

Variability in Muscle Size and Strength Gain after Unilateral Resistance Training

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ABSTRACT

HUBAL, M. J., H. GORDISH-DRESSMAN, P. D. THOMPSON, T. B. PRICE, E. P. HOFFMAN, T. J. ANGELOPOULOS, P. M. GORDON, N. M. MOYNA, L. S. PESCATELLO, P. S. VISICH, R. F. ZOELLER, R. L. SEIP, and P. M. CLARKSON. Variability in Muscle Size and Strength Gain after Unilateral Resistance Training. *Med. Sci. Sports Exerc.*, Vol. 37, No. 6, pp. 964–972, 2005. **Purpose:** This study assessed variability in muscle size and strength changes in a large cohort of men and women after a unilateral resistance training program in the elbow flexors. A secondary purpose was to assess sex differences in size and strength changes after training. **Methods:** Five hundred eighty-five subjects (342 women, 243 men) were tested at one of eight study centers. Isometric (MVC) and dynamic strength (one-repetition maximum (1RM)) of the elbow flexor muscles of each arm and magnetic resonance imaging (MRI) of the biceps brachii (to determine cross-sectional area (CSA)) were assessed before and after 12 wk of progressive dynamic resistance training of the nondominant arm. **Results:** Size changes ranged from -2 to $+59\%$ (-0.4 to $+13.6$ cm²), 1RM strength gains ranged from 0 to $+250\%$ (0 to $+10.2$ kg), and MVC changes ranged from -32 to $+149\%$ (-15.9 to $+52.6$ kg). Coefficients of variation were 0.48 and 0.51 for changes in CSA ($P = 0.44$), 1.07 and 0.89 for changes in MVC ($P < 0.01$), and 0.55 and 0.59 for changes in CSA ($P < 0.01$) in men and women, respectively. Men experienced 2.5% greater gains for CSA ($P < 0.01$) compared with women. Despite greater absolute gains in men, relative increases in strength measures were greater in women versus men ($P < 0.05$). **Conclusion:** Men and women exhibit wide ranges of response to resistance training, with some subjects showing little to no gain, and others showing profound changes, increasing size by over 10 cm² and doubling their strength. Men had only a slight advantage in relative size gains compared with women, whereas women outpaced men considerably in relative gains in strength. **Key Words:** HYPERTROPHY, GENDER DIFFERENCES, VARIATION, 1RM, MRI

Numerous studies have documented that progressive resistance training causes gains in both strength and skeletal muscle size (for recent review see (17)). It has been commonly observed that some people who take up resistance training experience vastly different gains in strength and size than others. This was noted in 1954, when Sheldon et al. (28) observed that individuals with different physiques had different abilities to gain muscle mass in response to training. However, to date, no study has been

undertaken with a large enough sample size of subjects to fully quantify the range of human responses to a given strength training program. This information is needed to help define which factors significantly influence a muscle's response to resistance exercise, including genetic underpinnings of muscle growth capabilities.

Factors known to affect strength gain and hypertrophy include gender, age, physical activity level, previous training status, and endocrine status (for reviews see (12,27)). Gender has a large effect on skeletal muscle morphology and function (6,27). Men have greater muscle size and strength than women, due to greater body size and higher levels of anabolic hormones. However, it is unknown whether men and women exhibit different levels of variability in size and strength responses after a resistance training program. The only data available are coefficients of variations (CV) of baseline and posttraining measures, as calculated from published means and standard deviations, and these have been equivocal as to whether men or women

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show greater variability in muscle size or muscle strength (2,15,25,26). Furthermore, data are also equivocal regarding whether there is an effect of training, gender, or an interaction effect between training and gender. The lack of a definitive answer concerning potential gender differences in variability is likely due to relatively small sample sizes used in previous studies (fewer than 20 men and women per group). However, because some of these studies indicate the existence of gender differences, and based on higher ranges of androgens in men, we hypothesized that men would have greater variability in both absolute and relative size and strength gains than women.

Although men gain greater amounts of absolute strength and muscle mass than women after resistance training, data concerning relative changes are equivocal. Some previous studies found gender differences in either strength or size changes after resistance training (16,19,32), whereas the majority of recent studies have documented similarities in relative strength and size changes after training (2,9,10,15). Again, one factor that may explain these equivocal findings is the small sample sizes used in previous studies, limiting the statistical power of these studies to detect significant differences between men and women. Based on data from studies showing similar size and strength gains (2,10,11,23,32), we hypothesized that men and women will display similar relative changes in CSA and strength gains.

We had the unique opportunity to study a cohort of 585 subjects participating in an investigation of genetic variations and their associations with strength and size changes after unilateral resistance training in the elbow flexors. Here we document the range of responses of men and women to 12 wk of progressive resistance training of the nondominant elbow flexors, and compare between genders for differences in relative size and strength gains.

