ABSTRACT: The mechanisms governing the increases in force production in response to short periods of strength training have yet to be fully elucidated. We examined whether muscle architectural adaptation was a contributing factor. Ultrasound imaging techniques were used to measure quadriceps muscle architecture at 17 sites in vivo in trained and untrained legs of men and women after 2.5 and 5 weeks of unilateral knee extension training, as well as in a nontraining control group. Despite increases in knee extensor strength of the trained and untrained (women only) legs, there were no changes in muscle thickness, fascicle angle, or fascicle length in any of the muscles tested. The moderate correlation between vastus lateralis thickness (middle site) and eccentric ($r = 0.55; P < 0.05$) and concentric ($r = 0.46; P < 0.1$) torque after, but not before, training is suggestive of neural rather than architectural adaptations predominating in the early phase of training.

LACK OF HUMAN MUSCLE ARCHITECTURAL ADAPTATION AFTER SHORT-TERM STRENGTH TRAINING

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A muscle’s phenotype is strongly governed by its architecture or fiber geometry. Muscles with long fibers (or fascicles) generate forces over greater ranges of length and at higher shortening velocities, but at greater metabolic cost than muscles with short fibers. Moreover, muscles whose fibers insert at large angles onto the tendon or aponeurosis have a large physiological cross-sectional area relative to their volume and are therefore capable of generating large relative peak forces. Using ultrasound and magnetic resonance imaging techniques to measure muscle architecture in vivo, researchers have shown that significant increases in fascicle angle occur with increases in muscle cross-sectional area or thickness in response to prolonged periods (>14 weeks) of heavy, isotonic/isoinertial weight training in previously untrained human subjects.1,17 These increases in fascicle angle allow a greater muscle physiological cross-sectional area and maximum force capacity; the increase in fascicle angle reported after prolonged heavy strength training is thought to be one mechanism by which muscle force increases after training. Thus, muscle architecture appears to be highly plastic, and these changes are thought to contribute to the changes in strength expression seen in weight-trained subjects.

Although early (e.g., <4 weeks) increases in strength in previously untrained subjects are accompanied by significant increases in muscle contractility, often little or no observable muscle hypertrophy occurs.3,23,26 This has led to general acceptance of the concept that short-term strength increases are neurally mediated. However, muscle architectural adaptations occur after 5 weeks in athletes who cease heavy weight training but increase their speed-type training.5 This result suggests that muscle architecture change may occur rapidly in humans. In animals, immobilization of muscle or muscle fibers in a
lengthened position for periods of days to weeks has resulted in increases in the number of serially arranged sarcomeres and overall fiber length,\textsuperscript{28,29,33} whereas moderate stretching performed for only 30 min.day\textsuperscript{-1} was enough to reduce or reverse the fiber shortening that accompanied short-length immobilization in rat muscle.\textsuperscript{32} Also, variations in muscle loading (eccentric vs. concentric muscle actions) in rats have produced significant changes in the number of sarcomeres in series within 3 days of a 5-day exercise stimulus.\textsuperscript{21} Despite the data demonstrating a rapid architectural adaptation in animals, studies investigating muscle architectural adaptation in humans have not ascertained its temporal response. Thus, insufficient information is available with which to build a complete picture of gross muscle adaptation in response to muscle loading in humans. In order to test the hypothesis that increases in muscle fascicle angle occur after short-term strength training in previously non–strength-trained adults, we measured architectural characteristics at proximal, middle, and distal sites in the four heads of the quadriceps femoris in trained legs of men and women after 2.5 and 5 weeks of isokinetic strength training.

MATERIALS AND METHODS

Subjects. Thirty-two subjects gave their written informed consent to participate in the study, and 29 subjects consisting of 14 men [age, 20.6 ± 2.6 (SD) year; height, 1.80 ± 0.09 m; weight, 76.0 ± 1.3 kg] and 15 women (age, 19.9 ± 3.4 year; height, 1.70 ± 0.39 m, weight; 64.6 ± 0.4 kg) completed the study; 3 subjects withdrew for reasons not pertaining to the study. The research was approved by the institutional review board. The subjects had no known musculoskeletal disorders, inflammatory conditions, or recent injury that would preclude participation. None of the subjects had performed resistance training previously, but they were all recreationally active.

