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ORIGINAL ARTICLE

Effects of strength training and detraining on regional muscle in young and older men and women

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Abstract To examine the effects of 9 weeks of strength training (ST) and 31 weeks of detraining on regional muscle area in young and older men and women, three regions of the quadriceps muscle area (proximal, middle, and distal) were measured via MRI in 11 men ages 20–30, 11 men ages 65–75, 10 women ages 20–30, and 11 women ages 65–75. These effects were assessed by determining the difference between the control limb and the trained limb (T-UT) at all three time points. This design provided control for possible influences of biological, methodological, seasonal variations, as well as influences due to attention or genetic differences that commonly occur between experimental and control groups. There were no significant differences in any of the three regions at any of the three time points, when comparing subjects by age. However, men had significantly greater T-UT CSA at the after ST time point [6.9 (3.7) cm^2] when compared with women [2.8 (3.7) cm^2, $P < 0.05$]. Baseline T-UT CSA was higher than after detraining T-UT CSA for young men in the proximal and middle regions [0.1 (3.6), 0.4 (3.6) cm^2 vs. 2.8 (4.0), 2.4 (3.6) cm^2, $P < 0.05$], but there were no significant differences within the other three groups. These data indicate that sex may influence changes in regional CSA after ST, whereas age does not influence regional muscle gain or loss due to ST or detraining.

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Introduction

Aging is associated with a decline in skeletal muscle cross-sectional area (CSA) and muscular strength. Loss in muscle size and strength of the knee extensors is of particular relevance because the ability of these muscles to generate force rapidly has been shown to be critical when performing several activities of daily living including climbing stairs, walking, and preventing falls (Bassey et al. 1992).

Numerous investigations have examined the increase in CSA of the knee extensors in response to resistive exercise training (Hakkinen et al. 2000; Higbie et al. 1996; Housh et al. 1992; Narici et al. 1996; Narici et al. 1989; Roth et al. 2001). Narici et al. (1988) demonstrated through magnetic resonance imaging (MRI) that the knee extensors do not have a uniformly distributed CSA. The CSA of the knee extensors increases from the head of the femur reaching a maximal value near the mid-point of the femur and then decreases distally towards the knee. Because of this non-uniform distribution, analysis of specific regions of the knee extensors with strength training (ST) can lead to varying results. For this reason, some investigators have examined multiple regions, such as the regions proximal and distal to the mid-point of the thigh and the mid-thigh region (Hakkinen et al. 2001; Higbie et al. 1996; Housh et al. 1992; Narici et al. 1996, 1989). Narici et al. (1996) demonstrated that ST-induced hypertrophy of the knee extensors occurs to a significantly greater extent at the proximal and distal ends of the individual knee extensor muscles. They attributed this to possible greater protein synthesis occurring in these regions (Goldspink et al. 1991). In contrast, Hakkinen et al. (2001) concluded that the greatest hypertrophy occurred at points of maximal CSA, the proximal region for vastus lateralis (VL) and the distal region for vastus medialis (VM), which is approximately the mid-thigh region. Thus, when the knee extensors are analyzed as 1 U, it may be that the point of maximal CSA, i.e., mid-thigh, will show the greatest response to ST.

The few studies reporting regional changes in quadriceps CSA in response to ST have studied young men (Housh et al. 1992; Narici et al. 1996, 1989) young women (Higbie et al. 1996), older women (Hakkinen et al. 2001), or older men and women (Harridge et al. 1999), but have not reported age and sex comparisons in response to ST and detraining. Moreover, these studies have not included data of a control (untrained) limb or a control group in their analyses. This is an important limitation to these studies because using control data can help account for influences of biological, seasonal and methodological variations, common to a single group pre–post design. However, a no exercise control group cannot control for genetic differences between the two groups, which can affect muscle mass (Ivey et al. 2000; Riechman et al. 2004) and muscle function (Delmonico et al. 2007; Kostek et al. 2005) responses to ST. Another problem is the training group receiving more attention than the control group and other differences resulting from group heterogeneity. Therefore, we recommend unilateral limb training, using the untrained limb as a control, as a means of isolating the independent effects of ST and minimizing these threats to internal validity. We are aware of only two studies that have investigated the effects of detraining on CSA of various regions of a muscle group (Hakkinen et al. 2000; Narici et al. 1989). A decrease in the regional CSA of the knee extensors was reported by Narici et al. (1989) for young men, whereas Hakkinen et al. (2000) reported changes in middle-aged and elderly men and women, but only in the distal region, with no comparisons made between age or sex groups.

