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Non-uniform in vivo deformations of the human Achilles tendon during walking

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ABSTRACT

The free Achilles tendon (AT) consists of distinct fascicles arising from each of the triceps surae muscles that may give rise to non-uniform behavior during functional tasks such as walking. Here, we estimated in vivo deformations of the human AT during walking using simultaneous ultrasound and motion capture measurements. Ten subjects walked at three speeds (0.75, 1.00, and 1.25 m/s) on a force-measuring treadmill. A custom orthotic secured a linear array transducer in two locations: (1) the distal lateral gastrocnemius muscle-tendon junction and (2) the free AT, on average centered 6 cm superior to calcaneal insertion. We used motion capture to record lower extremity kinematics and the position and orientation of the ultrasound transducer. A 2D ultrasound elastography algorithm tracked superficial and deep tissue displacements within the free AT. We estimated AT elongation (i.e., change in length) relative to the calcaneal insertion by transforming the orthotic, transducer, and calcaneus kinematics into a common reference frame. Superficial and deep regions of the free AT underwent significantly different longitudinal displacements and elongations during walking. For example, we found that the superficial AT exhibited 16–29% greater peak elongation than the deep AT during the stance phase of walking ($p < 0.01$). Moreover, superficial-deep AT tissue deformations became less uniform with faster walking speed ($p < 0.01$). Non-uniform deformations of the free AT, which could reflect inter-fascicle sliding, may enable the gastrocnemius and soleus muscles to transmit their forces independently while allowing unique kinematic behavior at the muscle fiber level.

1. Introduction

The Achilles tendon (AT) transmits substantial forces from the gastrocnemius and soleus muscles during movement. Considerable research has characterized the gross biomechanical behavior of the AT during walking [1–6]. However, these landmark studies generally do not consider the complex architecture of the AT and may thereby simplify in vivo musculotendon behavior. The free AT (i.e., calcaneus to soleus muscle-tendon junction) consists of distinct fascicle bundles arising from the triceps surae muscles; superficial fascicles arise from the medial gastrocnemius and deeper fascicles arise from the soleus and lateral gastrocnemius [7]. This unique anatomy gives rise to relative motion between fascicle bundles of the free AT [8,9]. However, the relevance of such non-uniform AT deformations to biomechanical function remains unclear, particularly for tasks such as walking which involve complex coordination between these plantarflexor muscles [10–13].

Comparative studies suggest that sliding between adjacent fascicles may be a key biomechanical feature in energy-storing tendons [14]. Direct and indirect evidence for non-uniform deformations within the human free AT comes from cadaver experiments or from measurements made during isolated ankle exercises [8,9,15–19]. For example, varying knee flexion can elicit differential displacements of the soleus and gastrocnemius aponeuroses [19]. Similarly, our research group showed that knee flexion modulates the uniformity of AT tissue displacements [9]. In addition, Haraldsson et al. [20] found negligible inter-fascicle force transmission within the AT and suggested that sliding may allow AT fascicles to act as functionally independent structures. These results imply that inter-fascicle sliding within the AT may be important to normal function. Biomechanically, sliding would enable the gastrocnemius and soleus muscles to stretch their

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associated tendinous structures more independently. Such behavior could thus allow muscles to operate at independent fiber lengths, which may be more tuned for effective force generation. Indeed, there is evidence that the gastrocnemius and soleus muscles exhibit markedly different behavior. For example, Ishikawa et al. [3] found that during the late stance phase of walking, medial gastrocnemius muscle fibers remain isometric or shorten while soleus muscle fibers lengthen. Further, it has been shown that the gastrocnemius and soleus muscles perform unique biomechanical functions during walking (i.e., propulsion vs. body weight support) [10–13,21], with greater distinction observed at faster walking speeds [13,21] Consequently, non-uniform deformations of the free AT may be critical to coordinate the triceps surae muscles across a range of walking speeds. Moreover, if functionally relevant, deformations within the free AT may become less uniform with faster walking speed.

Ultrasound imaging of the distal muscle-tendon junctions has contributed much to the research on AT function during walking (also see [5,6]). However, it is challenging to use traditional anatomical feature tracking to resolve spatial variations in tendon tissue deformation. Thus, our research group introduced a 2D ultrasound elastography algorithm to resolve regional variations in tendon tissue deformations [22]. This approach uses phase information inherent in ultrasound radiofrequency signals and, in cyclically loaded tendons, provides deformations that agree well with prescribed displacements ($R^2 > 0.97$) [22] and with digital image correlation ($R^2 > 0.92$) [23].