Overview. The subjects were randomly assigned to either training (N = 15; 7 men and 8 women) or control (N = 14; 7 men and 7 women) groups. Prior to, and after 2.5 and 5 weeks of unilateral isokinetic knee extension training, maximal concentric and eccentric knee extensor torque was measured using an isokinetic dynamometer (Kin-Com, Chattanooga Group, Hixson, Tennessee), and muscle architecture (muscle thickness, fascicle angle, and fascicle length) of quadriceps femoris was quantified in both trained and untrained legs, as described below. Control subjects performed no training but continued their normal daily activities. They were assessed for knee extensor strength and muscle architecture on the same days as the training subjects. All testing was performed at the same time of day to minimize diurnal effects.

Training. Maximal isokinetic, concentric–eccentric knee extension training of the right leg of the training subjects was performed at a velocity of 60°.s\textsuperscript{-1} three times a week for 5 weeks. Sessions were separated by at least 1 day. Allowing for testing days after 2.5 weeks of training, subjects performed 10.5 ± 1.2 of a possible 12 training sessions over the training period. In the first 2.5 weeks of training (6.0 ± 0.9 sessions), four sets of six maximal concentric–eccentric knee extensions were performed through a range of motion from 100° of knee flexion to full extension (−0–10°). In the second 2.5 weeks (4.3 ± 0.8 sessions), five sets of six repetitions were completed. Rest for 1 minute was allowed between sets. These sessions are similar in intensity and volume to those used by Kawakami et al.,\textsuperscript{17} whose subjects trained at maximum intensity for five sets of eight repetitions of a “French press” exercise; thus differences in training are limited largely to the duration of training (5 weeks vs. 16 weeks). The present subjects always performed a 5-min cycle warm-up with a 0.5 kg (women) or 1 kg (men) load at 60 rev.min\textsuperscript{-1} before training and no stretching was allowed before or after the training. In order to ensure that maximum torque was achieved, straps were placed securely across the subjects’ waists and torsos to minimize extraneous movement, and loud verbal encouragement and performance feedback was given for all sets. Training volumes for each training session are shown in Figure 1.

FIGURE 1. Training volume performed in each session over 5 weeks. Vertical line indicates training performed before the midtraining testing (4 sets × 6 repetitions) and after (5 sets × 6 repetitions).
Testing. Knee Extension Torque. Warm-up included a 5-min cycle (as above) and three practice knee extension trials in which subjects were instructed to produce torques of approximately 50%, 70%, and 90% of their perceived maximum. After a 1-min rest, maximal concentric and eccentric torque of the right and left legs of both trained and untrained subjects was measured on the isokinetic dynamometer at an angular speed of 60°.s⁻¹ with the hip angle at 85°. The knee of the exercising leg was aligned approximately 2 cm anterior to the axis of rotation of the dynamometer. This ensured the lateral condyle of the femur was in line during maximum efforts when the small deformation of the chair and padding on the attachment occurred. Subject positioning was adjusted if misalignment of the lateral condyle and axis of rotation occurred during the most maximal (i.e., the third) practice trial. After two to three maximal practice trials, the subjects were allowed three maximal trials to register concentric or eccentric peak torque with the knee moving between 100° of flexion and full extension (≈0–10°). Subjects were verbally encouraged during the testing, and a 2-min rest was allowed between testing of concentric (always tested first) and eccentric torque. In order to prevent muscle adaptation prior to the commencement of the study and to allow task learning to contribute to overall strength increases, subjects did not perform familiarization sessions. Thus, any increases in peak torque in the training or control subjects could be partly explained by learning of the movement, whereas any architectural changes observed will have occurred from a true “nontraining” starting point. Peak concentric and eccentric torque was recorded for analysis.

