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Passive and active muscle stiffness in plantar flexors of long distance runners

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ABSTRACT

The aim of the present study was to compare passive and active muscle stiffness and tendon stiffness between long distance runners and untrained men. Twenty long distance runners and 24 untrained men participated in this study. Active muscle stiffness in the medial gastrocnemius muscle was calculated according to changes in estimated muscle force and fascicle length during fast stretching after submaximal isometric contractions. Passive muscle stiffness was also calculated from estimated passive muscle force and fascicle length during slow passive stretching. Tendon stiffness was determined during isometric plantar flexion by ultrasonography. Passive muscle stiffness of long distance runners was significantly higher than that of untrained men ($p < 0.001$). Active muscle stiffness at all torque levels of long distance runners was also significantly higher than that of untrained men ($p < 0.001$). No significant difference was observed in tendon stiffness between long distance runners and untrained men ($p = 0.869$). These results suggested that passive and active muscle stiffness were higher in long distance runners than in untrained men, whereas no significant difference was observed in tendon stiffness between the two groups.

1. Introduction

In the last decade, several studies have demonstrated that plyometric training improves running performance and economy in long distance runners (Paavolaine et al., 1999; Saunders et al., 2006; Spurrs et al., 2003). One of the proposed explanations for these improvements is the increase in stiffness in muscle–tendon complex of lower limb allow elastic energy to be stored and utilized efficiently during running (Barnes and Kilding, in press). Muscle can be modeled by three components, consisting of a contractile component and two elastic components, parallel elastic component and series elastic component (Zajac, 1989). Mechanical properties of parallel elastic component of human muscle were measured under passive condition during slow stretching (Gajdosik, 2001; Herbert et al., 2011; Hoang et al., 2007; Kubo et al., 2002; Morse et al., 2008; Muraoka et al., 2005). However, mechanical properties of muscle have not yet been assessed under passive conditions in long distance runners. On the other hand, passive muscle stiffness measured using this method has been partially linked to flexibility, e.g., range of motion (Magnusson et al., 1997; McHugh et al., 1998). For example, McHugh et al. (1998) showed that there was a significant correlation relationship between change in passive tension within a given range of motion and maximal joint range of motion ($n = 16$, $r = -0.81$). Previous studies showed that long distance runners had tighter hamstrings and plantar flexors than untrained subjects (James et al., 1978; Wang et al., 1993). Considering these findings on flexibility of runners, passive muscle stiffness of long distance runners may be higher than that of untrained subjects.

Regarding series elastic component of muscle, mechanical properties of muscle under active conditions have been studied using several methods, such as sinusoidal pertubations (Petit et al., 1990), the quick release test (Goubel and Marini, 1987), and the short range stiffness experiment (Proske and Rack, 1976; Walmsley and Proske, 1981). Walmsley and Proske (1981) performed a short range stiffness experiment and showed that series elastic elements of cat muscle containing predominantly type I fibers were stiffer than those of muscle with higher proportion of type II fibers. On the other hand, trained long distance runners are known to have many slow twitch fibers in their lower limbs (Costill et al., 1976; Thorstensson et al., 1977). Furthermore, Goubel and Marini (1987) reported that endurance training resulted in an increase in type I muscle fibers with an increase in muscle stiffness. Therefore, the

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mechanical properties of muscle under active conditions may be stiffer in trained long distance runners than in untrained men.

More recently, Kubo (2014) claimed that the stiffness of human muscle could be determined under active conditions in vivo through observations of lengthening of fascicle during fast stretching. The aim of the present study was to compare passive and active muscle stiffness and tendon stiffness in plantar flexors between long distance runners and untrained men. We hypothesized that long distance runners with higher percentage of slow-twitch fibers had stiffer plantar flexors under passive and active conditions than untrained men, and also that there was no difference in stiffness of tendon structures in plantar flexors between the two groups.