The purpose of the current study was to examine the effects of ST and detraining on multiple regions (proximal, middle, and distal) of the knee extensors and to compare age and sex differences. Both the absolute magnitude and percent change of mid-thigh CSA in young men and women were greater than older men and women in the study by Roth et al. (2001). Moreover, when compared to young women, older men, and older women, young men were the only group who showed significantly higher muscle volume values after detraining than baseline in the study by Ivey et al. (2000). Therefore, our primary hypothesis was that regional CSA changes with ST and detraining will be associated with aging, such that ST-induced increases in regional CSA will be greater in young subjects; whereas, detraining-induced decreases will be greater in older subjects. Ivey et al. (2000) also showed greater ST-induced increases and detraining-induced losses in muscle volume in young men than in young women, which supports our secondary hypothesis that ST-induced regional increases and detraining-induced losses in the CSA of the knee extensors will be greater in young men than young women. In contrast, we hypothesized that older men would show similar ST-induced increases and detraining-induced decreases as older women, based on the study by Ivey et al. (2000). Lastly, we hypothesized that the middle region would increase to a greater extent than the distal or proximal region after ST.

Methods

Ethical approval

This project was approved by the Institutional Review Board at the University of Maryland, College Park and all participants provided written informed consent prior to participation. This study conformed to the standards set by the *Declaration of Helsinki*.

Subjects

Participants included 10 young women, 11 young men, 11 older women, and 11 older men. The ages ranged from 20 to 30 years for the young men and women and 65–75 years for the older men and women. All subjects underwent a medical history, physical exam, and a graded exercise test (GXT) supervised by a physician prior to participating in the study to ensure the health of the participants and for screening purposes. Only healthy subjects with a negative GXT were permitted to participate in the study. Subjects were excluded from the study if they were found to be smokers or have any type of cardiovascular, metabolic, or musculoskeletal disorder. Only sedentary subjects who did not exercise for the past 6 months (<2*x*/week; <30 min) participated. All subjects provided written informed consent prior to participation and the project was approved by the Institutional Review Board at the University of Maryland, College Park.

Aerobic capacity (VO_{2max})

To characterize the subjects and confirm that they were not aerobically trained, VO_{2max} was assessed on a treadmill using an incremental incline and a constant speed protocol. The specific protocol was described in detail previously (Lemmer et al. 2000). The SensorMedics V_{max} 229 metabolic cart (SensorMedics Corp., Yorba Linda, CA) was used to measure oxygen uptake values every 30 s throughout the test. The test was terminated when subjects could no longer continue or demonstrated ECG abnormalities. To be classified as achieving a true VO_{2max}, subjects had to meet two of the following three criteria: (1) plateau in VO_2, (2) RER > 1.1, or (3) HR within ten beats of their age-predicted HR_{max}.

Body composition

Total body fat free mass and total body fat mass were measured by dual X-ray absorptiometry using a Lunar DXP-L (Lunar Corporation, Madison, WI) before and after ST. Dual X-ray absorptiometry scans were completed in the morning after an overnight fast. To ensure reliability of the measurements, a calibration standard was scanned daily. A water/oil phantom sample containing 41% fat was also scanned monthly. The coefficient of variation of repeated measurements was <1.0% (Tracy et al. 1999).

Assessment of muscle CSA

A Picker Edge 1.5 T MRI scanner was used to obtain a series of axial slices from the superior border of the patella to the anterior superior iliac spine surrounding the entire quadriceps femoris muscle group. Fifty-two axial scans, 9 mm thick (1 mm gap), T1-weighted, with an echo time of 14 ms and a relaxation time of 700 ms, encompassing the entire quadriceps muscle group were produced. All scans were performed at approximately the same time in the morning. Subjects did not eat after midnight prior to the MRI scanning and all post ST MRI scans took place at least 48 h after their last training session.

The validity and reliability of muscle area determination was assessed by repeat scans of a lean beef phantom that approximated the dimensions of the human quadriceps muscle, as we reported previously (Tracy et al. 1999). Results revealed a 0.12% difference between repeated scans, indicating excellent reliability.

NIH Image version 1.61 was used to analyze the MRI scans on a Macintosh PC (Apple, Inc.). The axial scans were cross-sectional slices of the muscles and the images were viewed as if looking at a cross-section of the human thigh. Three regions were examined from the MRI scans: region 1, proximal to the hip from the midpoint, region 2, the midpoint of the quadriceps group, and region 3, proximal to the knee from the midpoint. The CSA of each region was determined by outlining the quadriceps muscle group and subtracting any visible fat and bone with the use of a trackball. To determine the regions of interest, the following methods were used: Two bony landmarks marked the proximal and distal points of all slices containing quadriceps muscle tissue. This involved using the first slice that showed a clear image of the head of the femur and the last slice contained the superior border of the patella. The total number of slices containing muscle tissue was multiplied by 0.5. This number represents 50% of femur length, when counting down starting from the head of the femur. The first region (proximal to the hip) was 30% and the third region (proximal to the knee) was 70% and was determined by multiplying the total number of slices by 0.3 and 0.7, respectively.