Measurement of Muscle Thickness and Fascicle Angle. Muscle architecture was examined in vivo using B-mode ultrasonography (Acuson Sequoia; Acuson, Mountain View, California) with a 3.8-cm, 7.5-MHz linear-array probe. Subjects lay supine with knees flexed (but stationary) to 45°. Pilot testing had shown that moderate knee flexion reduced fascicle curvature and improved the reliability of repeated measurements, but still allowed significant interindividual variation to be seen. The probe was coated with a water-soluble transmission gel to aid acoustic contact and remove the need for the probe to make contact with the skin. Thus, no pressure was applied to the muscle that might affect muscle thickness and fascicle angle measurements. Scans were taken with the probe oriented along the sagittal plane of the fascicles and perpendicular to the skin. The angle of the probe relative to the longitudinal axis of the thigh therefore varied between subjects. Appropriate probe alignment was achieved when several fascicles could be traced without interruption across the image (i.e., they did not run out of the plane of the sonogram). Scans were taken at three sites on each of vastus lateralis, rectus femoris, and vastus medialis muscles of the right (trained) leg, and at three sites on vastus intermedius with the probe placed over both vastus lateralis (frontal plane scan) and rectus femoris (sagittal plane scan) of the right (trained) leg. Scans were also taken of vastus lateralis and vastus intermedius at a single site on the left (untrained) leg with the probe placed over vastus lateralis (i.e., frontal plane scan of vastus intermedius). Scanning sites are shown in Figure 2; scans were taken from a total of 17 sites in both training and control subjects (1,479 images). An example scan image is shown in Figure 3. After pre-training scanning, the ultrasound scanning sites were mapped onto a flexible, transparent plastic sheet to ensure accuracy in repeated scanning.

Ultrasound images were imported into image digitizing software (Peak Motus, Peak Technologies, Centennial, Colorado) and landmarks pertaining to the aponeuroses and muscle fascicles were digitized as shown in Figure 3. For fascicles, the origin of the fascicle was digitized at a point approximately 3–4 mm from the deep aponeurosis and the end was digitized at the mid-level (Fig. 3). Fascicle curvature was imperceptible throughout most of the muscles,
but there was a tendency for fascicles to curve at the insertion onto the deep aponeurosis. In other images, the insertion point was invisible. Thus, measuring from approximately 3–4 mm above the aponeurosis allowed accurate delineation of the fascicles. Muscle thickness was calculated as the mean of the distances between superficial and deep aponeuroses measured at each edge of the ultrasound image. Fascicle angle was calculated as the positive angle between the deep aponeurosis and the line of the fascicle. Each image was digitized twice on separate occasions and the values for muscle thickness and fascicle angle compared. Image pairs were re-digitized separately if muscle thickness measures differed by more than 2 mm or fascicle angle differed by more than 1.

**Fascicle Length Estimation.** As fascicles were usually too long to be fully captured by our probe, fascicle length was estimated using eq. (1), where MT is the muscle thickness, \( \theta \) is the fascicle angle, and \( \gamma \) is the aponeurosis angle.

\[
\text{Fascicle length} = \sin(\gamma + 90^\circ) \times \frac{\text{MT}}{\sin(180^\circ - [\gamma + 180^\circ - \theta])} \quad (1)
\]

Fascicle length was only estimated at the mid-section of each muscle for two reasons: (1) estimates using this technique assume that no fascicle or aponeurosis curvature exists, which appeared to be true only at the mid-point of the muscles, and (2) these techniques assume that muscle architecture is relatively isotropic, which is not true toward the end of muscles where they generally change shape in response to space constraints. Fascicle length estimates for vastus medialis proved to be unreliable and were thus not included in analyses. Similar methods of estimating fascicle length when the entire fascicle cannot be visualized have been used previously, with errors of approximately 2%–7%. These small errors contribute to a slightly lower reliability of length measures compared to muscle thickness and fascicle angle, as described below.