METHODS

Study Overview

This study was part of the FAMuSS, or Functional Polymorphisms Associated with Human Muscle Size and Strength study, a large multiinstitutional cooperative effort designed to identify synonymous single nucleotide polymorphisms (SNP) in selected muscle proteins contributing to baseline elbow flexor muscle size and strength and their response to 12 wk of resistance exercise training (29). Briefly, after obtaining written informed consent (approved through each participating institution's institutional review board) from all individuals, isometric and dynamic strength of the forearm flexors and cross-sectional diameter of the upper-arm musculature was measured before and after 12 wk of elbow flexor and extensor resistance training in 585 subjects aged 18–40 yr. Subjects over 40 yr old were excluded to avoid studying men who have potentially experienced the marked decrease in testosterone levels that occur in older age groups (18). Pretraining isometric strength measurements were performed over three testing days. Posttraining strength measurements were performed on two testing days. Cross-sectional

area of the upper-arm musculature was measured using magnetic resonance imaging (MRI).

Subjects

Men and women were excluded if they used medications known to affect skeletal muscle such as corticosteroids; had any restriction of activity; had chronic medical conditions such as diabetes; had metal implants in arms, eyes, head, brain, neck, or heart that would prohibit MRI testing; had performed strength training or employment requiring repetitive use of the arms within the prior 12 months; consumed on average more than two alcoholic drinks daily; or had used dietary supplements reported to build muscle size/strength or cause weight gain such as protein supplements, creatine, or androgenic precursors.

A total of 585 subjects (243 M, 342 W) completed the study at the time of manuscript revision and were used for data analyses. Demographics are included in Table 1. On average, men were approximately 1 yr older than the women at the onset of the study (24.8 vs 23.9 yr, respectively; $P < 0.05$). At baseline, men were taller and heavier than the women, with a slightly higher body mass index than women (24.7 vs 23.7, respectively; $P < 0.05$).

Dietary Control Procedures

Subjects were instructed to maintain their habitual dietary intake and physical activity levels (with the exception of the addition of the unilateral arm training) over the course of the study so that significant weight loss or gain was avoided. Individuals who had supplemented their diet with additional protein or taken any dietary supplement reported to build muscle or to cause weight gain (dietary supplements containing protein, creatine, or androgenic precursors) were not included. Data for subjects who lost a significant amount of body weight were excluded from analysis. As slight weight gain would be expected with the addition of muscle volume, those that increased body weight were included in the analysis.

Muscle Testing

Isometric biceps strength testing. Isometric strength (MVC) of the elbow flexor muscles of each arm was determined before and after 12 wk of strength training using a specially constructed, modified preacher bench and strain gauge (model 32628CTL, Lafayette Instrument Company,

TABLE 1. Pre- and posttraining subject characteristics of entire cohort and grouped by gender; data represent means \pm SEM.

Group	Age (yr)	Height (cm)	Weight (kg)	BMI
All ($N = 585$)				
Pretraining	24.3 \pm 0.2	169.8 \pm 0.5	70.3 \pm 0.7	24.1 \pm 0.2
Posttraining		170.0 \pm 0.5	70.6 \pm 0.6	24.3 \pm 0.2
Men ($N = 243$)				
Pretraining	24.8 \pm 0.4*	176.3 \pm 0.9*	77.8 \pm 1.0*	24.7 \pm 0.3*
Posttraining		176.8 \pm 0.5*	78.0 \pm 1.0*	24.9 \pm 0.3*
Women ($N = 342$)				
Pretraining	23.9 \pm 0.3	165.2 \pm 0.4	65.0 \pm 0.7	23.7 \pm 0.2
Posttraining		165.2 \pm 0.4	65.4 \pm 0.7	23.9 \pm 0.2

* Denotes a significantly greater mean in men vs women ($P < 0.05$). No significant interactions were detected between gender and time.

Lafayette, IN). Baseline measures of isometric strength were assessed on three separate days spaced 24–48 h apart in the week before the onset of training (29). The first of these sessions was used for familiarization of the subjects to the MVC testing protocol, and the pretraining MVC was calculated as the average of the second and third pretraining testing sessions. Only two posttraining sessions were used, as subjects had already been familiarized with the protocol. The first posttraining MVC test occurred immediately before the final training session. The second posttraining MVC test occurred 48–72 h after the final training session.

Intraclass reliability coefficient (r) values for elbow flexor isometric strength at 90° elbow flexion range from 0.95 to 0.99 (7,8). The average of the results obtained on the second and third testing days was used as the baseline criterion measurement. Details of the testing procedure have been published previously (29).

