Short Communication

# Muscle aponeurosis area in hypertrophied and normal muscle

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***Objective***: It is unknown whether muscle aponeurosis area is exaggerated in pennate muscle that has undergone extreme hypertrophy as a result of exercise. We compared the morphological characteristics of deep muscle aponeurosis in resistance-trained athletes with those in untrained students.

***Design***: Cross-sectional study.

***Methods***: Eight elite male Olympic weightlifters and 8 male college students volunteered for the study. Magnetic resonance imaging was used to obtain images from the first cervical vertebra to the ankle joint for each subject, and total and thigh skeletal muscle volumes were determined. Deep muscle aponeurosis in the vastus lateralis (VL) muscle was determined by summing the product of the length of the dark black line (aponeurosis) in each MRI slice and the slice thickness.

***Results***: Fat-free mass and total and thigh muscle masses were greater ($P$<0.01) in the weightlifters than in the students. Aponeurosis length in the VL was similar in both groups, but the maximal width of the VL aponeurosis was greater ($P$<0.01) in the weightlifters (11.7 cm) than in the students (8.8 cm). Additionally, VL aponeurosis area in the weightlifters (176 $cm^2$) was 32% higher than that of the students (133 $cm^2$). When combined data were used, aponeurosis area was correlated with maximal width of the aponeurosis (r=0.75, $P$<0.01), and there was a significant correlation between quadriceps muscle mass and VL aponeurosis area (r=0.85, $P$<0.01).

***Conclusion***: Muscle aponeurosis area may be increased by high-intensity resistance training, which is associated with muscle mass accumulation and muscle fiber geometry in hypertrophied muscle.

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**Key words**: muscle architecture ■ strength training ■ hyperplasia ■ weightlifting ■ muscle hypertrophy

A large skeletal muscle mass is, in many cases, advantageous for power- and sprint-type sport performance[1], and changes in morphologic and architectural characteristics have been observed in exercise-induced muscle hypertrophy[2]. Based on the model described by Maxwell et al[3], muscle fiber enlargement in pennate muscle must accompany an increase in pennation angle when muscle length, fiber length, and fiber number remain constant. Many studies have reported muscle enlargement, including increases in the cross-sectional area (CSA) of individual muscle fibers as well as increases in the fascicle pennation angle.[4-8] On the other hand, Henriksson-Larsen et al[9] showed that fiber angulation of the vastus lateralis (VL) muscle was independent of fiber size. Similarly, Rutherford and Jones[7] did not find any increase in fascicle angle within hypertrophied muscle after resistance training, although the measurement includes low repeatability.

Greater pennation angles make it possible to arrange more contractile material within a limited area.[10] However, greater pennation angles are disadvantageous for force transmission from muscle fibers to tendon owing to the decreased component of fiber force to the line of pull of the muscle.[2,5] Supposing a change in the area where muscle fibers attach, eg, the muscle aponeurosis, a discrepancy between changes in the pennation angle and muscle fiber hypertrophy (and/or hyperplasia) would occur, enabling an increase in the physiological CSA without an increase in pennation angle. On the other hand, indirect and direct evidence for hyperplasia has been shown in studies of human bodybuilders[11] and animal models[12]. Results from animal studies show that de novo fiber formation is the major mechanism contributing to exercise-induced increases in muscle fiber number.[13] As the formation of new fibers in the interstitial area of muscle occurs, additional area in the aponeurosis for the fibers may be needed. However, previous studies have not focused on aponeurosis area and its adaptation to hypertrophy.

The purpose of the present study was to measure deep muscle aponeurosis in vivo using magnetic resonance imaging (MRI) and compare the morphological characteristics of deep muscle aponeurosis in resistance-trained athletes with those in untrained students. Finally, we investigate the relationship between muscle mass and aponeurosis area.

## Methods

Eight elite male college Olympic weightlifters and 8 male college students were recruited for this study. The Olympic weightlifters had been training competitively for a minimum of 5 years and participated in resistance training on a regular basis (5 times per week). Resistance training consisted mainly of a high-intensity (>80%) training program for improving

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snatch as well as clean and jerk performance. College students had played recreational sports (eg, swimming, running, or athletic training) for at least 3 years (1-2 times per week). None of the weightlifters had ever tested positive for anabolic steroids. All subjects received a verbal and written description of the study and gave their informed consent to participate prior to testing. The study was conducted according to the Declaration of Helsinki and was approved by the Ethics Committee for Human Experiments of the academic institute.