**Physiological Muscle Thickness Calculation.** As changes in fascicle angle would alter the distance between the aponeuroses measured perpendicular to the fascicles (i.e., the physiological thickness), this distance was calculated by eq. (2), where MT is the muscle thickness and \( \theta \) is the fascicle angle.

\[
\text{Physiological thickness} = \sqrt{(\text{MT}^2 + [\tan \theta \cdot \text{MT}])^2} \quad (2)
\]

**Reliability of Muscle Architecture Measurements.** Reliability was determined for: (1) the digitizing of images at different muscle sites, and (2) the repeatability of the entire procedure, including location of imaging sites, acquisition and digitization of images, and calculation of architectural parameters at each muscle’s midpoint. Data for calculation of digitizing reliability were available since all images were digi-
Digitization reliability was assessed at each site on all muscles of the trained leg for muscle thickness and fascicle angle. Reliability of repeated measurements of the whole process was calculated using the same procedures.

**Statistical Analysis.** Pre-training differences between training and control groups were analyzed by multiple analyses of variance (MANOVA). Changes in peak concentric and eccentric knee extensor torque, and changes in muscle architectural measures, were examined by separate repeated-measures multiple analysis of variance (RM ANOVA) with muscle site (proximal, middle, and distal) and time (0, 2.5, and 5 weeks) as within-subject factors and training group as the between-subjects factor. Significant main or interaction effects were further analyzed by Bonferroni univariate tests. Normality of the data was checked using Kolmogorov–Smirnov's test, and equality of error variance was assessed and confirmed using Levene's test of error variance. The linear relationship between torque and muscle architecture variables were assessed using Pearson's product moment correlations after curve-fitting procedures were applied to ensure nonlinear relationships did not exist between the variables. The alpha level was set at 0.05 for all tests. Values are presented as means ± SD.

**RESULTS**

**Reliability of Muscle Architecture Measurements.**
The reliability of digitizing of repeated images was high for muscle thickness and fascicle angle. Intraclass correlations ranged 0.948–1.000, with some variation between muscles and muscle sites. Typical errors ranged 0.08–0.63 mm and 0.27–0.63°, respectively. Repeated measurements incorporating the mapping of measurement sites, acquisition of images and digitizing those images were also very reliable with intertrial reliabilities (ICC) of 0.882–0.970, 0.899–0.991, and 0.758–0.863 (typical errors of 0.74–0.97 mm, 0.24–1.22°, and 10.2–19.4 mm) for muscle thickness, fascicle angle, and fascicle length, respectively.

**Knee Extensor Torque.** There were no changes in knee extensor strength of the control group in either right or left legs. In the training group, there was a moderate but significant increase in concentric strength of the right (trained) leg (184.1 ± 41.4 to 200.0 ± 34.9 Nm, Δ = 8.7%; P < 0.05) and a large and statistically significant change in eccentric strength (216.4 ± 51.8 to 309.5 Nm ± 94.7 Nm, Δ = 42.8%; P < 0.01). In the left (untrained) leg, there was no change in concentric strength (182.6 ± 44.9 to 183.7 ± 32.9 Nm, Δ = 0.6%), although there was a near-significant increase in eccentric strength (230.3 ± 49.5 to 248.7 ± 68.6 Nm, Δ = 8.0%; P < 0.08). In contrast, eccentric strength improved significantly for both genders (women, 175.7 ± 35.3 to 256.0 ± 50.2 Nm, 82 Lack of Muscle Adaptation
Δ = 45.7%; men, 252.0 ± 68.0 to 361.9 ± 134.6 Nm, Δ = 43.6%). In the untrained leg, there was no change in concentric or eccentric knee extensor torque in men, although there was a trend toward greater concentric strength after 2.5 weeks but no further increase by 5 weeks. In women, there was small and nonsignificant increase in concentric strength (8.7%; P = 0.25) after 5 weeks, but a significant increase in eccentric strength (41.1%; P < 0.01). Thus, the response of men and women was not the same in the untrained leg.