One-repetition maximum biceps strength testing. The dynamic strength of the elbow flexor muscles of each arm was assessed by determining the one-repetition maximum (1RM) on the standard preacher curl exercise. The 1RM testing was performed before and after 12 wk of strength training. Unlike the isometric strength testing, baseline 1RM testing was completed in one day, during the third and second strength testing visits at baseline and at the end of the study, respectively. Posttraining 1RM was measured 48–72 h after the final training session (either after the final MRI scan or 48 h before the final MRI scan).

The 1RM test protocol modified from Baechle et al. (4) was used and investigators were carefully trained to carry out the test. To ensure that the investigators were trained, all investigators received on-site training at least once per year, and an instructional video was made for all sites to follow describing the procedure in detail. At each site, one experienced investigator typically supervised all 1RM tests both before and after training. Details on subject position were recorded at baseline to assure proper position during posttraining testing. Each subject performed two warm-up sets with increasing weight, with 3 min of rest between sets. During the test, subjects were instructed to go through a full range of motion starting from 180° to full flexion. Care was taken to assure that the subject completed the full range of motion. After warm-up, weights were increased, and each subject attempted to perform one full contraction. If the subject successfully completed one contraction without assistance, weights were raised slightly (0.563–1.125 kg), and the subject again attempted to complete one repetition. One minute of rest was given between attempts. The need for assistance on an attempt or failure to extend the arm fully during the contraction was not considered to be successful attempt. Weights were chosen so that the 1RM could be determined in three to five attempts, though more attempts were completed when necessary. The test was terminated when the subject completed a contraction with a given weight and failed at the next weight increment. Further details can be found in Thompson et al. (29).

Muscle size: cross-sectional area testing. MRI was performed before and after exercise training to assess

changes in the biceps brachii cross-sectional area (CSA) as previously described (13,24). Pretraining MRI was performed either before or after strength testing, and at least 48 h before or after 1RM testing to ensure temporary effects of the 1RM protocol were avoided. Posttraining MRI was performed 48–96 h after the final training session, ensuring that temporary exercise effects such as water shifts were again avoided, while also avoiding any reduction of muscle size from detraining. Posttraining CSA data were compared with pretraining values to determine training-induced changes. Pre- and posttraining MR images were obtained separately from both the dominant (untrained) and non-dominant (trained) arms, thereby allowing the dominant arm to act as a control.

Because MR images were collected on two separate occasions, it was important that each subject's positioning within the MR magnet be reliably reproduced in order to avoid coregistration errors. To accomplish this, MRI of each arm was performed at the site corresponding to the maximum circumference of the upper arm (i.e., in the belly of the muscle). The maximum circumference was identified with the arm abducted 90° at the shoulder, flexed 90° at the elbow, and the biceps maximally contracted. This location, or the point of measure (POM) was marked on the subject's skin using a radiographic bead (Beekley Spots, Beekley Corp., Bristol, CT) and the circumference of the arm measured with a vinyl, nonstretchable tape measure. At each imaging site, the on-site investigator located and marked the POM before each MRI measurement.

Subjects were scanned in the supine position with the arm of interest at their side and their palms up, taped in place on the scanner bed surface. The POM was centered to the alignment light of the MRI. A sagittal scout image (six to nine slices) was obtained to locate the long axis of the humerus. Fifteen serial fast spoiled gradient images of each arm were obtained (TE = 1.9 s, TR = 200 ms, flow artifact suppression, 30° flip angle) using the POM as the center most point. These axial/oblique image slices (i.e., perpendicular to the humerus) began at the top of the arm and proceeded toward the elbow such that the belly of the muscle occurred at slices 8 and 9. The slices were 16 mm thick with a 0 mm interslice gap, 256 × 192 matrix resolution, 22 × 22 cm field of view, number of acquisitions (NEX) = 6. Subjects were repositioned for each arm so that the arm was centered in the magnet. This method imaged a 24-cm length of each arm.

MR images from each investigational site were transferred to the central MR imaging facility at Yale University via either magneto optical disk (MOD) or CD-ROM. Images were analyzed using a custom-designed interactive processing and visualization program that operates in Matlab (The Math Works, Inc., Natick, MA). This software enabled the user to assign regions of interest (ROI) in an image set by tracing region borders with a mouse. Muscle is easily identifiable on MR images and its CSA was measured using this computerized planimetry technique. Intraobserver reliability for ROI assignment, tested by repeated measures, was less than 1%. When interobserver reliability was tested between

two different observers over 74 different subjects the mean difference was 1.1% and the two series' were significantly correlated ($r^2 = 0.9636$). Once the ROI was defined, the program reported the number of pixels contained in the selected ROI. Based upon the MR acquisition data (i.e., field of view and matrix resolution), the CSA (cm^2) of the defined ROI was then calculated. When the pretraining CSA (cm^2) was subtracted from the posttraining CSA (cm^2), the training effect (Δcm^2) could be compared between subjects.

