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Tendon properties and muscle architecture for knee extensors and plantar flexors in boys and men

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ABSTRACT

Background: The purpose of this study was to compare the elastic properties and size of tendinous structures and muscle architecture for knee extensors and plantar flexors in boys and men.

Methods: Twenty-two early pubescent boys (9.6–12.7 yrs) and 23 young adult men (19.8–26.2 yrs) participated in this study. The maximal strain and thickness of tendinous structures for knee extensors and plantar flexors were measured using ultrasonography. In addition, the fascicle lengths of vastus lateralis and medial gastrocnemius muscles were measured.

Findings: The maximal strain of tendinous structures for plantar flexors was significantly greater in boys than in men, while there was no difference in the maximal strain for knee extensors between the two groups. The relative thickness (to body mass$^{1/3}$) of Achilles tendon was significantly greater in boys than in men, although there was no difference in that of patellar tendon between the two groups. The relative fascicle length (to limb length) of vastus lateralis muscle was significantly lower in boys than in men, although there was no difference in that of medial gastrocnemius muscle between the two groups.

Interpretation: These results suggest that the amount of changes in the elastic properties and sizes of tendinous structures and in the fascicle lengths from early pubescence to maturity is different for different muscle groups (in particular, the knee extensors and the plantar flexors).

1. Introduction

The number of children who participate in competitive sports is increasing. As a result, injuries from overuse (e.g., Osgood–Schlatter disease, calcaneal apophysitis, Little League elbow) are now being recognized in pre-adolescent athletic populations (Hawkins and Metheny, 2001; Micheli and Klein, 1991). The main reason for this problem is that the immature musculoskeletal system is less able to cope with repetitive biomechanical stress during various activities (Gerrard, 1993; Kujala et al., 1985). Furthermore, previous researchers pointed out that the longitudinal growth of bone was faster than that of muscle, so that the muscles became progressively tighter during a period of rapid growth (Malina, 1974; Micheli, 1983). Considering these points, more compliant and larger tendon and longer muscle fiber (fascicle) are considered to contribute for preventing these injuries in growing children. In lower limb, on the other hand, Osgood–Schlatter disease was commonly involved followed by calcaneal apophysitis (Lau et al., 2008; Omey and Micheli, 1999). Therefore, the difference in frequency of occurrence between Osgood–Schlatter disease and calcaneal apophysitis would be related to the difference in growth changes in the elastic properties and size of tendon structures and fascicle length between knee extensors and plantar flexors.

Recent studies using ultrasonography have demonstrated that the elastic properties of human tendinous structures change by aging, training, and immobilization (Arampatzis et al., 2007; Kubo et al., 2007, 2009; Reeves et al., 2005). However, little is known about growth changes in the human tendon properties *in vivo* (Kubo et al., 2001; Neugebauer and Hawkins, 2012; O'Brien et al., 2010; Waugh et al., 2012, 2013). Among them, the tendinous structures for knee extensors (Kubo et al., 2001) and patellar tendon (O'Brien et al., 2010) were more compliant in children (pre-pubertal; about 10 yrs) than in adults. To be concrete, the tendon strain at a given stress of children was significantly greater than that of adults (Kubo et al., 2001; O'Brien et al., 2010). On the other hand, Waugh et al. (2012) did not find the difference in the maximal strain of the tendinous structures in plantar flexors between children and adults. Although the reasons for the discrepancy among these reports are unknown, there is a possibility that the difference in the tendon properties between children and adults would differ among the sites. At present, however, few studies have simultaneously investigated the age-related differences in the elastic properties of tendinous structures for knee extensors and plantar flexors.

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Growth changes in the elastic properties of tendinous structures as mentioned above are considered to be due to changes in the size (including thickness and cross-sectional area), material properties, or both of tendinous structures. Hence, it is important to know growth changes in size as well as their elastic properties for grasping the detailed mechanism of changes in tendinous structures during the period of growth. Many previous studies have demonstrated that muscle size (thickness, cross-sectional area, and volume) increased rapidly during and after puberty (e.g., Kanehisa et al., 1994, 1995). However, few studies have been available so far regarding comparison of the size of tendons *in vivo* between children and adults (O'Brien et al., 2010; Waugh et al., 2012). Magnusson et al. (2003a, 2003b) reported that the cross-sectional area of the Achilles tendon was greater in elderly individuals than in the young ones, which may reduce the risk of injury to the tendon in the elderly. If this finding applies to the immature tendinous structures in children, it is likely that the tendon size of children is relatively greater than that of adults to reduce the imposed stress and thereby prevent injuries.

According to the animal experiments (Heslinga and Huijing, 1990; Woittiez et al., 1989), whole muscle length (corresponding to bone length) increased to a greater extent than muscle fiber length during growth. Indeed, we found that the ratio of the fascicle length of human vastus lateralis muscle to thigh length (corresponding to bone length) was significantly lower in children than in adults (Kubo et al., 2001). However, Morse et al. (2008) reported that there was no difference in the ratio of the fascicle length of gastrocnemius muscle to whole muscle length between early pubescent boys and adult men. Therefore, it may be that the growth rate of fascicle length for knee extensors (vastus lateralis muscle) is different from that for plantar flexors (gastrocnemius muscle).