Two investigators measured the regional CSA of both the trained and untrained limb in men and women, respectively, before and after ST as well as after 31 weeks of detraining. Both investigators were blinded to time point and training status. A pilot study was also carried out to ensure test–retest reliability between investigators. Repeat measurements were performed on different days of 50 axial scans, blinded to subject's sex, age, and time point (before or after ST and after detraining). The test-retest correlation was, $R^2 = 0.94$.

Strength testing

The subjects underwent three familiarization sessions prior to performing the muscle strength tests using the Keiser K 300 air powered leg extension machine. These low-resistance training sessions were conducted in order to familiarize the subjects with the equipment, to help control for the large 1-RM strength gains that commonly result from skill (motor learning) acquisition during the initial stages of training, and to help prevent injuries and soreness following ST.

One-repetition maximum (1RM) strength testing of the knee extensors was performed in both limbs after the familiarization sessions, both before and after the ST program as described previously (Tracy et al. 1999). The same investigator performed the 1RM strength test before and after ST and testing procedures were standardized on the basis of specific seat adjustments, body positions, number of trials (~5–7), levels of vocal encouragement, etc. The final 1RM value was defined as the highest resistance at which one repetition could be successfully completed.

ST program

Unilateral, knee extensor ST of the dominant limb was performed three times per week for 9 weeks. Training was performed on a Keiser K-300 air powered exercise machine for the knee extensors as described in detail previously (Tracy et al. 1999). Prior to each session the subject performed a warm-up on a cycle ergometer for 3 min followed by supervised stretching of the knee flexors and extensors. The training protocol was specifically designed to elicit near maximal effort in an individualized manner on all repetitions following warm-up, while maintaining high volume, as we have described previously in detail (Tracy et al. 1999). The untrained control limb was kept in a relaxed position throughout the training program. A total of five sets of knee extension, including warm-up, were completed at each training session.

The first set was a warm-up of 5 repetitions at 50% of the subject's original 1RM with a rest interval of 30 s. The second set consisted of five repetitions at the 5RM resistance with 90 s of rest prior to starting the next set. The third set consisted of ten repetitions. The first five repetitions were completed at the subjects 5RM. The resistance was then decreased just enough so that the subject could complete two or three more repetitions. This procedure was repeated until a total of ten repetitions were completed. For the fourth and fifth set, the same procedure was followed as the third set except 15 and 20 repetitions were completed on the fourth and fifth set, respectively. Rest intervals for the third and fourth sets were 150 and 180 s, respectively. Thus, each training session consisted of 50 repetitions, excluding warm-up. The shortening phase (formerly called the concentric phase) of the exercise was performed in ~1 s and the lengthening phase (formerly called the eccentric phase) was performed in ~2 s. The 5RM values were increased on an individual basis every week which provided a progressive overload stimulus to the muscle. The design of this training program allowed for heavy resistance (5RM) and high volume (high number of repetitions) in the same training session. This was done by having each repetition at or near maximal resistance. If a subject missed a session, the number missed was added to the end of the 9 weeks so that a minimum of 27 sessions were completed by all subjects. One-on-one supervision by qualified exercise leaders was provided for all exercise sessions.

Detraining

After completion of the 9-week ST program, participants were instructed to resume their normal lifestyle while avoiding any form of regular exercise for 31 weeks. Subjects were contacted each month during this period to ensure compliance.

Statistical analysis

To assess whether changes in CSA at each of the three time points differed between age and sex groups, a four-way ANOVA with repeated measures was used to analyze CSA (trained minus the untrained leg) with training and detraining in an age × sex × time point × region (2 × 2 × 3 × 3) ANOVA. Changes in CSA at all three time points were calculated by subtracting the CSA of the control leg from that of the trained leg at each time point. A four-way ANOVA with repeated measures was also used to analyze the CSA of the trained and untrained legs with training and detraining in an age × sex × time point × region (2 × 2 × 3 × 3) ANOVA. To assess whether 1RM strength in the trained and untrained legs differed with ST and detraining within age and sex groups, 1RM strength of both legs during ST and detraining were analyzed in an age × sex × time (2 × 2 × 3) ANOVA. Specific comparisons or interactions were assessed using preplanned, syntax-based contrasts. Statistical analyses were performed using SAS version 9.1.2 for Windows with data being expressed as means (SD). The level of significance was set at an alpha of 0.05.