Body mass and standing height were measured using standardized techniques and equipment. Body density was measured by hydrostatic weighing with simultaneous measurement of residual lung volume by oxygen dilution.[14] Body fat percentage (%fat) was calculated from body density using the Brozek et al[15] equation. Fat-free mass (FFM) was estimated as total body mass minus fat mass.

MRI images were prepared using a Signa 1.5-T scanner (GE, Milwaukee, WI, USA), described previously.[16] Briefly, a T1-weighted spin-echo, axial-plane sequence was performed with a 150-ms repetition time and a 4.2-ms echo time (50-cm field of view, matrix 512 x 512 pixels). Subjects rested quietly in the magnet bore in a supine position with their legs and arms extended. The distance between the skull and the first cervical vertebra served as the point of origin for the 1.0-cm slices (0-cm interslice gap); slices were terminated at the ankle joints for each subject. Using the MRI data, total body, thigh, and quadriceps muscle volumes were determined as follows.[16] All MRI data were transferred to a personal computer using a scanner. For each transferred slice, muscle CSA was digitized in the personal computer using specially designed image analysis software (Tomo Vision Inc., Montreal, Canada). Finally, muscle volume ($cm^3$) was calculated by multiplying muscle CSA ($cm^2$) by slice thickness (cm). The coefficient of variation (CV) of this muscle volume measurement was 2.1%.

The deep aponeurosis of the VL muscle was delineated as the visible dark black segment between the VL and vastus intermedius muscles in the thigh MRI images (Figure 1). The tangent line of the VL muscle and the dark black segment in each cross-sectional image was traced and scanned into a personal computer. Using the software, the length of the dark black line in each image was defined as the width of the deep VL aponeurosis (Apo-width). The area of the deep aponeurosis (Apo-area) was calculated by summing the Apo-width of each slice and multiplying the total by the slice thickness. The distance between the most proximal slice and the most distal slice in which the aponeurosis was visible was defined as the length of the deep aponeurosis (Apo-length) (Figure 1). Tracing the tangent line in each slice to calculate the Apo-area by computer was performed twice on different days at least a week apart. The correlation between the two measurements was exceptionally high (r=0.99, $P<0.001$), and the mean values of those measurements were almost same. The CV of this measurement was 1.3%.

To confirm the actual deep Apo-area of the VL muscle, an embalmed male cadaver (age, 78 years; thigh length, 38 cm) was dissected, and the deep VL aponeurosis was carefully separated manually from the fibers using a surgical knife. The

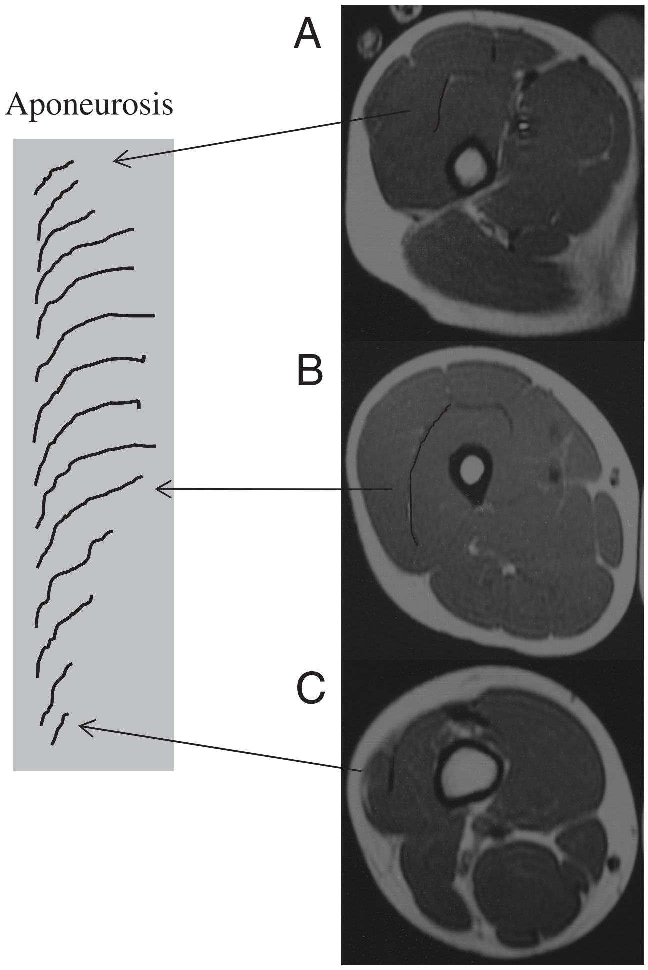


**Figure 1.** Typical magnetic resonance images of the thigh, including the most proximal slice in which the aponeurosis was visible (A), a middle part (B), and the most distal slice in which the aponeurosis was visible (C). The visible black segment between the vastus lateralis (VL) and vastus intermedius muscles in the MRI image was defined as the deep aponeurosis of the VL muscle. The length of the visible black segment was measured as aponeurosis length.

shape of the deep aponeurosis was transcribed on a transparent plastic sheet and scanned into a personal computer. The length, maximal width, and total area of the aponeurosis were calculated using the software.