In the present study, we aimed to compare the elastic properties (maximal strain) and size (thickness) of human tendinous structures and muscle architecture (fascicle length) in knee extensors and plantar flexors between early pubescent boys and young adult men. We hypothesized that the differences in extensibility and size of tendinous structures and fascicle length between boys and men were different between knee extensors and plantar flexors.

2. Methods

2.1. Subjects

Twenty-two early pubescent boys (9.6–12.7 yrs) and 23 young adult men (19.8–26.2 yrs) participated in this study. The ages and physical characteristics of each group are shown in Table 1. Adult men were either sedentary, or mildly to moderately active. Early pubescent boys were not involved in any specific physical training program beyond their normal school curriculum activities. The procedures, purpose, and risks associated with the study were explained to all subjects and their parents (for boys) before they gave their written informed consent to participate in this investigation. This study was approved by the office of the Department of Sports Sciences, University of Tokyo, and complied with their requirements for human experimentation.

2.2. Elastic properties of tendinous structures

Maximal voluntary isometric contraction (MVC) was measured by means of specially designed dynamometers (Applied Office, Tokyo, Japan) for knee extension and plantar flexion, respectively. Prior to the test, the subject performed a standardized warm-up and sub maximal contractions to become accustomed to the test procedure. All measurements were performed on the right lower limb. During each task, subjects exerted isometric torque from zero (relax) to MVC within 5 s. The measurement was repeated twice per subject with at least 3 min between trials. If the two peak torque values differed by >10%, the subject was requested to perform a third. The highest peak torque among the trials was adopted to analyze elongation of tendinous structures. Torque signals were amplified and sampled at 1 kHz using a 16-bit A/D converter (PowerLab/16SP, AD Instruments, Australia). During the knee extension task, the hips and back were held tightly in the seat using adjustable lap belts. The right ankle was firmly attached to the lever arm of the dynamometer with a strap and fixed with the knee joint flexed at an angle of 90 deg (full extension = 0 deg). During the plantar flexion task, subjects lay prone on a test bench and the waist and shoulders were secured by adjustable lap belts and held in position. The ankle joint was set at 90 deg with the knee joint at full extension and the right foot was tightly secured by two straps to a footplate connected to the lever arm of the dynamometer.

Table 1
Age and physical characteristics of the subjects. Data are mean (SD).

	Boys ($n = 22$)	Men ($n = 23$)
Age (yrs)	11.2 (1.1)	22.2 (2.2)
Height (cm)	141.9 (6.1)	170.6 (5.8)
Body mass (kg)	33.7 (4.8)	68.1 (10.1)
Thigh length (cm)	32.9 (2.0)	38.9 (1.5)
Lower leg length (cm)	32.8 (1.9)	38.6 (2.0)

Elongations in tendinous structures (including outer tendon and aponeurosis) for knee extensors and plantar flexors were assessed during isometric contractions. An ultrasonic apparatus (SSD-6500, Aloka, Tokyo, Japan) with an electronic linear array probe (7.5 MHz wave frequency with 80 mm scanning length; UST 5047-5, Aloka, Tokyo, Japan) was used to obtain longitudinal ultrasonic images of vastus lateralis and medial gastrocnemius muscles by procedures described previously (Kubo et al., 2010). Two measured sites were selected for measurements: at 50% of the distance between the greater trochanter and the lateral epicondyle of the femur for vastus lateralis muscle and at 30% of the distance between the popliteal crease and the center of the lateral malleolus for medial gastrocnemius muscle. Ultrasonic images were recorded on videotape at 30 Hz and synchronized with recordings of a clock timer (VTG-55, For-A, Japan) for subsequent analysis. The tester visually confirmed the echoes from the aponeurosis and fascicles. The point at which one fascicle was attached to the aponeurosis was visualized on ultrasonic images (Fig. 2 of Kubo et al., 2001). This point moved proximally during isometric torque development up to maximum. A marker was placed between the skin and the ultrasonic probe as the landmark to confirm that the probe did not move during measurements. Therefore, the displacement of this point is considered to indicate lengthening of the deep aponeurosis and distal tendon, i.e., tendinous structures. The tendon elongation value (L) was converted to strain by the following equation (Kubo et al., 2003, 2007):

$$\text{Strain}(\%) = L \cdot \text{TL}^{-1} \cdot 100$$

where TL is the length of the tendinous structure at rest (initial length of tendinous structures), which was estimated over the skin as the distance between the measured site (position of the probe) and the insertion of the patella and Achilles tendons (confirmed using ultrasonography).

The displacements of tendon and aponeurosis will be attributed to both angular rotation and contractile tension, since any angular joint rotation occurs in the direction of knee extension and ankle plantar flexion during an “isometric” contraction. Thus, angular joint rotation needs to be accounted for to avoid an overestimation of tendon displacement during an isometric contraction. To monitor joint angular rotation, an electrical goniometer (Penny and Giles, Biomechanics Ltd., Gwent, UK) was placed on the lateral aspect of each joint. To correct the measurements taken for the tendon and aponeurosis elongation, additional measurements were taken under passive conditions. The displacement of each site caused by rotating the knee and ankle from 110 deg to 70 deg was digitized in sonographs taken. Thus, for each subject the displacement of each site obtained from the ultrasound images