Results

Physical characteristics

Table 1 shows the physical characteristics of the subjects separated by age and sex. In comparison to older subjects (men and women combined), young subjects (men and women combined) were significantly taller [174 (10) vs. 168 (9) cm $P < 0.01$] and had significantly lower body fat, both before [27 (8) vs. 34 (7) %, $P < 0.0001$] and after ST [27 (8) vs. 34 (7) %, $P < 0.0001$]. No significant changes occurred in body weight or percent body fat with ST in any group except young and older men who displayed a small but significant increase in body weight ($P < 0.05$).

Muscle strength

Detailed analysis of strength data has been reported previously by Lemmer et al. (2000). It should be noted that there were some subjects in the study by Lemmer et al. (2000) who did not participate in the CSA analysis reported in the

Table 1 Subject characteristics before and after 9 weeks of ST

	Men (n = 11)		Women (n = 10)	
	Baseline	AT	Baseline	AT
Young				
Age (years)	25 (3)	–	26 (2)	–
Height (cm)	179 (9)	–	168 (6)	–
Weight (kg)	82 (19)	83 (19)*	64 (12)	64 (12)
Percentage of body fat	23 (8)	23 (8)	31 (7)	31 (5)
VO_{2max} (ml kg^{-1} min^{-1})	44 (4)	–	33 (7)	–
	Men (n = 11)		Women (n = 11)	
	Baseline	AT	Baseline	AT
Older				
Age (years)	69 (3)	–	68 (3)	–
Height (cm)	174 (5)	–	161 (7)	–
Weight (kg)	80 (8)	81 (8)*	68 (9)	68 (8)
Percentage of body fat	29 (5)	29 (4)	39 (6)	38 (6)
VO_{2max} (ml kg^{-1} min^{-1})	23 (5)	–	20 (3)	–

All values are means (SD)

Baseline before ST, *AT* after training

* Significantly different from baseline ($P < 0.05$)

Table 2 Thigh CSA of the quadriceps (trained leg)

Region	Baseline	AT	Detrained	Percentage change (baseline to AT)	Percentage change (AT to detrained)
Young men (n = 11)					
1	67.2 (9.2)	73.2 (9.9)*	70.2 (9.9)*,†	9	4
2	83.7 (9.2)	91.3 (9.9)*	87.4 (9.9)*,†	9	4
3	65.5 (9.2)	72.0 (9.9)*	67.3 (9.9)†	10	6
Young women (n = 10)					
1	42.3 (9.8)	44.4 (9.8)	41.4 (9.8)†	4	6
2	57.9 (9.8)	62.5 (9.8)*	57.2 (9.8)†	8	7
3	47.2 (9.8)	51.9 (9.8)*	48.4 (9.8)†	7	4
Older men (n = 11)					
1	53.0 (9.2)	58.7 (9.9)*	53.3 (9.9)†	11	9
2	63.5 (9.2)	68.6 (9.9)*	64.5 (9.9)†	6	6
3	48.1 (9.2)	51.7 (9.9)*	48.9 (9.9)†	7	5
Older women (n = 11)					
1	34.9 (9.2)	37.3 (9.9)*	33.3 (9.9)†	7	11
2	45.2 (9.2)	50.6 (9.9)*	44.6 (9.9)†	12	12
3	37.8 (9.2)	42.9 (9.9)*	36.9 (9.9)†	13	14

Data are means and (SD) in cm^2

Region 1 proximal, *2* middle, *3* distal, *baseline* before ST, *AT* after training, *detrained* after 31 weeks of detraining

* Significantly different from baseline

† Significantly different from AT ($P < 0.05$)

current study. When examining only those subjects who provided both 1RM and CSA data, all four subject groups demonstrated significant increases in 1RM strength of the trained limb with ST (27–35%), as well as significant reductions after detraining (7–14%). All groups, except older women, maintained significantly greater strength in the trained limb after detraining ($P < 0.05$). In the untrained limb, all groups displayed modest but significant increases in strength (10–11%) with ST due to the well established cross education effect (Lee and Carroll 2007). Only young men maintained strength values in the untrained limb that were significantly higher than baseline ($P < 0.05$).

Muscle CSA

Thigh regional CSA of the trained limb are presented in Table 2 for all four subject groups. All groups significantly increased CSA in the proximal, middle, and distal regions after ST for the trained limb with the exception of young women, whom increased CSA significantly in only the middle and distal regions. Thigh regional CSA also significantly decreased in all four groups in all three regions after detraining. Only young men maintained a significantly larger CSA in the proximal and middle regions after detraining when compared to baseline.

Thigh regional CSA for the untrained limb are presented in Table 3. Minimal changes occurred in the untrained limb with ST and detraining when compared to baseline. However, a significant reduction was found in the middle region of the untrained limb in older men with ST ($P < 0.05$). Yet after detraining, this region returned to a value similar to baseline. Significant decreases were also detected in the middle and distal regions of older women after detraining compared to the after ST time point. The middle region of young men significantly increased after detraining when compared with post-training. However, after the detraining period, values were not significantly different from baseline for older women and young men.

