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Short communication

Evidence for intermuscle difference in slack angle in human triceps surae

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ABSTRACT

This study examined whether the slack angle (i.e., the joint angle corresponding to the slack length) varies among the synergists of the human triceps surae in vivo. By using ultrasound shear wave elastography, shear modulus of each muscle of the triceps surae was measured during passive stretching from 50° of plantar flexion in the knee extended position at an angular velocity of 1°/s in 9 healthy adult subjects. The slack angle of each muscle was determined from the ankle joint angle–shear modulus relationship as the first increase in shear modulus. The slack angle was significantly greater in the medial gastrocnemius ($20.7 \pm 6.7°$ plantarflexed position) than in the lateral gastrocnemius ($14.9 \pm 6.7°$ plantarflexed position) and soleus ($2.0 \pm 4.8°$ dorsiflexed position) and greater in the lateral gastrocnemius than in the soleus. This study provided evidence that the slack angle differs among the triceps surae; the medial gastrocnemius produced passive force at the most plantarflexed position while the slack angle of the soleus was the most dorsiflexed position.

1. Introduction

Passive slack length of a muscle is defined as the length beyond which the muscle begins to develop passive force. The parameter is critical for investigating muscle characteristics such as the force–length relationship (Ackland et al., 2012; Hoy et al., 1990) as well as for understanding clinical conditions where these properties might be altered, like muscle contracture (Diong et al., 2013). In human experiments, passive torque–joint angle measurements have been classically used to determine the slack angle (i.e., the joint angle corresponding to the slack length) of muscle–tendon units (Barber et al., 2012; Muraoka et al., 2005; Muraoka et al., 2004). However, the joint torque is not a measure specific to responses of individual muscles and their tendon, because the joint torque results from a composite of contractile (i.e., agonists and antagonists) and non-contractile tissues such as tendon, skin, ligament and articular structures. Additionally, although other studies have used B-mode ultrasonography in addition to the torque–angle measurement (Herbert et al., 2011; Hoang et al., 2007), B-mode ultrasonography per se can provide information only about architecture such as fascicle length and displacement of muscle–tendon junction, not about mechanical properties. In other words, even if a muscle and fascicles within the muscle are lengthened, the muscle and fascicles do not necessarily begin to develop passive force which means to take up the slack. Thus, other methods are required to assess the slack angles of individual muscles in human in vivo.

Recently, ultrasound elastography has been implemented to quantify mechanical properties of in vivo tissues. Ultrasound shear wave elastography can localize tissue elasticity along the longitudinal axis of the probe (Bercoff et al., 2004; Chen et al., 2009; Palmeri et al., 2008). With the gastrocnemius and tibialis anterior of fresh roaster chickens, Koo et al. (2013) have reported a linear relationship between the shear modulus measured by ultrasound shear wave elastography and passive muscle force. Human experiments took advantage of this technique to detect the slack angle on the medial gastrocnemius (MG) (Maïsetti et al., 2012), biceps brachii (Lacourpaille et al., 2013; Lacourpaille et al., 2014), and tibialis anterior (Koo et al., 2014). To the best of our knowledge, so far only Lacourpaille et al. (2013) have compared the slack angles among synergistic muscles. They reported similar slack angles between the two heads of the biceps brachii. However, this does not necessarily hold for other muscle groups. Hug et al. (2013) have reported that slack angle for MG was less plantarflexed position than that for the Achilles tendon in the knee extended position. This tempts us to hypothesize that the slack angle of the soleus (Sol) is more plantarflexed than that of MG. By the use of ultrasound shear wave

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elastography, therefore, the purpose of the present study was to clarify whether the slack angle differs among each muscle of the human triceps surae at the knee extended position.

2. Methods

2.1. Subjects

Nine healthy adult subjects (five men and four women; 166.9 ± 8.4 cm, 59.2 ± 6.7 kg, 21.1 ± 2.0 years) with no current musculoskeletal injuries specific to the ankle joint were recruited for the present study. This study was approved by the local ethics committee and performed in accordance with the Declaration of Helsinki. The subjects were fully informed of the procedures used as well as the purpose of the study. Written informed consent was obtained from all subjects.

2.2. Experimental setup and protocol

Subjects lay prone on a dynamometer (CON-TREX MJ, PHYSIOMED, Germany) bench with their right knee fully extended. The right foot was firmly secured to the dynamometer footplate. The rotation axis of the ankle was aligned with that of the dynamometer. The ankle joint angle was passively dorsiflexed from 50° plantar flexion (0° = neutral position (i.e., the sole of the foot at right angles to the tibia axis)) at an angular velocity of 1°/s. The very slow angular velocity was used to obtain a better resolution for the determination of slack angle and to avoid or minimize the stretch reflex (Hug et al., 2013; Morse et al., 2008), which would stiffen the stretched muscles. The angular displacement of the ankle joint was measured with an electronic goniometer (SG110/A, Biometrics, UK) fixed to the ankle joint with double-sided adhesive tape. Throughout the stretching maneuver, the subjects were asked to completely relax and not to resist the movement of the footplate. In order to accustom the subjects to the procedure and to ensure that they were as relaxed as possible, a familiarization session of 2 cycles was performed before the start of the testing session. This familiarization session also has a role to exclude a conditioning effect of passive stretching on the elasticity of muscle and tendon (Konrad et al., in press; Konrad and Tilp, 2014). Therefore, the measurements were conducted during the 3rd cycle and later.