Muscle Architecture. There were no changes in muscle size, fascicle angle, or estimated fascicle length at any of the 15 sites tested on the trained leg, or in the middle of vastus lateralis or vastus intermedius of the untrained leg in trained subjects. Pre- and post-training muscle architecture results for vastus lateralis are shown in Table 1 as an example; results for the other 14 sites are presented as Supplementary Tables on the Journal’s website. There was a strong correlation (r² > 0.90) between muscle thickness and physiological muscle thickness that did not change with training; therefore physiological muscle thickness data have not been presented. Before training, there were no differences between men and women for architectural parameters, except that the fascicle angle in the proximal region of vastus medialis was slightly greater for men than for women (pre-training men = 11.5 ± 2.9°; women = 8.7 ± 2.6°; P < 0.05). This pre-training difference persisted consistently through the duration of the study, so our subjects were considered homogeneous for our purpose.

DISCUSSION

We investigated the effect of 5 weeks of unilateral, isokinetic strength training on knee extension torque and quadriceps muscle architecture in trained and untrained legs. The training group significantly improved their knee extensor strength in the trained leg in response to the 5-week training program. The improvement in eccentric strength (42.8%) was greater than concentric (8.7%) strength. The results are consistent with previous reports of greater increases in eccentric strength after periods of isokinetic strength training.19 The results are suggestive that a greater capacity for eccentric adaptation exists, which is borne out during isokinetic training where both concentric and eccentric contractions are performed maximally. Absolute and relative strength increases in the trained leg of men and women were the same, so gender effects did not influence the results. Strength changes in the untrained leg were smaller. There was no change in concentric strength after the 5-week training period (Δ = 0.6%); a slight mean increase in eccentric strength did not reach statistical significance (Δ = 8.0%; P < 0.1). The responses of men and women were slightly different, however. There was no change in knee extensor torque of the untrained leg in men, whereas in women there was a small and nonsignificant increase in concentric strength (8.7%; P = 0.25) after 5 weeks and a significant increase in eccentric strength (41.1%; P < 0.01). The lack of contralateral strength changes in the men is not an uncommon finding,24 but the conditions under which this lack of response occurs are unclear.

However, a major finding of this study was that, despite significant increases in knee extensor torque of the trained and untrained (women only) legs, no changes occurred in muscle thickness, fascicle angle, or fascicle length at any of the 17 ipsi- and contralateral sites. Thus, the strength changes resulting from the training cannot be explained by architectural

| Table 1. Vastus lateralis architecture (N = 29). |
|-----------------|-----------------|-----------------|
|                 | Muscle thickness | Fascicle angle | Fascicle length |
|                 | Control          | Training        | Control          | Training        | Control          | Training        |
| Week | Site | Mean (mm) | SD  | Mean (mm) | SD  | Mean (deg) | SD  | Mean (deg) | SD  | Mean (mm) | SD  |
| 0    | Distal | 20.9 | 3.5 | 21.9 | 3.4 | 9.4 | 4.1 | 9.1 | 4.1 | 91.1 | 13.1 |
|      | Mid    | 21.9 | 3.2 | 23.2 | 3.5 | 13.9 | 1.7 | 12.8 | 4.4 | 108.2 | 16.8 |
|      | Proximal | 14.1 | 2.9 | 18.5 | 5.3 | 11.7 | 3.7 | 12.3 | 3.7 | 102.7 | 17.9 |
| 2.5  | Distal | 21.9 | 3.1 | 21.5 | 2.9 | 9.4 | 4.6 | 9.1 | 4.0 | 102.7 | 17.9 |
|      | Mid    | 22.3 | 2.6 | 23.4 | 3.5 | 12.4 | 3.1 | 12.6 | 1.8 | 102.7 | 17.9 |
|      | Proximal | 16.1 | 5.6 | 17.9 | 4.6 | 12.2 | 4.2 | 13.5 | 3.6 | 102.7 | 17.9 |
| 5    | Distal | 20.1 | 2.9 | 22.4 | 3.1 | 9.7 | 3.1 | 10.1 | 3.5 | 102.7 | 17.9 |
|      | Mid    | 22.0 | 4.3 | 23.9 | 2.8 | 13.1 | 2.4 | 12.8 | 2.4 | 102.7 | 17.9 |
|      | Proximal | 13.7 | 2.7 | 17.3 | 5.4 | 12.3 | 3.8 | 12.4 | 2.2 | 102.7 | 17.9 |
adaptation. Although muscle cross-sectional area or volume was not measured in the present experiments, the lack of change in superficial-to-deep muscle thickness or of any change in fascicle angle or length suggests that muscle volume changes were small or zero. Given that increases in superficial-to-deep muscle thickness have been previously shown to accompany changes in muscle volume and that no change in muscle thickness was shown at any of the 17 muscle sites, we feel it is unlikely that any increases in muscle size occurred. A lack of increase in muscle size in response to short-term loading in previously non–strength-trained subjects has been noted in earlier studies.