Our primary purpose was to use ultrasound elastography to investigate in vivo deformations of the human free AT during treadmill walking. We resolved superficial-deep variations in tendon tissue elongation (i.e., change in length) by coupling our ultrasound measurements with motion capture. We used these data to test the hypotheses that: (1) superficial and deep regions of the free AT would undergo different longitudinal displacements and elongations, and (2) superficial versus deep deformations would become less uniform with faster walking speed.

2. Materials and methods

2.1. Subjects and experimental design

We present data for 10 healthy subjects (age: 23.9 ± 4.0 years, mass: 70.3 ± 12.0 kg, height: 1.76 ± 0.14 m, 4 females and 6 males) who provided written informed consent as per the University of Wisconsin-Madison Internal Review Board. We conducted walking trials on a dual-belt, force-measuring treadmill (Bertec Corporation, Columbus, OH). Subjects walked for 2 min at each of three speeds (0.75, 1.00, 1.25 m/s) to become familiar with the treadmill and to precondition the AT. Subjects then completed a series of 2 min walking trials at each speed as outlined below. An 8-camera motion capture system (Motion Analysis, Corp., Santa Rosa, CA) recorded the 3D positions of retroreflective markers placed as detailed previously [24] on subjects' pelvis and right and left legs at 200 Hz. We recorded electromyographic (EMG) activity at 2000 Hz from single-differential electrodes (Trigno, Delsys, Inc., Boston, MA) placed over the following right leg muscles using recommendations by Cram and Kasman [25]: lateral gastrocnemius (LG), soleus (SOL), and tibialis anterior (TA). Subjects completed the experiment barefoot to facilitate placement of the ultrasound transducer near the calcaneus.

2.2. Ultrasound measurements

Also on the right leg, a single 10 MHz, 38 mm linear array transducer (L14-5 W/38, Ultrasonix Corporation, Richmond, BC) was positioned via a custom orthotic (Fig. 1) over either: (1) the free AT, on average centered 6 cm superior to the posterior calcaneus marker (20 mm depth at 155 frames/s), or (2) the distal LG muscle-tendon junction (MTJ) (30 mm depth at 128 frames/s). These maximum sampling rates depended upon the depth of the tissues of interest. We first randomized the order of transducer locations. Subjects then completed 2 min walking trials at each speed in random order. We selected the LG MTJ so that the transducer would not interfere with the swing leg. We aligned the transducer to capture ultrasound radiofrequency (RF) data from a longitudinal cross-section with an image resolution of 128 × 1560 (0.297 mm × 0.019 mm pixels). Due to a delay introduced as the machine saved RF data, we recorded 5 strides per condition distributed over each 2 min trial. These strides were later identified in our motion analysis data to within 5 ms using a burst waveform from a signal generator triggered by the Ultrasonix system when sampling lines of RF data. We tracked transducer position and orientation using three retroreflective markers placed on the orthotic [4]. The orthotic limited axial rotation of the probe relative to the leg to values (range, 6.3 ± 1.8° at 1.25 m/s) less than those previously published [4].

2.3. Data analysis

We defined strides in the ultrasound and kinematic data using synchronized ground reaction force (GRF) measurements.

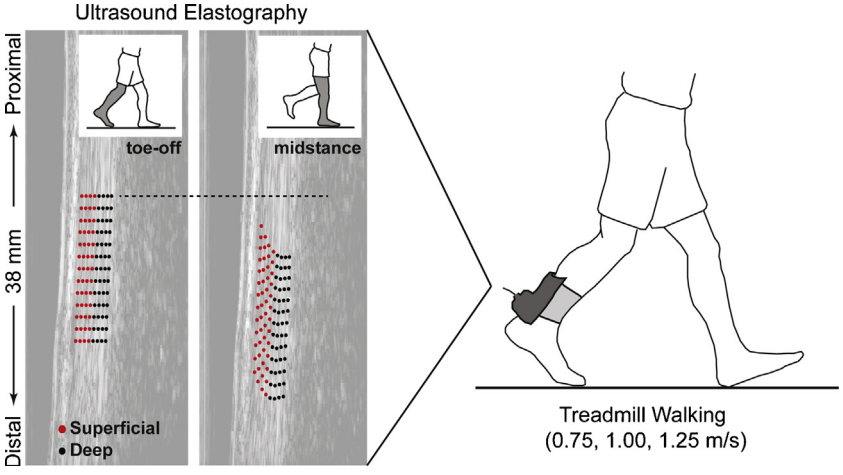

Fig. 1. We used a custom orthotic and 2D ultrasound elastography speckle tracking method to track superficial and deep tissue displacements within the AT on average centered 6 cm superior to the posterior calcaneus marker on the right leg. Subjects walked at three speeds (0.75, 1.00, and 1.25 m/s) on a force-measuring treadmill.