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Short communication

Slack length of gastrocnemius medialis and Achilles tendon occurs at different ankle angles

François Hug [a,b], Lilian Lacourpaille [a], Olivier Maïsetti [a,c], Antoine Nordez [a,*]

[a] University of Nantes, UFR STAPS, Laboratory "Motricité, Interactions, Performance" (EA 4334), Nantes, France
[b] The University of Queensland, NHMRC Centre of Clinical Research Excellence in Spinal Pain, Injury and Health, School of Health and Rehabilitation Sciences, Brisbane, Australia
[c] University of Paris-Est Créteil Val de Marne, Créteil, France

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ABSTRACT

Although muscle–tendon slack length is a crucial parameter used in muscle models, this is one of the most difficult measures to estimate *in vivo*. The aim of this study was to determine the onset of the rise in tension (*i.e.*, slack length) during passive stretching in both Achilles tendon and gastrocnemius medialis. Muscle and tendon shear elastic modulus was measured by elastography (supersonic shear imaging) during passive plantarflexion (0° and 90° of knee angle, 0° representing knee fully extended, in a random order) in 9 participants. The within-session repeatability of the determined slack length was good at 90° of knee flexion ($SEM = 3.3°$ and 2.2° for Achilles tendon and gastrocnemius medialis, respectively) and very good at 0° of knee flexion ($SEM = 1.9°$ and 1.9° for Achilles tendon and gastrocnemius medialis, respectively). The slack length of gastrocnemius medialis was obtained at a significantly lower plantarflexed angle than for Achilles tendon at both 0° ($P < 0.0001$; *mean difference* $= 19.4 \pm 3.8°$) and 90° of knee flexion ($P < 0.0001$; *mean difference* $= 25.5 \pm 7.6°$). In conclusion, this study showed that the joint angle at which the tendon falls slack can be experimentally determined using supersonic shear imaging. The slack length of gastrocnemius medialis and Achilles tendon occurred at different joint angles. Although reporting this result is crucial to a better understanding of muscle–tendon interactions, further experimental investigations are required to explain this result.

1. Introduction

Muscle–tendon slack length is defined as the length beyond which muscle and tendon begin to develop passive elastic force and determines the compliance of individual tendons. Although this is a crucial parameter used in muscle models (Ackland et al., 2012; Garner and Pandy, 2003; Hoy et al., 1990; Zajac, 1989) this is one of the most difficult measures to estimate *in vivo* (Garner and Pandy, 2003).

Passive torque–angle curves of a joint are classically used to assess mechanical properties of the passive musculo-articular complex. Some studies determined the slack length as the muscle–tendon length at which the passive joint torque first exceeds zero (Barber et al., 2012; Muraoka et al., 2004, 2005). However, passive torque is influenced by all structures crossing the joint [*e.g.*, all the agonist/antagonist muscles, skin, and tendons; (Riemann et al., 2001)], therefore this measure is unlikely to correspond to the true slack length of an individual musculo-tendon complex. Other studies have used ultrasonography to isolate the slack length of one muscle–tendon unit (Herbert et al., 2011; Hoang et al., 2007). As muscle fascicles, aponeurosis and free tendon are classically considered to be in-series (Zajac, 1989), the slack length of these structures has been considered to occur at the same muscle–tendon length or joint angle (Hoang et al., 2005, 2007). However, this assumption has not been confirmed experimentally *via* direct measurements of muscle and tendon stress.

Elastographic techniques can be used to determine the local mechanical properties (*e.g.*, shear elastic modulus) of soft tissues by measuring the propagation velocity of shear waves. We have recently shown that an ultrasound shear wave elastographic technique called "supersonic shear imaging" (SSI) is able to accurately quantify shear elastic modulus of a targeted muscle during passive stretching (Koo et al., 2013; Maisetti et al., 2012). Taking advantage of this technique, muscle slack length was determined on gastrocnemius medialis (Maisetti et al., 2012) and on each head of biceps brachii (Lacourpaille et al., 2013).

During pilot experiments that aimed to test the reliability of shear elastic modulus measurement on Achilles tendon, preliminary observations suggested that the slack length of Achilles tendon and gastrocnemius medialis occurs at different ankle angles.

* Corresponding author. Tel.: +33 2 51 83 72 28; fax: +33 2 51 83 72 10.
E-mail address: antoine.nordez@univ-nantes.fr (A. Nordez).