We also tested the hypothesis that rapid changes in fascicle angle and length do not occur after short periods of strength training. This hypothesis has never been tested in humans despite significant scientific data suggesting the possibility that adaptations might occur rapidly in both humans and other animals. For example, fascicle angle and length changes occurred after 5 weeks in athletes who significantly altered their training. Although the specific changes in gene expression and protein synthesis that underpin architectural changes are not known, muscle protein synthesis is upregulated immediately following muscle loading and stretch stimuli, which occurs subsequent to rapid increases in gene expression. Also, rapid muscle-specific gene expression changes have been shown after single bouts of eccentric contractions in mice and after 3 days of gastrocnemius overload resulting from ablation of synergists in rats. Furthermore, animal studies provide compelling evidence that rapid architectural adaptations are possible. Repetitive stretching of rat gastrocnemius, overload of the plantaris muscles by ablation of synergists, and percutaneous stimulation of tibialis anterior and extensor digitorum longus during muscle lengthening have resulted in significant increases in the activity of myogenic regulatory factors within hours. These reports are consistent with the rapid changes in fiber lengths that were shown in immobilized and passively stretched muscles of various animals. Thus, rapid muscle adaptation very likely occurs under the appropriate loading conditions, and, at least in animals, these adaptations occur with a time course similar to changes in muscle architecture. Regardless of the rapid increases in protein synthesis in animals and humans, and the rapid changes in muscle architecture shown in animals, there were no observable changes in fascicle angle or length of the trained leg in the present study. As discussed below, the precision and sensitivity of our measurements were such that very small changes in architecture that were undetectable would not have been functionally significant. Our results, therefore, do not support the hypothesis that fascicle adaptations occur rapidly in response to strength training.

We also examined changes in the untrained leg. Unilateral immobilization of limbs in rats has been associated with significant changes in muscle architecture of nonimmobilized limbs when compared to control rats where no immobilization was used, although it is possible that altered activity patterns could account for these changes. Also, Yasuda and Miyamura showed a greater muscle blood flow to the nonexercising arm during an endurance handgrip task after 3 and 6 weeks of unilateral training. Eklund et al. had previously shown that the increase in blood flow to a nonexercising unilateral limb was not a result of inadvertent muscle activation. Such a phenomenon would allow circulating anabolic hormones to perfuse the nonexercised muscle and make remote muscle adaptation theoretically possible. Thus, physiological adaptations to unilateral exercise seem to be worthy of further consideration, and only one study has examined architecture in a nontraining limb. Nonetheless, we found no evidence of architectural adaptation in the untrained leg. The lack of change is consistent with the results of Kim et al. who did not find an increase in resting myofibrillar or mixed protein synthesis rates in vastus lateralis of an untrained leg, despite significant increases in the trained leg. Our data are also in agreement with those of Kawakami et al. who did not find changes in the untrained (control) arm in subjects after 16 weeks of strength training. Thus, there is presently no evidence that architectural adaptation occurs in an untrained limb after training of the contralateral limb. As suggested by other authors, the small increases in strength of the contralateral limb in the present study possibly resulted from spinal (e.g., alterations in reflex sensitivity and afferent feedback) or supraspinal adaptations (e.g., diffusion of impulses to the contralateral motor cortex during unilateral training), or improved postural stabilization and coordination.

