3 ± 1</td>
<td>6 ± 2†</td>
<td>9 ± 2†</td>
</tr>
</tbody>
</table>

All data rounded up to the nearest centimetre. †Indicates significant increase from before to after training (p< 0.05). ‡Indicates significantly greater increase than axial slices 1, 2, 10 and 11 (p< 0.05). Values presented as mean ± SD.
Figure 2

A

B

C

D

Pixel Intensity

Frequency

Pixel Intensity

Frequency
Figure 3
Figure 4
Figure 5
Figure 6
FIGURE LEGENDS

Figure 1 - The 11 axial slices of the thigh taken perpendicular to the longitudinal axis of the femur with slice 6 taken at the level of the oil bead positioned equidistant between the superior border of the patella and the superior inferior iliac crest.

Figure 2 - Pixel intensity threshold for distinguishing contractile and non-contractile tissue within the knee extensor muscle compartment in a representative young woman (21 years; A and B) and elderly woman (65 years; C and D). A region of interest containing approximately 50% fat and 50% muscle was manually outlined (A and C) and the pixel intensity histogram was displayed (B and D). The peak on the right-hand side of the pixel intensity histograms corresponds with contractile tissue. The threshold between contractile and non-contractile tissue within the image was then determined (arrows).

Figure 3 - Method for calculating lean knee extensor muscle cross-sectional area based on the pixel intensity for a young woman (21 years; A and B) and an elderly woman (65 years; C and D). The knee extensor muscle compartment area is outlined in axial slice 6. The pixel intensity histogram is displayed and the intensity threshold as determined from the region of interest containing approximately 50% fat and 50% muscle is used to distinguish between contractile and non-contractile tissue within the muscle compartment. Lean knee extensor muscle compartment area was calculated by subtracting the number of pixels below the intensity threshold from the total number of pixels.

Figure 4 - Method used to determine voluntary activation. A) An example superimposed maximal voluntary isometric contraction during the assessment of interpolated twitch amplitude. The vertical line intersecting the torque-time curve at approximately 4.4 seconds indicates the delivery of the electrical stimulus. B) Extracted superimposed twitch from the same contraction as A. The vertical line intersecting the torque-time curve at approximately 25ms indicates the delivery of the electrical stimulus. C) Example of the method used to calculate voluntary
activation from A and B. Voluntary activation was determined by expressing interpolated twitch amplitude as a percentage of resistance control twitch amplitude; Voluntary Activation (%) = \{1 - \frac{\text{Interpolated Twitch Amplitude (a)}}{\text{Resting Control Twitch Amplitude (b)}}\} \times 100.

**Figure 5** - Peak isometric torque for the knee extensors torque for the young women (YW) and elderly women (EW) during the 13-week study period. *Indicates significant difference from the elderly women. #Indicates significance from week 0 in both age groups (p< 0.05). +Indicates significance from week 0 and week 3 in both age groups (p< 0.05). Values presented as the mean ± SD.

**Figure 6** - EMG amplitude during the 13-week study period for the young women (YW) and elderly women (EW). Data presented as a percentage of peak to peak M-wave amplitude. *Indicates significant difference from week 0 in both age groups (p< 0.05). #Indicates a significant difference from weeks 0 and 3 in both age groups (p< 0.05). Values presented as the mean ± SD.