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Therefore, the aim of this study was to extend this preliminary observation. For that purpose, the onset of the rise in passive tension (*i.e.*, slack length) was determined during passive stretching, independently in Achilles tendon and gastrocnemius medialis.

2. Methods

2.1. Participants

Nine healthy males volunteered to participate in this study (age: 22.6 ± 1.8 years). Participants were informed of the purpose of the study and methods used before providing written consent. The local ethics committee approved the experiment and all procedures adhered to the Declaration of Helsinki.

2.2. Instrumentation

2.2.1. Ergometer

An isokinetic dynamometer (Biodex 3 medical, Shirley, NY, USA) was used to measure ankle angle, joint angular velocity, and torque during passive ankle dorsiflexions. The participant's right foot was attached securely to the footplate of the dynamometer and the ankle joint aligned with the axis of the dynamometer. Participants laid prone so that the back of the seat could be moved to change the knee angle without moving the lower leg that stayed horizontal. Torque and angle provided by the Biodex dynamometer were collected at 1000 Hz with an analog/digital converter (Bagnoli 16, Delsys Inc, Boston, USA).

2.2.2. Surface electromyography (EMG)

Dry-surface electrodes (Delsys DE 2.1, Delsys Inc., Boston, USA; 1 cm interelectrode distance) were placed on the gastrocnemius medialis and soleus. EMG signals were amplified ($\times 1000$) and digitized (6–400 Hz bandwidth) at a sampling rate of 1 kHz (Bagnoli 16, Delsys, Inc. Boston, USA).

2.2.3. Elastrography

An Aixplorer ultrasound scanner (version 4.2; Supersonic Imagine, Aix-en-Provence, France) coupled with a linear transducer array (4–15 MHz. SuperLinear 15-4, Vermon, Tours, France) was used in SSI mode (musculo-skeletal preset) as previously described (Bercoff et al., 2004). Assuming a linear elastic behavior, the muscle shear elastic modulus was calculated as follows:

$$\mu = \rho V s^2$$

Where ρ is the density of soft tissues (1000 kg m^3) and *Vs* is the shear wave speed. For each passive stretching cycle the transducer was held manually by an experienced examiner and was orientated perpendicularly to the skin and parallel to the muscle fascicles (gastrocnemius medialis) or tendon fibers (Achilles tendon). Maps of the shear elastic modulus were obtained at 1 Hz with a spatial resolution of 1×1 mm.

2.3. Protocol

To account for a possible effect of conditioning (Nordez et al., 2008), participants first performed five slow (10°/s) passive loading/unloading cycles between 50° of plantarflexion and 80% of the maximal range of motion in dorsiflexion previously determined (0° = foot perpendicular to the leg). Then they were immediately tested at 0° and 90° of knee angle (0° = knee fully extended) in a random order. For each knee angle, the ultrasound transducer was placed either on the free Achilles tendon or gastrocnemius medialis (in a random order) and participant's calf was passively stretched through slow loading cycles (1°/s and 2°/s for tendon and gastrocnemius medialis, respectively) between 50° of plantarflexion and 80% of the maximal range of motion in dorsiflexion. This difference in angular velocity is justified by the saturation limit of the elastographic scanner (*i.e.*, 266 kPa) combined to the maximum recording duration of 1-min. As tendon is stiffer, it achieved this saturation level earlier than the muscle and thus a lower angular velocity was preferable for obtaining a better precision in the slack length determination. For each transducer location (*i.e.*, Achilles tendon and gastrocnemius medialis) two passive loadings (*i.e.*, dorsiflexion) were performed. Online EMG feedback was provided to the participant and to the examiner. Participants were asked to stay as relaxed as possible through the passive stretching. A requirement was that EMG activity was less than 1% of that recorded during maximal isometric contractions performed at the end of the testing session (McNair et al., 2002; Nordez et al., 2008).

2.4. Data analysis

SSI recordings were exported from software (Version 4.2, Supersonic Imagine, Aix en Provence, France) in "mp4" format and sequenced in "jpeg". Image processing converted the colored map into shear elastic modulus values. For each image, the average value of shear elastic modulus was calculated over a region of interest (ROI) corresponding to the largest muscular region for gastrocnemius medialis (size $\approx 12 \times 12$ mm) and largest tendon region for Achilles tendon (size $\approx 3.5 \times 10$ mm) (Fig. 1). The ankle angle corresponding to the tendon and muscle slack length was visually determined (blind to structure, knee angle and trial) by an experienced examiner (Lacourpaille et al., 2013).