Table 4 shows the mean CSA differences of the trained minus the untrained legs (T-UT). No significant differences existed between age groups at any of the three time points in any of the three regions. When groups were compared by age and sex, young men displayed significantly higher T-UT CSA after ST than young women in all three regions ($P < 0.05$). Older men also displayed significantly higher increases after training ($P < 0.05$), but only in the proximal region when compared to older women. In addition, Fig. 1 shows the mean changes in regional hypertrophy averaged across all four groups. For all subjects, a significant region × time interaction ($P < 0.0001$) indicated that T-UT CSA for each of the three regions after ST was significantly greater than baseline and after detraining, but at baseline values were not significantly different than after detraining. There was also a significantly greater increase in the middle region than the proximal [5.9 (4.6) vs. 4.4 (4.6) cm^2] and than in the distal region [4.1 (3.9) cm^2, all $P < 0.001$), supporting our hypothesis that greater hypertrophy occurs in the middle region of the knee extensors.

Further analysis revealed a significant sex × time interaction ($P < 0.001$). When T-UT CSA was averaged across all regions, men had significantly greater values after ST when compared with women, but did not differ at baseline or after detraining (Fig. 2).

Table 3 Thigh CSA of the quadriceps (untrained leg)

Region	Baseline	AT	Detrained	Percentage change (baseline to AT)	Percentage change (AT to detrained)
Young men ($n = 11$)					
1	67.1 (9.3)	66.5 (9.0)	67.4 (9.3)	−1	1
2	83.3 (9.3)	82.0 (9.0)	85.0 (9.3)†	−2	4
3	65.6 (9.3)	64.2 (9.0)	65.7 (9.3)	−2	2
Young women ($n = 10$)					
1	42.1 (9.2)	42.2 (8.9)	41.6 (9.5)	0	−1
2	58.6 (9.2)	59.0 (8.9)	57.8 (9.5)	1	−2
3	48.5 (9.2)	50.1 (8.9)	48.5 (9.5)	3	−3
Older men ($n = 11$)					
1	52.7 (9.3)	52.3 (9.0)	53.9 (9.3)	−1	3
2	63.6 (9.3)	61.6 (9.0)*	64.0 (9.3)†	−3	4
3	47.9 (9.3)	47.7 (9.0)	47.6 (9.3)	−1	0
Older women ($n = 11$)					
1	33.7 (9.3)	34.9 (9.0)	34.7 (9.3)	4	−1
2	45.3 (9.3)	46.7 (9.0)	44.3 (9.3)†	3	−5
3	38.6 (9.3)	40.2 (9.0)	37.2 (9.3)†	4	−7

Data are means and (SD) in cm^2

Region 1 proximal, *2* middle, *3* distal, *baseline* before ST, *AT* after training, *detrained* after 31 weeks of detraining

* Significantly different from baseline

† Significantly different from after ST ($P < 0.05$)

Discussion

The present study is the first to compare both age and sex responses to ST and detraining on region specific muscle hypertrophy. Using a training protocol designed to control for threats to internal validity, it was determined that age did not influence regional CSA changes with ST or detraining, thus refuting our initial hypothesis.

We could only find one study that compared sex and age differences in regional hypertrophic responses within a muscle group (Hakkinen et al. 2000). Hakkinen et al. (2000) compared middle-aged (43–57 years) and older (64–73 years) men and women. They showed a non-significant 3 and 7% increase in the distal region of the quadriceps as measured by ultrasound, in both middle-aged and older subjects, respectively, with ST. In the current study, the distal region of the quadriceps in the trained limb increased by 10, 10, 7, and 13% for young men, young women, older men, and older women, respectively, in only 9 weeks. It is possible that the high volume, heavy resistance ST program, in which each exercise repetition represents near maximal effort, could at least partially explain the differences between the two studies.

Other studies that have investigated regional hypertrophy have used unilateral isotonic (Higbie et al. 1996; Housh et al. 1992; Narici et al. 1996) and isokinetic (Narici et al. 1989) ST programs, but only tested young men (Housh et al. 1992; Narici et al. 1996, 1989), or young women (Higbie et al. 1996). All studies showed significant increases in CSA in one or more regions of the quadriceps. For example, Narici et al. (1989) demonstrated increases of 9% in CSA of the middle region of the quadriceps in young men, whereas Housh et al. (1992) showed an 11% increase in the same region of similar aged men. Both studies used isokinetic ST at the same speed (2.09 rad/s) for approximately 8 weeks.