The data are expressed as mean (SD). The differences between weightlifters and untrained students were tested for significance by a one-way analysis of variance. PearsonÅfs correlation analysis was performed to determine the relationship between thigh/quadriceps muscle volume and aponeurosis parameters (Apo-length, Apo-width, and Apo-area). Statistical significance was set at $P<0.05$.

## Results

There were no differences in age, standing height, and %fat between the two groups. Weightlifters had a 51% greater body mass and a 45% greater FFM than the college students (both $P<0.01$). Total body, thigh, and quadriceps muscle masses

**Table 1.** Body composition and skeletal muscle mass in male weightlifters and college students

| | Weightlifters (n=8) | | College students (n=8) | |
|---|---|---|---|---|
| | Mean | Range | Mean | Range |
| Age, y | 21.4 (0.9) | 20-22 | 20.3 (0.5) | 20-21 |
| Height, m | 1.72 (0.06) | 1.63-1.85 | 1.71 (0.06) | 1.63-1.77 |
| Weight, kg | 86.1 (17.1)[a] | 63.1-117.9 | 56.9 (6.4) | 48.3-63.2 |
| Body fat, % | 15.5 (6.2) | 4.4-23.7 | 12.6 (4.3) | 9.3-22.4 |
| FFM, kg | 72.0 (9.6)[a] | 60.3-90.0 | 49.6 (5.2) | 42.7-55.0 |
| SMM, kg | | | | |
| Total body | 35.2 (4.1)[a] | 30.1-41.3 | 20.3 (2.2) | 17.6-24.1 |
| Thigh | 6.7 (0.6)[a] | 5.8-7.4 | 3.7(0.6) | 2.9-4.6 |
| Quadriceps | 2.6 (0.5)[a] | 2.0-3.5 | 1.6 (0.2) | 1.3-2.0 |
| Aponeurosis | | | | |
| Length, cm | 22.1 (2.8) | 20-28 | 22.0 (2.1) | 20-25 |
| Width-max, cm | 11.7 (1.3)[a] | 9.7-14.4 | 8.8 (0.8) | 8.0-10.4 |
| Area, $cm^2$ | 176 (24)[a] | 156-224 | 133 (13) | 114-151 |

Abbreviations: FFM, fat-free mass; SMM, skeletal muscle mass; Width-max, maximal width of aponeurosis. Significant difference with college students, [a] $P < 0.01$.

were also greater ($P$<0.01) in weightlifters than in the students. Apo-length in the VL was similar in both groups, but the maximal Apo-width as well as the Apo-area was greater ($P$<0.01) in the weightlifters than in the students (Table 1). Apo-area was correlated with maximal Apo-width (r=0.75, $P$<0.01), and there was a significant correlation between Apo-area and thigh (r=0.74, $P$<0.01) as well as quadriceps (r=0.85, $P$<0.01) muscle mass (Figure 2). Maximal Apo-width was also correlated with thigh (r=0.76, $P$<0.01) as well as quadriceps muscle mass (r=0.75, $P$<0.01) (Figure 2), but there was no relationship between Apo-length and thigh (r=0.10) as well as quadriceps (r=0.26) muscle mass (Figure 2). VL Apo-length, maximal Apo-width, and Apo-area of the cadaver were 23 cm, 7.8 cm, and 120 $cm^2$, respectively. The values measured in the cadaver were in the same range as those measured in the college students.