To synchronize both shear elastic modulus and ankle joint angle, SSI recordings were started five seconds before the beginning of the loading passive stretching.

2.5. Statistics

First, for each structure (*i.e.*, gastrocnemius medialis and Achilles tendon) and each knee angle (*i.e.*, 0° and 90°) the standard error of measurement (*SEM*) was calculated between the two passive loadings to assess the intra-session repeatability of the determined ankle angle corresponding to the slack length. The repeatability was assessed on 6 participants for gastrocnemius medialis at 90° of knee flexion (3 trials were excluded because of noisy signals). The two repeat measurements were then averaged for the following analysis.

Two separated repeated measures ANOVAs [factors: structure (tendon and muscle) and knee angle (0° and 90°)] were performed to test the effect of structure and knee angle on both the ankle angle corresponding to the slack length and the resting shear elastic modulus values measured at 50° of plantarflexion (*i.e.*, first value measured during the passive stretching). Post-hoc analyses were performed when appropriated using Scheffe's method. The statistical significance was set at $p < 0.05$.

3. Results

A significant main effect of "structure" ($P < 0.0001$) was found for the resting shear elastic modulus value measured at 50° of plantarflexion (5.0 ± 1.2 *vs*. 35.3 ± 6.7 kPa for gastrocnemius medialis and Achilles tendon, respectively). There was neither no significant main effect of "knee angle" ($P = 0.20$), nor significant "structure × knee angle" interaction ($P = 0.14$).

Typical examples of ultrasound images and of the shear elastic modulus–angle relationship are depicted in Fig. 1. As tendon is stiffer than muscle, the shear elastic modulus measurements saturated at about $20 \pm 5°$ of plantarflexion. However, it did not influence the slack length determination. The within-session repeatability of the determined slack length was good at 90° of knee flexion (*SEM* = 3.3° and 2.2° for Achilles tendon and gastrocnemius medialis, respectively) and very good at 0° of knee flexion (*SEM* = 1.9° and 1.9° for Achilles tendon and gastrocnemius medialis, respectively). ANOVA revealed a significant "structure × knee angle" interaction ($P = 0.025$). More precisely, the slack length of gastrocnemius medialis was obtained at a significantly lower plantarflexed angle than for Achilles tendon at both 0° ($P < 0.0001$; *mean difference* = $19.4 \pm 3.8°$) and 90° of knee flexion ($P < 0.0001$; *mean difference* = $25.5 \pm 7.6°$). In addition, the slack length of gastrocnemius medialis with knee fully extended ($-24.3 \pm 5.8°$) appeared at a significantly ($P = 0.004$) more plantarflexed angle than with knee flexed at 90° ($-16.8 \pm 5.2°$). No significant difference ($P = 0.89$) in the ankle angle corresponding to the slack length was found for the tendon between the knee fully extended ($-43.7 \pm 3.2°$) and the knee flexed at 90° ($-42.3 \pm 4.9°$).

4. Discussion

There is experimental evidence that the shear elastic modulus measured by SSI is linearly related to muscle stress during both isometric contraction (Bouillard et al., 2011, 2012) and passive stretching (Maisetti et al., 2012). Taking advantage of this technique, Maisetti et al., (2012) showed that the slack length of gastrocnemius medialis can be reliably determined and reported values of $\approx -20°$ of plantarflexion (knee fully extended), which are very close to the data reported herein ($-24.3 \pm 5.8°$). The present study extends these findings to the Achilles tendon showing very