Exercise training. Subjects underwent gradually progressive, supervised strength training of their nondominant arm in one of the eight collaborating exercise sites. The 1RM measured during pretraining testing was used to estimate the weights that could be lifted for 12, 8, and 6 repetitions using standard formulas (30). Training typically began 1–7 d after the completion of pretraining strength and size measurements, and no longer than 14 d after pretraining assessments.

Exercises were performed with the nondominant arm only. The exercises consisted of the biceps preacher curl, biceps concentration curl, standing biceps curl, overhead triceps extension, and triceps kickback. All training sessions were supervised and lasted approximately 45–60 min each. Two warm-up sets were used before the first biceps and first triceps exercise. Subjects rested for 3 min after each warm-up set and for 2 min after each testing set, and investigators used timers throughout the session to monitor the length of rest periods. Subjects were not allowed to perform any metabolically demanding activities during each rest period. The exercise progression used the following weekly training protocol: weeks 1–4: 3 sets with 12 repetitions of the 12RM weight; weeks 5–9: 3 sets with 8 repetitions of the 8RM weight; weeks 10–12: 3 sets with 6 repetitions of the 6RM weight. The primary interest was to train the elbow flexors, but we also trained the elbow extensors to balance muscle strength across the joint.

Standardization between sites. Adaptations to resistance training are highly specific to the training protocol. To control for differences among training sites, each site used an identical training protocol and identical exercise equipment purchased from the same manufacturers. The techniques for MRI, strength and anthropometrical measurements, and exercise training were videotaped, and research personnel from each study site reviewed the videotape before the start of each training group. In addition, meetings were held several times per year among group members to maximize compliance to the standard protocol, including hands-on training sessions.

Statistical analysis. Reliability of the baseline isometric test was assessed by intraclass correlation coefficient for the entire cohort and individually by site. Differences between men and women at baseline were tested by independent *t*-tests for each variable in question within each arm for the entire cohort.

Variability within the entire cohort and within each gender was calculated for each of the independent variables. Variability was calculated as the coefficient of variation and each resultant distribution is graphed as a histogram and de-

scribed using skewness and kurtosis. Additionally, Levene's test was used to test for equality of variances between genders. All analyses were assessed independently for each arm.

The effect of exercise on muscle size and strength (MVC and 1RM) was assessed using repeated measures ANCOVA (gender as grouping factor, baseline values as the covariate, and repeated measures over time) within the nondominant arm. Analyses were repeated on the nontrained arm.

RESULTS

Subject Characteristics

Pre- and posttraining subject characteristics are provided in Table 1. Slight weight and BMI gains across the training period in both genders were not significantly different ($P = 0.44$). These weight gains averaged less than 0.5 kg and could have been influenced by increased muscle mass in the arm.

Baseline Measures

The intraclass correlation coefficient between the second and third isometric strength baseline days was $R = 0.986$ for the nondominant arm and $R = 0.985$ for the dominant arm, respectively, and *t*-tests showed no overall difference between days for all sites ($P = 0.15$). Thus the reliability of this measure was good. Therefore, all values for MVC reported here are the average of the mean strength from day 2 and the mean strength from day 3. The 1RM test and the muscle cross-sectional area were performed only once at baseline. At baseline, men had greater values for all strength and size variables ($P < 0.01$) for CSA, MVC, and 1RM for each arm; Tables 2 and 3.

Training Effect

Muscle size. Baseline and posttraining biceps cross-sectional area measures for the trained arm are presented in Table 2, as well as calculated differences in the means and percent changes from baseline to posttraining. Coefficients of variation within each gender are also reported in Table 2, and a histogram of changes in CSA within each gender is depicted in Figure 1. Men demonstrated a skewness of 0.35 and a kurtosis of 0.44, whereas women demonstrated a skewness of 0.39 and a kurtosis of 0.62. Levene's test found a significant difference between men and women for absolute CSA change ($P = 0.00$), but no differences for variance were found for relative CSA change ($P = 0.44$). Furthermore, the number of subjects found to be outliers (± 2 SD from the mean) were similar between genders. We found that 0.08% of both men ($N = 2$) and women ($N = 3$) were low responders, whereas 3% of men ($N = 7$) and 2% of women ($N = 7$) were high responders.

An ANCOVA of cross-sectional area in the trained arm detected significant effects of gender and time ($P < 0.001$). Additionally, men gained significantly more absolute and relative biceps CSA in the trained arm than women after 12

TABLE 2. Size and strength changes in the trained arm.