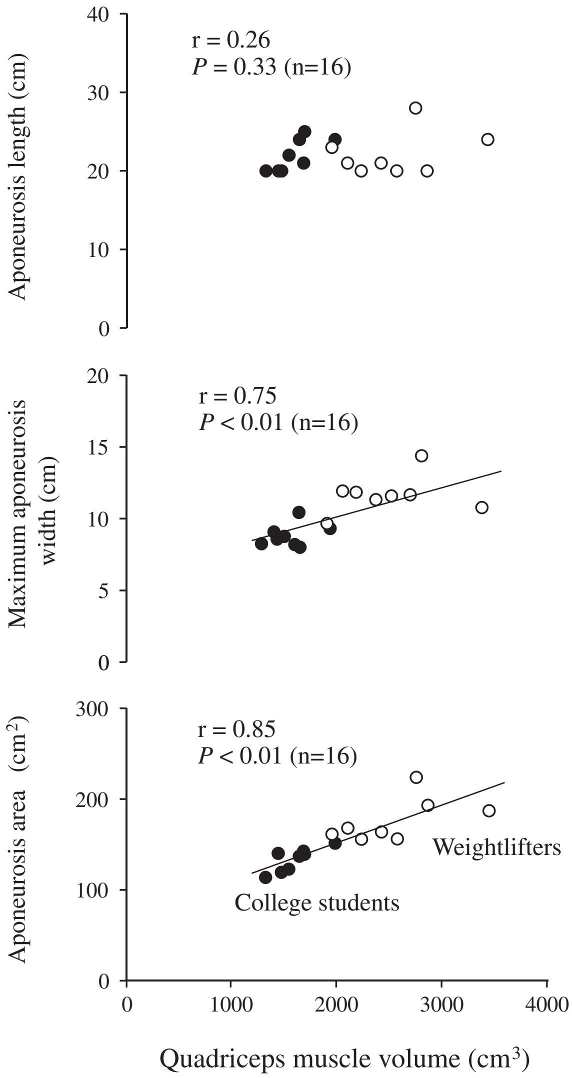


**Figure 2.** Relationship between the quadriceps muscle volume and the aponeurosis area, aponeurosis length, and maximal aponeurosis width.

## Discussion

The aim of this study was to determine to what extent exercise-induced muscle enlargement affects the morphological characteristics of the deep muscle aponeurosis in one of the quadriceps muscles. Data obtained from the VL muscle suggest that muscle that has undergone hypertrophy as a result of exercise includes a significantly larger Apo-area compared with normal muscle, and the Apo-area is correlated with quadriceps muscle volume. In addition, the maximal Apo-width, but not the Apo-length, is greater in hypertrophied than in normal muscle.

Increases in the CSA/volume of individual muscle fibers and de novo fiber formation require additional space for the fibers in the interstitial area of muscle. One of the possible architectural adaptations that occur is a change in fiber pennation angle. While the greater pennation angle enables many more arrangements of contractile material in-series, force to the line of pull of the muscle becomes small in proportion to the degree of the pennation angle. Conversely, the greater aponeurosis enables the same amount of contractile material arrangement with either no increase or less increase in pennation angle.

Kawakami and colleagues[5] have observed that there were significant correlations between muscle thickness and pennation angles for both the long and medial heads of the triceps muscle. Moreover, training-induced muscle hypertrophy of the triceps muscle (31.7% in muscle volume) accompanied an increase in the pennation angle (a 29.1% increase in the long head of the triceps).[2] In contrast, studies of the VL muscle failed to find such a relationship between muscle size and pennation angle in young women[9] and in male football players[17]. Moreover, training-induced hypertrophy in the VL muscle did not induce an increase in pennation angle. The highest values of VL pennation angles that have been reported in strength-trained male athletes is about 25 degree[1,6], while those of male college students range between 15 and 30 degree[18,19]. The differences in VL pennation angle between strength-trained athletes and college students are relatively small, even if there is a significant statistical difference between the two groups. Therefore, it is not possible to explain the relationship between fiber hypertrophy/de novo fiber formation and architectural muscle adaptation in an extremely hypertrophied muscle using only changes in pennation angle. Increases in the Apo-areas obtained in this study may be an important factor for adaptations related to exercise-induced muscle enlargement.

Another important aspect of the aponeurosis is its elastic properties. During locomotion, the aponeurosis is known to store and release energy and regulate muscle mechanical function.[20] The length along the line of pull and the CSA of the aponeurosis are important factors since the compliance of the elastic component is affected by these structural properties as well as by the quality of the material.[21] Using real-time ultrasonography, several studies have reported on the mechanical properties of the aponeurosis during muscle contraction.[22] Although it is not the mechanical properties of the aponeurosis alone, i.e., the tendon-aponeurosis complex, one study has reported training-induced changes in the mechanical properties of the tendinous tissue[26]. The architectural difference of the aponeurosis detected in the present study might have been related to its mechanical properties, but we did not measure that in this study.

## Conclusion

The resistance-trained group with hypertrophied muscle had a larger aponeurosis area than the control group. This result may suggest the possibility of an increase in aponeurosis area associated with muscle mass accumulation.

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