2.3. EMG and elastographic recordings

In order to ensure that the stretching procedures were passive, surface electromyographic (EMG) signals were recorded from MG, lateral gastrocnemius (LG), and Sol. After preparation of the skin by shaving, rubbing with sandpaper, and cleaning with alcohol, pairs of pre-amplified (gain: × 500, band-pass filtering: 5–450 Hz) active surface electrodes (electrode shape: parallel-bar, size: 1 mm width × 8 mm length, inter-electrode distance: 12 mm; FA-DL-141, 4-assist, Japan) were placed over the bellies of MG and LG and over the lateral or medial aspect of Sol (i.e., 3–4 cm distal to the muscle–tendon junction of LG or MG) along the fascicle direction of each muscle. The reference electrode was placed over the left medial malleolus.

Two real-time ultrasound shear wave elastography scanners (Aixplorer Ver. 6 and Ver. 7, Supersonic Imagine, France) with a 4–15 MHz linear probe (50 mm width; SL15-4, Supersonic Imagine, France) were used with musculoskeletal preset. Each ultrasound probe was placed next to the EMG electrodes of either MG, LG, or Sol in a randomized order across subjects. Since the three muscles were targeted with the two scanners, the passive stretching protocol as mentioned above was repeated. The probe orientation was adjusted to identify several fascicles without interruption across the B-mode image in a certain plane (Fig. 1). Care was taken not to press and deform the muscles while scanning.

The joint angle and EMG data were simultaneously sampled at 1 kHz by using a 16 bit analog-to-digital converter (PowerLab/16SP, ADInstrument, Australia), which was manually synchronized with elastography recording (sampling frequency = 1 Hz).

2.4. Data and statistical analysis

The spatial average of shear modulus of each muscle was computed for every 1° of the ankle joint during passive stretching. The slack angle of each muscle was visually determined from the ankle joint–shear modulus relationship as the first increase above the variation in shear modulus at the plantarflexed position (Fig. 1) (Lacourpaille et al., 2013, 2014). This determination of the slack angle was performed by three experimenters. The SD values between the experimenters were 0.3°, 0.9°, and 0.4° for MG, LG, and Sol, respectively. The mean value of the three experimenters was used for further analysis. The root mean square values of EMG signals (RMS-EMG) at the slack angle were calculated over a 500 ms period for each muscle. Then, the RMS-EMG value of each muscle at the slack angle was normalized to that obtained during isometric maximal voluntary contraction (MVC) which was performed at the neutral position (0°) of the ankle joint. For the slack angle and RMS-EMG data, one-way analyses of variance (ANOVAs) with repeated measures and Tukey post-hoc tests were performed. The significant level for all comparisons was set at $P < 0.05$. All the statistical analyses were performed with statistical software (SPSS Statistics 22, IBM Japan, Japan). Data are expressed as means and SDs.

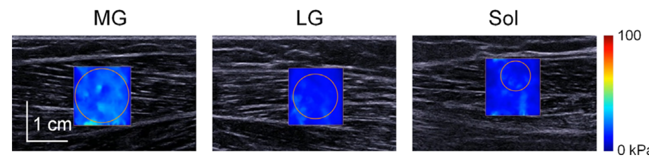

Fig. 1. Typical examples of shear modulus measurements of the medial (MG) and lateral gastrocnemius (LG) and soleus (Sol). The square region represents the shear modulus map with the scale to the right of the figure. Circle is the region of interest for determination of shear modulus.

3. Results

Fig. 2 shows the shear modulus–plantar flexion angle relationships and the slack angle of each muscle for individual subjects. A one-way ANOVA showed a significant main effect of muscle on slack angle ($P < 0.01$). A Tukey post-hoc test revealed that the slack angle of MG (20.7 ± 6.7° plantarflexed position) was significantly greater (i.e., plantarflexed position) than those of LG (14.9 ± 6.7°) and Sol (−2.0 ± 4.8° (i.e., 2.0° dorsiflexed position)). The difference in slack angle between LG and Sol was also significant. For each muscle, the RMS-EMG at slack angle was less than 0.9% MVC, and there was no significant difference among MG, LG, and Sol.

4. Discussion

The main finding of the present study was that there was a difference in slack angle at which muscles take up slack among the triceps surae when the knee is fully extended. The observed slack angle of MG (21° of plantar flexion) was similar to that obtained previously from in vivo MG (Hug et al., 2013; Maïsetti et al., 2012). Hug et al. (2013) reported that slack angle for MG was less plantarflexed position than that for the Achilles tendon. Based on their finding, we hypothesized that the slack angle of Sol is more plantarflexed than that of MG. However, the current results do not support this hypothesis. The reason for what causes an increase in the shear modulus of the Achilles tendon when none of the triceps surae are generating passive force is unclear, but may be related to the subcutaneous adipose tissue and/or the muscles' parallel elastic components such as the epimysium. The actual examination of the etiology and functional significance of the apparent difference in slack angles between the triceps surae and Achilles tendon is a very interesting research topic, but requires a more appropriate research design and is beyond the scope of the present study.

A potential reason for the observed inter-muscle difference in slack angle is the difference in sarcomere length when varying the ankle joint angle (Kawakami et al., 2000). Kawakami et al. (2000) have reported that the sarcomere length of MG is longer than that of Sol at a given ankle joint angle on human cadaver. Considering that passive force generally develops at or near the optimal length (Freehafer et al., 1979; Friden and Lieber, 2002), it is expected that the slack angle of MG is more plantarflexed than Sol. The current results confirmed this and provide evidence that the slack angle differs among each muscle of the human triceps surae in vivo.

In addition, the structures of the human triceps surae and Achilles tendon may also be involved as a factor inducing the inter-muscle difference in slack angle. Although three separate muscles (i.e., MG, LG, and Sol) merge via their aponeuroses into a common Achilles tendon to insert on the calcaneus, MG has more distal muscle–tendon junction than LG, while Sol inserts most distally onto the Achilles tendon (Ward et al., 2009; Wickiewicz et al., 1983).