Variable	Absolute Value					Relative to Baseline			
	Pretrain	Posttrain	Difference	Min	Max	Change (%)	Min	Max	CV
Muscle size									
All	16.8 ± 0.2	20.0 ± 0.3	3.2 ± 0.1			18.9 ± 0.4			
Men	21.3 ± 0.4	25.5 ± 0.4	4.2 ± 0.1	-0.4	13.6	20.4 ± 0.6*	-2.5	55.5	0.48
Women	13.6 ± 0.2	16.0 ± 0.2	2.4 ± 0.1	-0.5	7.2	17.9 ± 0.5	-2.3	59.3	0.51
Iso strength									
All	44.6 ± 1.0	52.2 ± 1.1	7.5 ± 0.3			19.5 ± 0.8			
Men	64.3 ± 1.4	73.6 ± 1.6	9.5 ± 0.6	-13.4	52.6	15.8 ± 1.1	-24.3	148.5	1.07
Women	30.8 ± 0.6	37.2 ± 0.7	6.1 ± 0.3	-15.9	26.1	22.0 ± 1.1*	-31.5	93.4	0.89
1RM strength									
All	8.5 ± 0.2	12.4 ± 0.2	3.9 ± 0.1			54.1 ± 1.4			
Men	11.7 ± 0.2	15.9 ± 0.2	4.3 ± 0.1	0.0	10.2	39.8 ± 1.4	0.0	150.0	0.55
Women	6.2 ± 0.1	9.9 ± 0.1	3.6 ± 0.1	0.0	9.1	64.1 ± 2.0*	0.0	250.0	0.59

Units for muscle size are centimeters squared and for MVC and 1RM are kilograms. Data represent means ± SEM. Significant gender and time main effects were found for all variables within the trained arm ($P < 0.05$).

* Denotes significant gender × time interaction ($P < 0.001$).

wk of training (relative gains of 20.4 vs 17.9% for men vs women, respectively, $P < 0.001$).

Muscle strength. Baseline and posttraining 1RM strength measures for the trained arm are presented in Table 2, as well as calculated differences in the means and percent changes from baseline to posttraining. Coefficients of variation within each gender are also reported in Table 2, and a histogram of changes in 1RM within each gender is depicted in Figure 2. Men demonstrated a skewness of 1.14 and a kurtosis of 2.84, whereas women demonstrated a skewness of 1.08 and a kurtosis of 2.67. Levene’s test found no differences between men and women for variance in absolute 1RM change ($P = 0.48$), but a significant difference in relative 1RM change ($P < 0.01$). The percentage of subjects found to be outliers (± 2 SD from the mean) was slightly higher in men versus women. No subject lost dynamic strength so that there were no low responders, whereas 3.4% of men ($N = 8$) and 2.6% of women ($N = 9$) were high responders.

An ANCOVA of 1RM detected significant effects of gender and time for both absolute and relative 1RM change ($P < 0.001$) in the trained arm. Additionally, the interaction term (gender × time) determined a significantly greater relative gain in 1RM for women versus men after 12 wk of training (64.1 vs 39.8% for women vs men, respectively; $P < 0.001$), despite greater absolute gains in the men.

Baseline and posttraining isometric strength measures (MVC) for the trained arm are presented in Table 2, as well

as calculated differences in the means and percent changes from baseline to posttraining. Coefficients of variation within each gender are also reported in Table 2 and a histogram of changes in MVC within each gender is depicted in Figure 3. Men demonstrated a skewness of 2.39 and a kurtosis of 16.66, whereas women demonstrated a skewness of 0.74 and a kurtosis of 1.16. This suggests a strong tendency for men toward the mean while women display more of a normal-type distribution. Levene’s test found differences between men and women for variance in both absolute and relative MVC ($P < 0.01$). With regards to outliers, we found that 0.9% of men ($N = 2$) and 0.6% of women ($N = 2$) were low responders, whereas 3.6% of men ($N = 8$) and 3.8% of women ($N = 12$) were high responders.

An ANCOVA of MVC detected significant effects of gender and time ($P < 0.001$) in the trained arm for both absolute and relative MVC change. Additionally, the interaction term (gender × time) determined a significantly greater gain in MVC for women versus men after 12 wk of training (22.0 vs 15.8% for women vs men, respectively; $P < 0.001$), despite greater absolute gains in the men.

TABLE 3. Size and strength changes in the untrained arm.