Given the lack of architectural change shown presently, we closely examined the precision of our measurements. The validity for using ultrasound techniques to assess in vivo muscle architecture has been shown previously by comparing ultrasound- and cadaver-based measurements. The precision and linearity of image reconstruction has also been shown. The sensitivity of measures is difficult to ascribe, but it is likely that positive changes of greater
than 1° of fascicle angle and 5 mm of fascicle length could be detected for the muscles analyzed in this study, if those changes occurred; changes smaller than this would not be functionally significant. We also used strict methodologies including the mapping of measurement sites for high accuracy in the repeated placement of the ultrasound transducer, double-digitizing of all images to minimize calculation errors, and the undertaking of all digitizing by a single operator to remove multiple-operator unreliability. We measured the reliability of both: (1) our digitizing procedure, and (2) the reliability of the complete procedure including the mapping of measurement sites, acquisition of images, and digitizing those images. With respect to digitizing, repeated measures were highly accurate with intraclass correlations (ICC) of 0.948–1.000 and typical errors for muscle thickness and fascicle angle of 0.08–0.65 mm and 0.27–0.65°, respectively. Moreover, repeated measurements of the whole procedure were also very reliable. We have obtained intertrial reliabilities (ICC) of 0.882–0.970, 0.899–0.991, and 0.758–0.863 (typical errors of 0.74–0.97 mm, 0.24–1.22°, and 10.2–19.4 mm) for muscle thickness, fascicle angle, and fascicle length, respectively. We believe these reliabilities are very high, although there is some reduction in reliability of the fascicle length estimates, as would be expected given that errors are a function of the small errors in muscle thickness, fascicle angle, and aponeurosis angle. Particularly for muscle thickness and fascicle angle measurements, errors of the magnitude of our typical errors are not likely to be functionally significant, so the lack of change in muscle architecture cannot be explained by measurement unreliability. Thus, the strength changes observed in our trained subjects must have resulted from mechanisms other than architectural adaptation.

In order to further explore the mechanisms responsible for the rapid increases in strength, the relationships between initial muscle architecture variables and the magnitude of strength change were examined. Given that relative strength increases in the trained subjects were similar for men and women, and that there were no between-gender differences in muscle thickness, fascicle angle, or fascicle length [with the single exception that fascicle angle at the proximal part of vastus medialis was greater in men (11.5 ± 2.9°) than women (8.7 ± 2.6°)], the data for men and women were pooled for further analysis. Before training, there was no difference in muscle thickness, fascicle angle, or fascicle length of the trained leg in subjects with greater-than-median or less-than-median knee extensor strength, and no correlation between strength and muscle architecture measures. After training, however, there was a stronger correlation between vastus lateralis thickness at mid-muscle (i.e., 39% of distance from lateral condyle) and torque developed eccentrically ($r = 0.55; P < 0.05$) and concentrically ($r = 0.46; P < 0.1$). Thus, subjects who had greater thickness of the vastus lateralis muscle prior to training produced greater knee extensor torque after training. Given that vastus lateralis accounts for a substantial proportion of total quadriceps femoris volume (e.g., 36%\(^3\)), it seems possible that intersubject size differences might have impacted on force development. It is possible then that strength increases occurred largely by an alteration in muscle recruitment strategies where those with larger vastus lateralis muscles benefited most clearly. Although muscle activation was not measured in the present study, rapid alterations in muscle recruitment in response to resistance training have been shown previously.\(^2\)

In summary, significant increases in knee extensor strength of previously untrained ipsi- and contralateral (women only) legs occurred without changes in muscle architecture. These data form an important part of the picture in understanding the early adaptations to muscle loading in humans. Given that there was a stronger correlation between vastus lateralis thickness and knee extensor torque after training, the rapid increase in strength can probably be explained by alterations in muscle recruitment strategies, with those subjects having larger muscles prior to training realizing the greatest strength improvements after training.

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