Higbie et al. (1996) reported quadriceps CSA increases in the proximal, middle, and distal regions with eccentric isokinetic training of 9, 9, and 5%, respectively, and 6, 6, and 4%, respectively, with combined eccentric and concentric ST. These findings are similar to the relative increases in quadriceps CSA of the young women in the present study of 5, 8, and 10%. Older women (64 years) were studied after 24 weeks of a total body, low volume resistance training program by Hakkinen et al. (2001). The women increased CSA significantly in all regions of the quadriceps from proximal to distal, with increases ranging from 6 to 11%. The older women in the current study increased regional CSA by 7, 12, and 13% for the proximal middle, and distal regions. Thus, the magnitude of regional hypertrophy in the current study compares favorably to other studies in similar age and sex groups, regardless of the type of ST program. However, data from the current study add to these findings by showing that individuals can significantly increase quadriceps CSA after ST regardless of age or sex.

The length of the resistance training interventions in the aforementioned studies (Higbie et al. 1996; Housh et al. 1992; Narici et al. 1989) were 6–10 weeks and percent increases in regional quadriceps CSA after resistance training were similar to those found in the present study. One notable exception was an extensive 6 month resistance training study by Narici et al. (1996) which showed much larger increases in quadriceps CSA on the order of 18, 13,

Table 4 Thigh regional CSA differences of the quadriceps (T-UT)

Region	Baseline	AT	Detrained
Young men (n = 11)			
1	0.1 (3.6)	6.7 (4.6)*,‡	2.8 (4.0)*,†
2	0.4 (3.6)	9.3 (4.6)*,‡	2.4 (3.6)*,†
3	−0.1 (4.3)	7.8 (4.0)*,‡	1.6 (3.6)†
Young women (n = 10)			
1	0.2 (3.8)	2.3 (4.7)	−0.1 (3.8)†
2	−0.8 (3.8)	3.4 (4.7)*	−0.5 (3.8)†
3	−1.3 (4.4)	1.7 (3.8)	−0.2 (3.8)†
Older men (n = 11)			
1	0.4 (3.6)	6.4 (4.6)*,§	−0.6 (4.0)†
2	−0.1 (3.6)	7.1 (4.6)*	0.4 (3.6)†
3	0.2 (4.3)	4 (4.0)*	1.2 (3.6)†
Older women (n = 11)			
1	1.2 (3.6)	2.4 (4.6)	−1.4 (4.0)*,†
2	−0.1 (3.6)	4 (4.6)*	0.3 (3.6)†
3	−0.8 (4.3)	2.7 (4.0)*	−0.3 (3.6)†

Data are means of differences and (SD) in cm^2

T-UT CSA of the trained leg minus CSA of the untrained leg, *region 1* proximal, *2* middle, *3* distal, *baseline* before ST, *AT* after training, *detrained* after 31 weeks of detraining

* Significantly different from baseline

‡ Significantly different from young women at same region

† Significantly different from AT

§ Significantly different from older women at region 1 ($P < 0.05$)

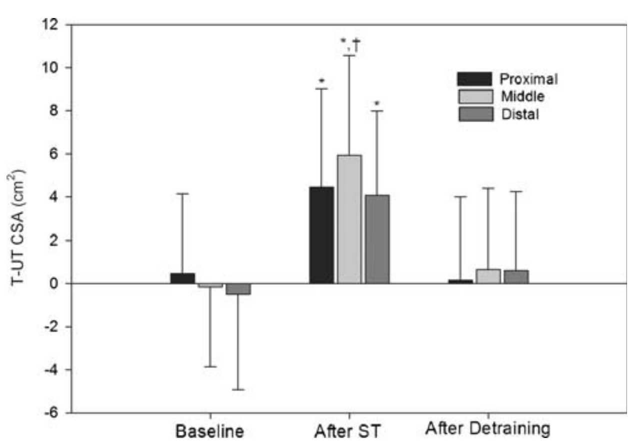

Fig. 1 Change in regional CSA of the proximal, middle, and distal regions of the knee extensors at baseline, after training, and after detraining, respectively. Data are means of differences with standard deviations as *error bars* in cm^2. *Significantly different versus baseline and after detraining ($P < 0.05$). †Significantly different versus proximal and distal after ST ($P < 0.05$)

and 21% for the proximal, middle, and distal regions. In that study, young men trained every other day for 24 weeks with loads of ~80% of 1RM. Whether these greater increases than previously reported, including values from the current study, are due to the length of training, higher