Variable	Pretrain	Posttrain	Differences	% Change
Muscle size				
All	17.4 ± 0.3	17.6 ± 0.3	0.2 ± 0.0	1.4 ± 0.3
Men	22.2 ± 0.4	22.4 ± 0.3	0.2 ± 0.1	1.1 ± 0.4
Women	14.0 ± 0.2	14.2 ± 0.2	0.2 ± 0.0	1.6 ± 0.3
Iso strength				
All	46.6 ± 1.0	48.0 ± 1.0	1.7 ± 0.3	5.3 ± 0.7
Men	67.4 ± 1.4	68.6 ± 1.4	1.8 ± 0.5	3.6 ± 1.0
Women	31.8 ± 0.5	33.9 ± 0.6	1.7 ± 0.3	6.4 ± 0.9
1RM strength				
All	9.1 ± 0.2	9.9 ± 0.2	0.8 ± 0.1	10.6 ± 0.8
Men	12.6 ± 0.2	13.2 ± 0.2	0.7 ± 0.1	6.2 ± 0.9
Women	6.7 ± 0.1	7.6 ± 0.1	0.9 ± 0.1	13.6 ± 1.1

Units for muscle size are centimeters squared and for MVC and 1RM are kilograms. Data represent means ± SEM. Significant gender and time main effects were found for all variables within the untrained arm ($P < 0.05$).

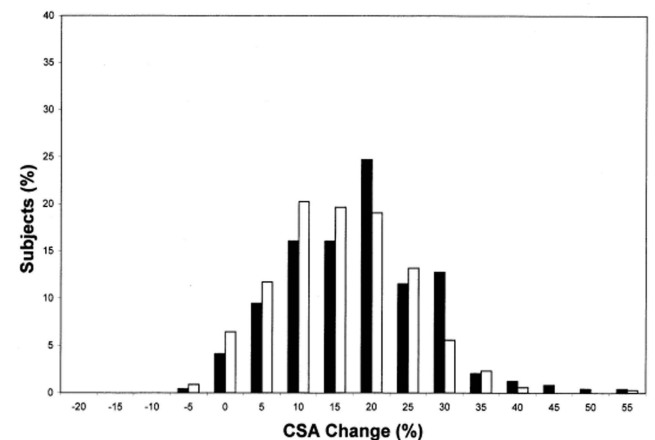


FIGURE 1—Biceps cross-sectional area. Histogram of biceps cross-sectional area changes (relative to baseline) within each gender for the trained arm. Black bars denote responses of men while white bars denote responses of women.

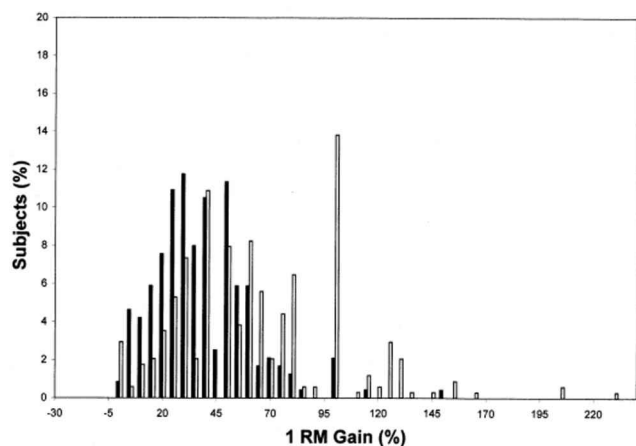


FIGURE 2—One-repetition maximum strength test. Histogram of 1RM changes (relative to baseline) within each gender for the trained arm, showing similar variability between men and women for muscle mass gains. Black bars denote responses of men while white bars denote responses of women.

Changes in Size and Strength in the Untrained Arm

Muscle size. Baseline and posttraining biceps cross-sectional area measures for the untrained arm are presented in Table 3, as well as calculated differences in the means and percent changes from baseline to posttraining. In the untrained arm, an ANCOVA of cross-sectional area detected significant effects of gender and time ($P < 0.001$), with very slight gains in CSA over time (1.5%). No significant interaction was detected between genders after 12 wk, indicating similar small gains in CSA in men and women ($P = 0.97$).

Muscle strength. Baseline and posttraining 1RM strength measures for the untrained arm are presented in Table 3, as well as calculated differences in the means and percent changes from baseline to posttraining. In the untrained arm, an ANCOVA of 1RM detected significant effects of gender and time ($P < 0.001$). No significant interaction was detected between genders after 12 wk, indicating similar gains in 1RM in men and women ($P = 0.10$).