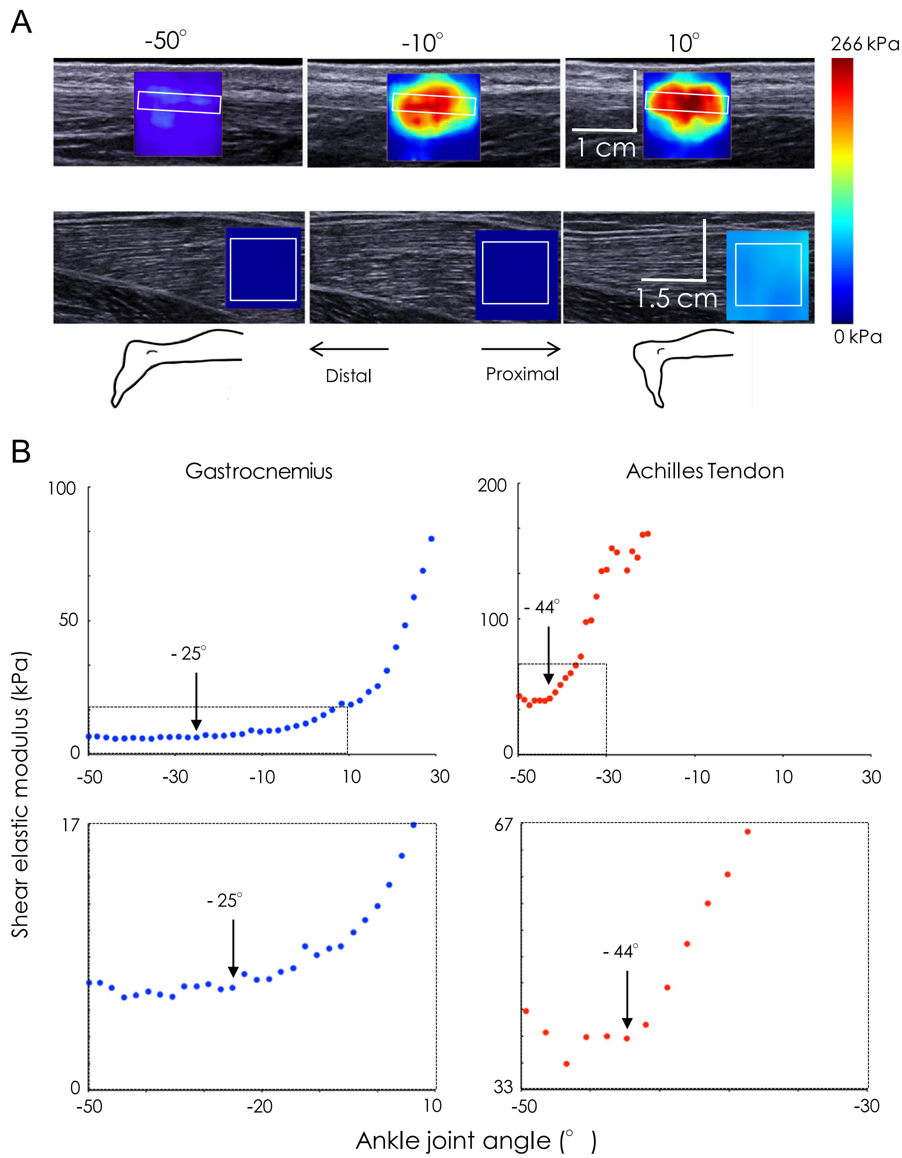

Fig. 1. Typical example of change in muscle and tendon shear elastic modulus during passive stretching. A—Maps of shear elastic modulus obtained at −50°, −10° and 10° of ankle joint angle (0° foot perpendicular to the leg) at 90° of knee flexion. The scale is depicted at the right of the figure. The region of interest used to calculate the mean shear elastic modulus is drawn in white. B—Relationship between shear elastic modulus and ankle joint for both gastrocnemius medialis and Achilles tendon (knee angle = 0°). The bottom panels correspond to a zoom of the region of interest defined as the rectangle on the top panels. These zoomed traces were used to detect the ankle angle corresponding to the slack length (indicated by an arrow).

good intra-session reliability of the slack length values. The present results demonstrated that muscle and tendon slack length occurs at different joint angles in the gastrocnemius muscle–tendon unit (difference ≈19°–25°, depending on the knee angle).

Several methodological issues must be considered. First, due to the nature of the shear elastic modulus/ankle angle relationship for the tendon, exponential models previously used to determine muscle slack length (*e.g.*, Maisetti et al., 2012) could not be used here. Therefore, the slack length was visually detected. As this visual determination led to similar values to those reported using the previous model (Maisetti et al., 2012) and because the repeatability led to values much lower than the substantial difference observed between the muscle and tendon slack length, the use of visual detection is not likely to have affected our findings. Second, as justified in the "methods" section, the passive loading cycles were performed at different velocities for the two structures. To check that the velocity of the loading cycles did not influence the slack length determination, pilot experiments were performed. They showed that the slack length was not affected by the velocity of the cycles (Fig. 2). Finally, it is necessary to consider that the observation of a different slack length of muscle and tendon arose because it was easier, in tendon than in muscle, to detect the slack length. This could have occurred, for example, because the tendon curve had a more abrupt transition. To overcome this, we performed one additional experiment in tibalis anterior. As this muscle does not share a tendon, a similar muscle and tendon slack length was expected, and was measured (Fig. 3). Overall, we believe that the substantial differences we reported between the tendon and muscle (<19°) could not be a "methodological" artifact.