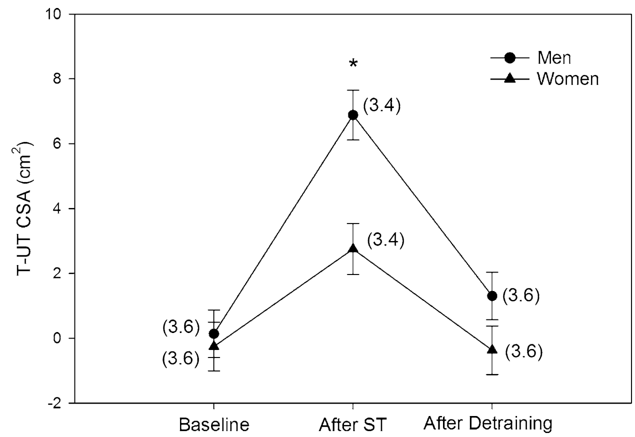

Fig. 2 Change in the T-UT CSA of the knee extensors in men and women at baseline, after training, and after detraining. Data are means of differences ±SED with standard deviations reported in *parentheses* in cm^2. *Significantly different versus women at the after ST time point ($P < 0.05$)

frequency of sessions, relative loads used in training or some other difference cannot be determined with certainty. The data from this study indicates that hypertrophy of the quadriceps occurs to the greatest extent at the middle region with similar increases occurring in the proximal and distal regions. It is difficult to discern which region in the previously discussed studies demonstrates the greatest increases, if any, in hypertrophy due to the absence of data reported as absolute increases.

In the present study, only T-UT CSA in the proximal region was significantly higher in older men compared to older women. This may be due to the reduced hypertrophy in the proximal region of older women compared to the middle and distal regions. Whether this is due to its smaller size or to other reasons is unclear. Examination of T-UT CSA between sexes revealed that men had significantly higher T-UT CSA after ST compared to women. The significance of this finding is that women typically have a smaller muscle mass in both the upper and lower body (Janssen et al. 2000) and are at higher risk for some of the functional consequences of sarcopenia with advanced age (Katz et al. 1983).

Another explanation for differences between sexes may be due to differences in the hormonal response to ST, both acute and chronic. While no measurements were performed on hormonal changes within subject groups in this study, previous research has shown elevated testosterone levels in men, but not women, after an acute bout of ST (Hakkinen and Pakarinen 1995; Weiss et al. 1983). Although some studies have reported significant acute elevations in testosterone in women (Cumming et al. 1987; Nindl et al. 2001), reports on chronic changes in testosterone have been inconsistent (see review by Kraemer and Ratamess 2005). Therefore, it is conceivable that differences in blood androgens could explain our finding of men displaying larger increases in T-UT CSA than women, but this cannot be determined from the results of the present study or from previous investigations, from the best of our knowledge.

It is well established that young and older men and women can increase skeletal muscle CSA with ST (Brown et al. 1990; Cureton et al. 1988; Fiatarone et al. 1990; Hakkinen et al. 1998; Harridge et al. 1999; O'Hagan et al. 1995) and that hypertrophy of the quadriceps occurs in a regional manner such that individual muscles hypertrophy to the greatest degree at points of maximal CSA. While the current study did not examine the individual muscles of the quadriceps, Narici et al. (1989) confirmed this through assessment of the four individual muscles of the quadriceps and identified maximal CSA in the vastus intermedius (VI) at the middle region, VL mid-way between the proximal and middle regions, VM at the distal region, and rectus femoris (RF) at the proximal region. Hakkinen et al. (2001) showed that CSA of the VL increased significantly in the proximal region whereas CSA of VM increased significantly in the distal region. They also observed significant increases in regions of maximal CSA for VL and VM, but not for RF and VI.

It is clear that there is a difference in the degree of hypertrophy occurring across all regions of the quadriceps (Hakkinen et al. 2001; Narici et al. 1996, 1989). The current study has shown preferential hypertrophy in the middle region of the quadriceps (Fig. 1). Recently, investigators have utilized electromyography (EMG) (Pincivero et al. 2004) and MRI (Akima et al. 2004) to study muscle recruitment patterns of the individual muscles of the quadriceps based on the mode of exercise used (e.g. leg press, knee extension, etc.) (Alkner et al. 2000) and joint angle (Pincivero et al. 2004). Knowledge of the specific recruitment and activation patterns of the quadriceps may further explain the regional hypertrophic response. This would be especially useful if different regions or particular muscles of the quadriceps are activated during functional activities such as rising from a chair or climbing stairs. It has been demonstrated that isometric maximal voluntary contractions at the knee joint angles of 0°, 10°, 30°, 50°, 70°, and 90° flexion indicate increasing EMG activity of VM from 0° to 90° flexion, whereas this pattern did not occur in VL and RF (Pincivero et al. 2004). Pincivero et al. (2004) also examined peak torque at these joint angles and calculated a muscle recruitment efficiency ratio of allometric-modeled average torque (N m kg^{-n}), which was normalized to values at 0° flexion to normalized EMG. Allometric torque uses a ratio of absolute torque and body mass and thus helps to control body mass as a covariate. Recruitment efficiency improved significantly more for VM from 70° to 90° flexion compared to RF and VL. The authors suggested that the improved recruitment efficiency indicates that the VM may provide greater knee extensor torque than the RF and VL at 90° flexion. Because standing from a seated position places the knee initially in 90° flexion, there may be added benefit to a larger CSA and/or greater neural activation in the distal region of the VM. Based on the VM having significantly higher normalized EMG data at 90° (Pincivero et al. 2004) compared to RF and VL, and that it reaches maximal CSA in the distal region (Hakkinen et al. 2001; Narici et al. 1989), identification of resistive exercises than can produce significant increases in the distal region of the quadriceps, specifically VM, may provide a greater functional benefit. However, other investigators have not found increasing EMG activity of VM from 10° to 90° of knee flexion (Zabik and Dawson 1996) thus weakening the argument that VM may contribute greater torque generating potential when the knee is in 90° flexion, such as when rising from a chair.