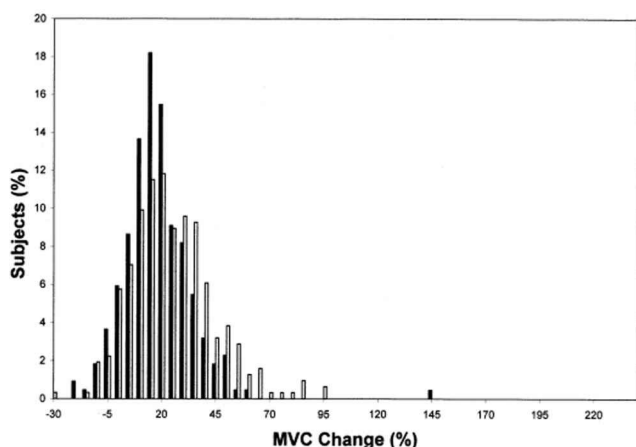


FIGURE 3—Isometric strength test. Histogram of isometric strength changes (relative to baseline) within each gender for the trained arm. Black bars denote responses of men whereas white bars denote responses of women.

Baseline and posttraining isometric strength measures (MVC) for the untrained arm are presented in Table 3, as well as calculated differences in the means and percent changes from baseline to posttraining. In the untrained arm, an ANCOVA of MVC detected significant effects of gender and time ($P < 0.001$). No significant interaction was detected between genders after 12 wk, indicating similar gains in 1RM in men and women ($P = 0.92$).

DISCUSSION

Although it is well documented that both men and women can gain muscle size and strength in response to resistance training, anecdotal evidence suggests that some people experience more dramatic size and strength gains than others. No study to date has attempted to quantify the amount of variation in size and strength gains in a large cohort of men and women after a controlled progressive resistance training program, especially using sensitive techniques such as MRI to assess muscle size. Additionally, there is some conflict concerning the existence of sex differences in the response to resistance training. In this study, we had the opportunity to document variability in training-induced changes in a single muscle group in 585 men and women, as well as to provide a definitive answer as to the existence of sex differences in size and strength gains after resistance training.

Variability

Variability in muscle size. Of the 585 subjects, 232 subjects showed an increase in CSA of between 15 and 25%. However, 10 subjects gained over 40%, and 36 subjects gained less than 5%. We hypothesized that men would demonstrate greater variability for absolute gains in muscle mass, because they have a much greater range of normal circulating levels of androgens than women (34). Androgens (especially testosterone) have been shown to drive muscle hypertrophy in a dose-dependent manner (5). Additionally, coefficients of variation calculated from published mean and standard deviation data from previous studies indicated that variability in muscle size at baseline (15,26) and after training (15) was greater in men versus women. In our study, we found significant differences in variability for absolute values pre- and posttraining. However, the variability in the relative change from pre- to posttraining was not significantly different between men and women. These data suggest that variation in the relative response of muscle to hypertrophic stimuli is not sex-dependent in healthy young adults.

Additionally, the lack of correlation in our study between age and changes in muscle size provides additional evidence that testosterone levels do not play a significant role in the variability of muscle size increases. Despite the large age range used in this study (18–40 yr of age), the correlation between age and muscle size was very weak ($r = -0.09$). We ascribe this to the upper age cutoff of 40 yr, as any significant decreases in testosterone levels do not occur until age 60 or older in most individuals (18).

Variability in muscle strength. Of the 585 subjects, 232 subjects showed an increase in 1RM of between 40 and 60%. However, 36 subjects gained over 100%, and 12 subjects gained less than 5%. For MVC, 119 subjects showed an increase in strength of between 15 and 25%, whereas 60 subjects gained over 40%, and 102 subjects gained less than 5%. As with muscle size gains, we expected broader androgen ranges in the men to confer higher variability for strength gains in men. For absolute gains, we found higher variability in men for MVC gain (but not 1RM gain). For relative change variability, we observed differences in variability between men and women regarding both isometric and dynamic strength gains. However, the pattern was mode-dependent, in that men had greater variability in isometric strength gains while women had greater variability in dynamic strength gains.

Although men in our study were more variable than women in the amount of relative change in the isometric strength measure after training, examination of the histogram (Fig. 3) shows that the preponderance of responses from men gravitate toward the mean (as evidenced by the kurtosis score of 16.7). This could be explained in part by the presence of one very high responder who displayed a gain of 150% in MVC. Without this one individual, the CV for the men drops from 1.07 to 0.94, closer to the 0.89 value demonstrated by the women (but still significantly different).

Women demonstrated greater variability in dynamic relative strength gains after training. The greater variability found in women could be the result of several factors. One of these could be a greater flexibility level in women at the elbow (3), making a full-extension maximal effort difficult and blunting strength gains. Another could be potential differences in skill acquisition during training, in that women were, on average, less skilled at the preacher curl before training than men, leading to higher relative gains that were not necessarily related to inherent strength gains in the muscle. This latter idea is in accordance with the theory put forth by Wilmore in 1979 that lower strength levels in untrained women is due to social and cultural restrictions rather than dramatic physiological differences between the sexes (33).

