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Short communication

Triceps surae muscle–tendon unit length changes as a function of ankle joint angles and contraction levels: The effect of foot arch deformation

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A B S T R A C T

The purpose of this study was to clarify how foot deformation affects the relationship between triceps surae muscle–tendon unit (MTU) length and ankle joint angle. For six women and six men a series of sagittal magnetic resonance (MR) images of the right foot were taken, and changes in MTU length (the displacement of the calcaneal tuberosity), foot arch angle, and ankle joint angle were measured. In the passive session, each subject's ankle joint was secured at 10° dorsiflexed position, neutral position (NP), and 10° and 20° plantar flexed positions while MR images were acquired. In the active session, each subject was requested to perform submaximal isometric plantar flexions (30%, 60%, and 80% of voluntary maximum) at NP. The changes in MTU length in each trial were estimated by two different formulae reported previously. The changes of the measured MTU length as a function of ankle joint angles observed in all trials of the active session were significantly ($p<0.05$) larger than corresponding values in the passive session and by the estimation formulae. In the passive session, MTU length changes were significantly smaller than the estimated values when the ankle was plantar flexed. The foot arch angle increased as the contraction level increased from rest ($117\pm4°$) to 80% ($125\pm3°$), and decreased as the ankle was positioned further into plantar flexion in the passive session ($115\pm3°$). These results indicate that foot deformation profoundly affects the triceps surae MTU length–ankle joint angle relationship during plantar flexion.

1. Introduction

Evaluation of length changes of the triceps surae muscle–tendon unit (MTU) during ankle joint movements is important to understand its mechanical function (i.e., force–length relationships of muscle and tendinous structures). The change in triceps surae MTU length for a given ankle joint rotation has been predicted by formulae developed on the basis of cadaveric data (Grieve et al., 1978; Hawkins and Hull, 1990). These formulae are based on the relationship between changes in ankle joint angle and MTU length (i.e., the displacement of the calcaneal tuberosity). However, proximal displacement of the calcaneal tuberosity occurs during isometric plantar flexion (Maganaris, 2005). This implies that the above formulae are not suitable for evaluating changes in triceps surae MTU length.

Other cadaveric studies have shown that the foot segment is deformed by the forces applied to it (Carlson et al., 2000; Ker et al., 1987). It is likely that the corresponding deformation also occurs *in vivo*, by the Achilles tendon force produced by the triceps surae muscles and other external forces that constrained the foot to move along a certain path or to rotate about a fixed axis. It can, therefore, be hypothesized that contraction-induced foot deformations give rise to a difference in the triceps surae MTU length–ankle joint angle relationships between conditions with and without contraction of the triceps surae muscles. The present study is aimed to test this hypothesis by measuring foot deformation *in vivo* under these conditions.

2. Methods

2.1. Subjects

Six women and six men voluntarily participated in this study. The mean values ± SDs for their age, height, mass, and lower leg length were 24 ± 2 yr,

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1.68 ± 0.08 m, 58 ± 8 kg, and 0.375 ± 0.019 m, respectively. Each subject was informed of the purpose and possible risks of this study before providing written consent to participate. This study was approved by the Ethics Committee on Human Research of Waseda University.

2.2. Experimental protocol

Each subject lay in a supine position on the bed of a 1.5-T MRI scanner (Signa HDxt, GE Medical Systems, USA). The subject's right thigh was firmly secured to the bed by a non-elastic strap with the knee fully extended. The subject underwent the following two separate sessions. In the passive session, the subject's right ankle (dominant) was aligned and fastened to a custom-made footplate (VINE, Japan) pre-configured at the footplate angles of 10° dorsiflexed position (DF10), neutral position (NP), and 10° and 20° plantar flexed positions (PF10 and PF20) while the muscles were relaxed. Prior to every passive trial the orientation of the footplate was aligned to the longitudinal direction of the tibia, and the foot was secured during measurement and then released immediately afterwards at every ankle joint angle. In the active session, each subject was requested to perform a series of isometric plantar flexions at 30%, 60%, and 80% of the maximal voluntary contraction (MVC) at NP. Then, the foot was secured onto the footplate throughout the active session. The trial was performed once for each target contraction level and ankle joint angle. The bending of the footplate induced by the isometric plantar flexion was measured a fiber using Bragg grating sensor (Shinko electric wire, Japan) that was fixed to the footplate (Fig. 1). The change in Bragg wavelength representing the amount of footplate bending was recorded at 100 Hz by a monitor (FB200, Yokogawa Electric, Japan) and used to determine the isometric plantar flexion torque. A head-mounted display (VisuaStim Digital's controller, Resonance Technology, USA) connected to the sensor was used to provide the subject with a visual feedback of the torque output. With this arrangement, the subject was able to sustain each prescribed force level during the acquisition of MR images for 18 s (Fig. 2). Actual values of the contraction levels during MRI scan for the corresponding target levels and the mean difference in the plantar flexion torque between the initial and final parts of the MRI scan are shown in Table 1. We considered that these changes in the plantar flexion torque during the trials were of minor influence on the present results. The resting period of at least 2 min was provided to minimize fatigue. Prior to the active session, the maximal voluntary isometric plantar flexion torque was measured 2–3 times for each subject so as to determine the highest torque (MVC torque) used as the reference to set each target contraction level.