2. Methods

2.1. Subjects

The subjects for this study were 20 well-trained male long distance runners and 24 untrained men. All long distance runners had participated in competitive meets at the regional or intercollegiate level within the preceding year, and their mean best official record in a 5000 m race within 1 year prior to these tests was 14.43 (SD 0.16) min. All untrained men were either sedentary or mildly active, but none had been involved in any type of regular exercise program for at least 1 year prior to the test. Data from UTM have been presented previously (Kubo, 2014). The physical characteristics of our subjects are summarized in Table 1. This study was approved by the Ethics Committee for Human Experiments, Department of Life Science (Sports Sciences), the University of Tokyo. Subjects were fully informed of the procedures to be utilized as well as the purpose of this study. Written informed consent was obtained from all subjects.

2.2. Muscle thickness and tendon cross-sectional area

An ultrasonic apparatus (SSD-900, Aloka, Japan) was used to determine muscle thickness of plantar flexor muscles, i.e., medial gastrocnemius muscle (MG), lateral gastrocnemius muscle (LG), and soleus muscle (SOL), at rest. Cross-sectional images were obtained at proximal levels of 30% (MG and LG) and 50% (SOL) of lower leg length. At that level, the mediolateral widths of MG and LG were determined over the skin surface, and the position of one-half of this width was used as measurement site for each muscle. The position of greatest thickness in lateral half of SOL was measured at the level described above. Furthermore, mean value of MG, LG, and SOL thicknesses was adopted as muscle size of plantar flexors. After the measurement of muscle thickness, cross-sectional area of Achilles tendon was also measured by an ultrasonic apparatus at the height of lateral malleolus. Since body mass of long distance runners was significantly lower than that of untrained men as shown in Table 1, absolute and relative (to body mass$^{1/3}$ for muscle thickness, to body mass$^{2/3}$ for tendon cross-sectional area) muscle thickness and tendon cross-sectional area values were presented (Kubo et al., 2010, 2014).

The repeatability of measurements of muscle thickness and tendon cross-sectional area was confirmed in our previous study (Kubo et al., 2014).

2.3. Passive muscle stiffness during slow stretching

To assess passive muscle stiffness, a specially designed dynamometer (Applied Office, Tokyo, Japan) was used to measure external torque and ankle joint angles. Subjects lay prone on a test bench with their right foot tightly secured by two straps to the dynamometer's footplate. The center of rotation of the dynamometer was visually aligned with lateral malleolus through which the axis of rotation of the ankle joint is assumed to act. The right ankle joint was set at 100° (with the foot perpendicular to the tibia = 90° with angles more than 90° being in plantar flexion) with knee joint at full extension. Subjects did not warm-up before stretch maneuver. While subject maintained completely relaxed muscles, the ankle was passively moved from 100° to 80° with a constant velocity of 5°/s. To minimize thixotropic effects as preconditioning (Hoang et al., 2007; Muraoka et al., 2002), we collected data during the 6th cycle after 5 cycles. Passive torque (TQ) measured during slow stretch was converted to muscle force (Fm) using the following equation:

$Fm = k \cdot TQ \cdot MA^{-1}$where k represents the relative contribution of physiological cross-sectional area of MG within plantar flexor muscles (Fukunaga et al., 1996), and MA is the moment arm length of triceps surae muscles at 90° of ankle joint, which is estimated from the lower leg length of each subject (Grieve et al., 1978) who reported the relationship between ankle joint angle and whole muscle length change of gastrocnemius muscle.

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

	Age (yr)	Height (cm)	Body mass (kg)	Lower leg length (cm)
Long distance runners	20.4 (1.0)	171.2 (4.8)	57.4 (4.6) ***	39.7 (1.8)
Untrained men	22. 2 (3.6)	172.3 (5.5)	66.4 (8.1)	39.1 (1.8)

*Significantly different from untrained men.
*** $p < 0.001$.