Further evidence has recently been generated to describe the recruitment pattern in neuromuscular compartments within the RF muscle. While previous investigators have found no significant differences in quadriceps EMG activity between leg press and knee extension (Alkner et al. 2000) showed that the neural recruitment of the RF during isokinetic knee extension is different between the proximal and distal portions of the neuromuscular compartments of RF. If there are different recruitment patterns with isokinetic exercise, there may be a difference in the hypertrophic response to a resistive training stimulus based on the type of contractions performed. Therefore, if VM is important in generating torque (e.g. when rising from a chair), exercises that improve recruitment of this muscle may offer an added benefit to elderly populations at risk for greater incidence of falls and a reduced quality of life.

Two other studies have examined the effects of detraining on regional quadriceps CSA. Narici et al. (1989) found a decrease of 4% in CSA after 40 days of detraining in the middle region of the quadriceps in young men. Despite an increased detraining period, young men showed a decrease of only 4% in the mid-thigh region. This value was not substantially altered by region or age of subjects. Young subjects decreased CSA by 6 and 7% in the middle and distal regions, whereas older subjects showed a 9 and 10% decrease in these regions. Hakkinen et al. (2000) used a similar time period of detraining (24 weeks) and observed a 9 and 11% decrease in the distal region of the quadriceps in middle-aged (37–44 years) and elderly (62–77 years) subjects, respectively.

Determining a physiological mechanism that would explain similar hypertrophy between age groups and greater hypertrophy in men compared to women was beyond the scope of this study. Therefore, we do not have data to support any potential mechanisms and can only speculate on possible explanations. In this context, however, Hikida et al. (1998) observed similar levels of muscle hypertrophy and myonuclei in young and older men. They also found that the percentage of satellite cells did not differ between young and older muscles and that satellite cells, responsible for contributing to myonuclear increase, did not decrease in numbers with aging. Contrary to these findings, recent data have found differences in satellite cell numbers of type II fibers, with higher values in young compared to older individuals whereas type I fiber satellite cell content did not differ (Verdijk et al. 2007). While the results of Hikida et al. (1998) may offer some insights into an explanation of our finding of no age-related differences in muscle CSA with ST, the findings of Verdijk et al. (2007) indicate that research in this area is controversial and future studies will need to examine this issue further. In regards to differences between men and women, Bamman et al. (2003) helped to rule out some explanations by concluding that sex differences in load-induced muscle hypertrophy cannot be explained by levels of circulating IGF-1 or dehydroepiandrosterone sulfate, or expression of myogenic transcripts. Testosterone-induced muscle hypertrophy is associated with increases in the numbers of myonuclei and satellite cells (Sinha-Hikim et al. 2003), but the relationship between ST-induced increases in myonuclei number and satellite cell quantity differs between men and women (Kadi et al. 2004; Kadi and Thornell 2000). These findings support the hypothesis that differences in androgen responses to ST might serve as one possible explanation for sex differences. However, no definitive conclusions can be made on this issue until future investigations provide data that support or reject hypotheses for specific mechanisms.

In summary, all subject groups in the current study showed significant ST-induced increases in CSA when subtracting the values of the untrained limb from those of the trained limb in all three regions (proximal, middle, and distal) of the quadriceps, with the middle region displaying the largest increase. Age did not influence T-UT CSA values such that both groups demonstrated similar values at all three time points. Sex did play a role such that men had significantly greater T-UT CSA but only post-training. Older men had significantly greater T-UT CSA only at the proximal region when compared to older women. Both age groups had similar T-UT CSA values at baseline, after ST, and after 31 weeks of detraining. Thus, age per se does not appear to influence the amount of gain or loss in regional CSA of the quadriceps muscle.

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