One factor that could have affected variability in both muscle size and strength changes differently in men and women would be the volume of training. In our study, each subject lifted progressively greater weights across the 12 wk within general intensity guidelines (i.e., goal in weeks 1–4 at 3 sets of 12 repetitions at 65–75% 1RM; goal in weeks 5–9 at 3 sets of 8 repetitions at 75–82% 1RM; goal in weeks 10–12 at 3 sets of 6 repetitions at 83–90% 1RM). Within these guidelines, some subjects obviously encountered greater training volumes (total amount of weight lifted) than others. One could hypothesize that men would have a greater range of starting weights and would therefore have a more variable gains. However, we saw no relationship between training volume and size gain ($r = 0.05$ for men and -0.09 for women). MVC change was also poorly correlated ($r = -0.06$ for men and -0.16 for women), whereas the 1RM was negatively correlated with training

volume ($r = -0.29$ for men and -0.35 for women), indicating a bias towards higher relative gains in those with the smallest starting weights.

Training Effect

Training effect on muscle size. Advances in technology have allowed researchers to use increasingly sensitive measures of muscle size, including CT or MRI (21). However, because of the cost associated with these techniques, these studies have been limited in sample size prohibiting definitive conclusions concerning sex differences in size gains. Although some studies found that increases in CSA were similar in men and women (10,23), Ivey et al. (15) found greater increases in men versus women for quadriceps volume increase after training. Each of these studies used fewer than 15 subjects per group, meaning that those studies that did not find a significant difference were simply underpowered.

In our study, we used highly accurate MRI measurements in a large cohort ($N = 585$) of males and females and demonstrated small, but significant, changes in muscle size for men and women after resistance training (20% in men and 18% in women). These increases are similar to those found by Cureton et al. (10) but greater than those found in the study by O'Hagen et al. (23), potentially because O'Hagen et al. used weight training machines rather than free weights. Although these studies reported that the differences were not statistically significant, the 2% difference in our study was highly significant ($P < 0.001$). One could likely assume that a sample size greater than 500 would have sufficiently powered the previous studies so that the 6–7% differences seen by Cureton et al. (10) and O'Hagen et al. (23) would have been statistically significant. These results provide conclusive evidence that intense resistance training produces a small but significantly greater relative increases in muscle size in the upper arm in men versus women.

Training effect on muscle strength. Untrained women are estimated to have approximately half of the upper-, and approximately two thirds of the lower-body strength of men (20). It is clear that men have the capability to increase absolute strength to a greater extent than women, on average. However, it is not clear whether relative gains in strength (percentage increases from baseline) are different in men and women. Several studies have indicated no difference in relative strength gains in the lower body (9,16,31) between men and women, whereas results for upper-body training have been equivocal (10,11,16,23). These studies' small sample sizes prohibit firm conclusions, because studies that do not find differences between men and women may simply not be sufficiently powered, and the chance of selecting a nonnormal distribution of subjects is increased with smaller sample sizes.

Our results show definitively that women gain significantly more relative isometric (MVC) strength and dynamic (1RM) strength with resistance training than men (22 vs 16%, $P < 0.01$; 64 vs 40%, respectively). These increases for dynamic

strength are similar to those found by Cureton et al. (10) (36.2% for men and 59.2% for women) for the same muscle group. This is likely because women have lower initial strength values. In fact, the correlation between initial 1RM and 1RM percent gains was -0.55 , whereas the correlation between initial MVC and MVC percent gains was -0.27 .

Training model considerations. The effects of resistance training on muscle size and strength are dependent upon many factors, including the muscle group chosen for training. Therefore, it is currently unknown whether the gender differences demonstrated in this study would be seen given a different training program (i.e., whole-body training or lower-body training). Our exercise training program led to an average of 18.9% gain in biceps CSA, which is similar to that found by Cureton et al. (10), and greater than or similar to the relative changes found after MRI analysis of muscle after total-body or lower-body programs (1,14). We also saw an average 19.5% gain in MVC, which is similar to gains seen after unilateral training in the leg (14,22), although direct comparison across studies for both size and strength gains are limited by differences in training mode or length. These data suggest that the choice of the unilateral arm model did not compromise relative size and strength

gains. Although absolute gains would likely be larger with activation of a larger muscle mass (i.e., use of whole-body or use of bilateral training), we believe that we provided a sufficient training stimulus to evoke a significant training response.

CONCLUSION

Analysis of muscle size and strength changes after 12 wk of progressive resistance training in the elbow flexors/extensors in 585 men and women demonstrated the following: 1) a large range of strength and size responses to training, with the frequency of high responders greater than that of low responders; 2) similar variability in men and women for relative size gains and mode-dependent gender differences for relative strength gains; 3) a slight advantage for men versus women in relative size gain after training; and 4) moderate to large advantages for women versus men in strength gain after exercise.

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