During slow stretching, a real-time ultrasonic apparatus (SSD-6500, Aloka, Japan) was used to continuously record longitudinal ultrasonic images of MG at the level of 30% of lower leg length. Ultrasonic images were recorded on a video tape at 30 Hz and synchronized with recordings of a clock timer for subsequent analysis. Fascicle length was defined as distance between insertion of fascicle into superficial and deep aponeurosis. In the present study, fascicle length was measured five times for the same images. The average value of three measurements excluding largest and smallest values was proposed and used as a representative value. The coefficient of variation of three measurements ranged from 0% to 4.5%.

Passive torque, joint angle, fascicle length, and electromyographic activity in the triceps surae muscles (see below) were continuously recorded over entire range of stretch maneuvers. The slope of portion of passive muscle force – fascicle length curve from 90° to 80°, was defined as passive muscle stiffness. The repeatability of passive muscle stiffness was confirmed in our previous study (Kubo, 2014).

2.4. Active muscle stiffness during fast stretching

The posture of subject and setup were similar to that for measurement of passive muscle stiffness, as described above. After a standardized warm-up, subjects performed two or three isometric maximal voluntary contractions (MVC) at 100° of ankle angle with 2 min of rest between each trial. The peak torque was recorded in every trial, and highest MVC value was used to determine the target torque during short range stretch experiment.

After 5 min rest period, subjects performed short range stretch experiment using previously described procedure (Foure et al., 2010; Kubo, 2014). The specially designed dynamometer was programmed to apply dorsiflexion stretches from 100° to 80°. Subjects were instructed to relax as soon as ankle motion was perceived. A 60-ms period after the stretch was analyzed because this time period was chosen to avoid any potential neural effects (Allum and Mauritz, 1984; Blanpied and Smidt, 1992; Foure et al., 2010). The range of motion was approximately 8° during this period. Angular velocity during stretch reached approximately 250°/s (Kubo, 2014). Before experiment, subjects were familiarized to short range stretch experiments at 50% MVC. An additional measurement was conducted two times at 0% MVC before short range stretch experiment for data correction purposes. The averaged torque during the relaxed condition was subtracted from the measured torque during each of the active stretch trials (Blanpied and Smidt, 1992). The short range stretch experiment was performed at 4 levels of submaximal torque in a random order (2 tests at each 20% MVC from 30% to 90% MVC) with visual aid of exerted torque on an oscilloscope. The measured values were the means of two trials.

During short range stretch experiment, fascicle length of MG was determined using a real-time ultrasonic apparatus. Ultrasonic images were stored at 98 Hz in the computer memory of the apparatus (Kubo, 2014). An electric signal was superimposed on the images to synchronize them to the torque, joint angle, and electromyographic activity. The location of probe, analysis of fascicle length, and calculated muscle force were similar to those for measurement of passive muscle stiffness, as described above. The slope of muscle force – fascicle length curve between 100° and 92° was defined as active muscle stiffness (Kubo, 2014), which in all case exceeded r^2=0.77 (0.87 ± 0.07; see Fig. 1). The repeatability of active muscle stiffness was confirmed in our previous study (Kubo, 2014).

2.5. Stiffness of tendon structures

The posture of subject (except for ankle angle) and procedure used were similar to those for measurement of passive muscle stiffness, as described above. The right ankle joint was set at 90° with the knee joint at full extension. Prior to the test, the subject performed a standardized warm-up and submaximal contractions to become accustomed to the test procedure. Subjects were instructed to develop a gradually increasing force from a relaxed state to MVC within 5 s. The task was repeated two times per subject with at least three minutes between trials. A real-time ultrasonic apparatus was used to obtain a longitudinal ultrasonic image of MG during the contraction. The displacement of the point at which one fascicle was attached to aponeurosis was considered to indicate the lengthening of tendon structures. Additional measurements were taken under passive conditions to correct measurements taken for the tendon and aponeurosis elongation. The displacement of each site obtained from the ultrasound images could be corrected for

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