This unexpected earlier rise in tension observed in Achilles tendon compared to gastrocnemius medialis might be explained by non-recorded synergist muscles. As it has been shown that the two heads of gastrocnemii behave similarly when passively lengthened (Maganaris et al., 1998), it is unlikely that the slack length of the lateral head of gastrocnemius would occur at a different ankle angle than the medial head. A monoarticular muscle such as soleus is more likely to explain this result.

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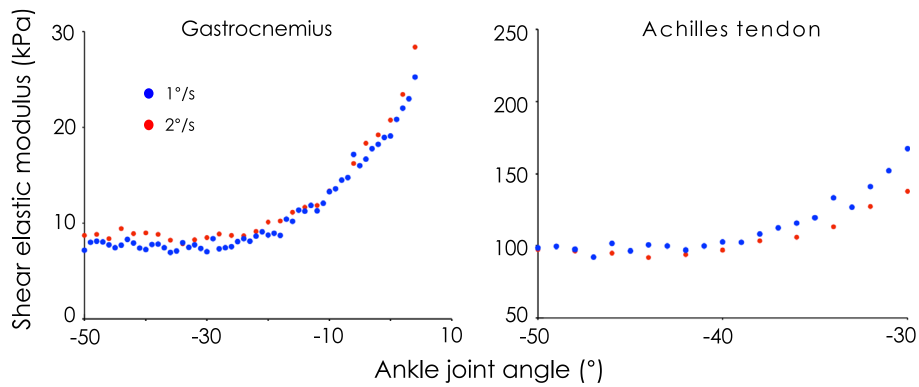

Fig. 2. Effect of the velocity of the loading cycles on the relationship between shear elastic modulus and ankle joint. To check that the velocity of the loading cycles did not influence the slack length determination, pilot experiments were performed. This figure represents an individual example of the results we obtained for both gastrocnemius medialis and Achilles tendon (knee angle = 0°).

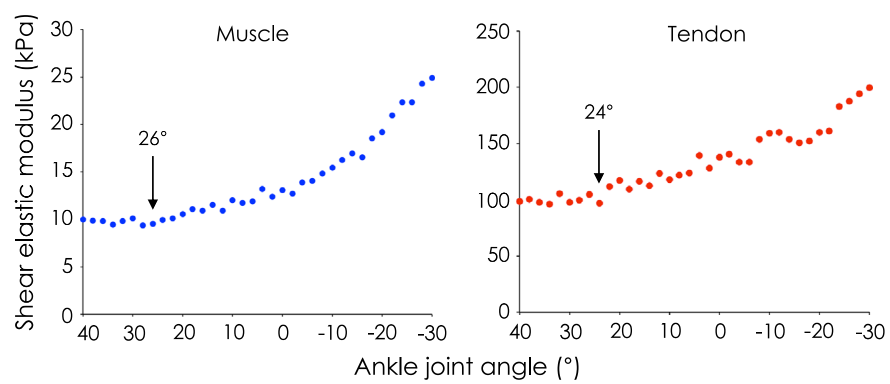

Fig. 3. Determination of the ankle joint angle corresponding to the slack length in both the tibialis anterior and its distal tendon. Muscle and tendon shear elastic modulus was measured by supersonic shear imaging during passive dorsiflexion (0° of knee angle; velocity of the loading cycle = 2°/s) in one participant. This figure represents the relationship between the shear elastic modulus and ankle joint angle for both the tibialis anterior and its distal tendon. The angle corresponding to the slack length was very similar for these two structures (*i.e.*, 26° and 24° for muscle and tendon, respectively). Note that because the tendon of the tibialis anterior is thinner that the Achilles tendon, it was more challenging to obtain a reliable shear modulus/angle relationship.

However, the ultrasound transducer used in the present study did not allow us to reliably measure muscle shear elastic modulus in soleus because of its complex architecture and/or its deeper location altering the propagation of the shear waves. In addition, this relative short slack length of the tendon could be explained by fascia or pulleys (Milz et al., 2002) that might stretch the tendon before the muscle fascicles.

In conclusion, this study showed that the joint angle at which the tendon falls slack can be experimentally determined using supersonic shear imaging. However, contrary to what is classically considered, the slack length of gastrocnemius medialis and Achilles tendon occurred at different joint angles. Although reporting this result is crucial to a better understanding of muscle–tendon interactions, further investigations are required to explain this result.

Conflict of interest

None

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