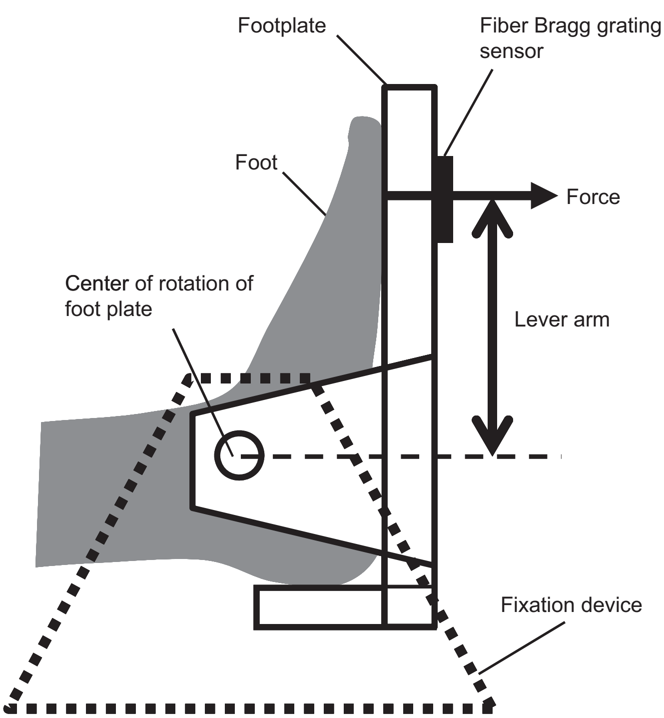

Fig. 1. Structure of the custom-made footplate for the measurement of isometric plantar flexion torque. A fiber Bragg grating sensor was attached on the footplate (corresponding to the metatarso-phalangeal joint of the foot) to measure the force applied to the footplate. The sensor was pre-calibrated to determine the mathematical relation between the change in Bragg wavelength and the moment of the force applied. The plantar flexion torque was calculated from the force and the lever arm of the footplate.

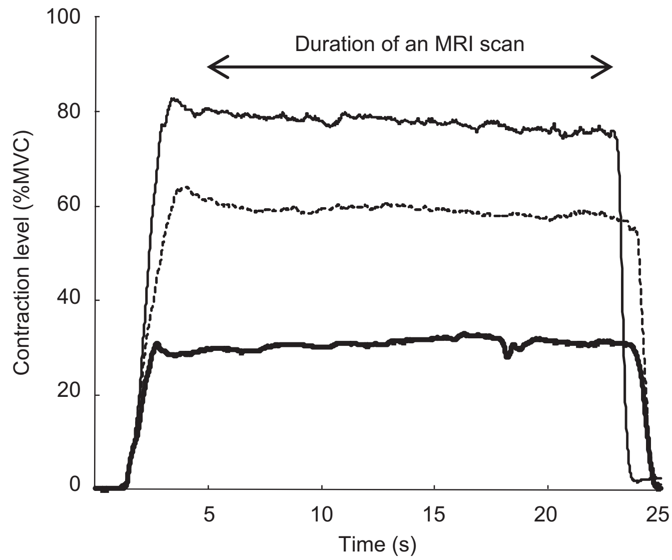

Fig. 2. Typical example of the contraction levels over time. Each subject was requested to perform isometric plantar flexions at 30% (bottom line), 60% (middle line), and 80% (top line) of MVC during MRI scan.

Table 1
(a) Average contraction levels during MRI scans for the three target levels and (b) mean difference in the plantar flexion torque between the initial and final parts of the single MRI scan.

(a) Target contraction level	Average contraction level
30%MVC	29.6 ± 1.1%MVC
60%MVC	58.7 ± 1.5%MVC
80%MVC	78.1 ± 1.9%MVC

(b) Target contraction level	Mean difference
30%MVC	0.1 ± 1.0%MVC
60%MVC	−1.8 ± 2.3%MVC
80%MVC	−3.2 ± 2.9%MVC

Table 2
MRI scan parameters.

Repetition time	1300 ms
Time to echo	20 ms
Slice thickness	5 mm
Interspaced distance	0 mm
Field of view	260 × 260 mm
Matrix	256 × 160 pixels
Number of excitation	0.5
Number of slices	13 slices
Resolution	1.01 mm/pixel

2.3. Image acquisition and analysis

A series of sagittal MR images of the ankle were obtained with a proton density weighted fast recovery fast spin echo sequence (Table 2). A single experienced tester analyzed all images using Adobe Photoshop (Adobe Systems, USA), and Image J (National Institutes of Health, USA). Each landmark described below was digitized in the selected images that gave the clearest representation of the landmark of interest.

In the present study, the foot was modeled as a link of two rigid segments (Wrbaskic and Dowling, 2007; Fig. 3a), consisting of a posterior segment representing the talus and calcaneus as a unit and an anterior segment representing the rest of the foot as a whole. The lines connecting from the anterior vertex of talus (P_{tal}) to the calcaneal tuberosity and to the distal tip of the first metatarsal