ACHILLES TENDON STRAIN DISTRIBUTIONS DURING CYCLIC INERTIAL LOADING OF THE PLANTARFLEXORS

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INTRODUCTION

Ultrasonic imaging has provided valuable insight into *in vivo* musculotendon function. For example, cine ultrasound images have been used to describe the synergistic length changes of the Achilles tendon and gastrocnemius muscle fascicles during walking [1]. The analysis of ultrasound images, however, is often based on the motion of a single anatomical landmark, such as the muscle-tendon junction. This approach only allows for an average estimate of overall tissue strain. In contrast, recent computational models suggest that highly nonuniform tissue strain patterns can emerge as a result of muscle architectural factors such as fiber pennation, aponeurosis geometry and moment arms [2]. These strain nonuniformities may be important to consider when assessing the biomechanical factors that contribute to partial tendon tears and tendinopathies [3]. In this study, we investigated the use of ultrasound elastography [4] to assess regional strain patterns in the Achilles tendon in response to cyclic inertial loading of the plantarflexor muscles. We hypothesized that the largest strains would be observed along the superficial edge of the tendon, due to variations in the plantarflexor moment arm across the tendon thickness.

METHODS

We constructed a mechanical device that induced inertial loading of the Achilles tendon in response to cyclic ankle dorsi- and plantarflexion (Fig. 1). A rigid footplate rotates about a pivot point aligned with the ankle joint, and is connected with a loading assembly by a kevlar belt. The loading assembly has a high overall gear ratio (30.8:1), such that relatively small inertial disks can induce a substantial load on the lengthening plantarflexors. Five healthy adults were recruited and asked to lie prone on an examination table with their knee extended (~20° of flexion). The foot was then securely strapped into a rigid soled shoe attached to the footplate. Subjects were instructed to cyclically dorsi- and plantarflex their ankle in time with a metronome set to 0.5 Hz. The ankle range of motion was ~30° resulting in a peak plantarflexion moment of ~10 Nm. Raw radiofrequency (RF) ultrasonic data were collected from a 10 MHz linear array transducer (Ultrasonic Corp) at 70 Hz. Data were collected in a 40 by 20 mm image window, positioned such that the superior edge of the calcaneus was visible. Each subject performed three trials, each lasting eight seconds in duration.

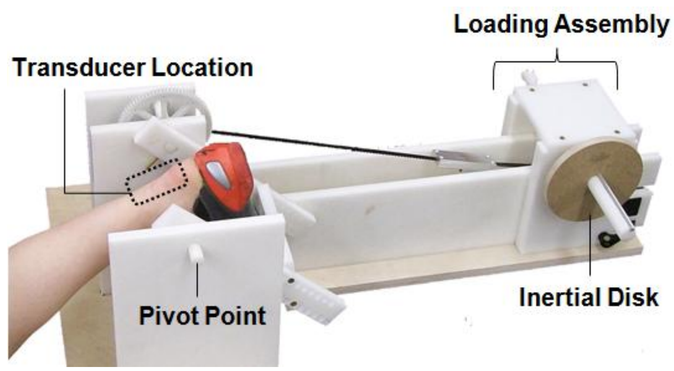

Figure 1. Inertial loading device.

Ultrasonic data were analyzed using a custom elastography algorithm. First, the two-dimensional frame-to-frame displacements of small kernels (0.3 by 1.0 mm) were estimated from the RF data using a statistical cross-correlation approach [5]. A triangular element mesh (edge length of 0.5 mm) was then overlaid onto the visible tendon, and nodal displacements were computed by averaging nearby pixel displacements. Nodal displacements were integrated over time in both the forward and backward directions, and the nodal trajectories were taken as the weighted average of the integration results. Small strain analysis of the nodal trajectories was used to estimate cumulative strain in the along-fiber and transverse directions, with the reference nodal positions chosen as those from the most plantarflexed position.

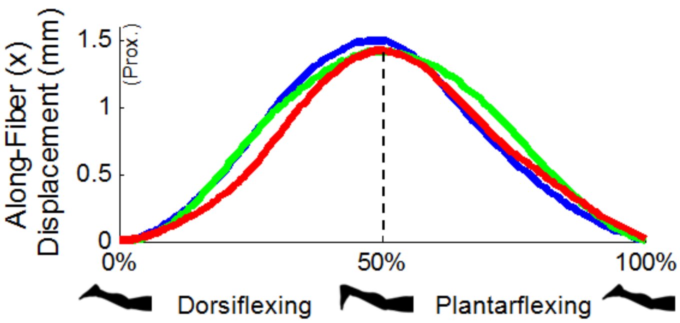

Figure 2. Average tendon motion across successive cycles for one subject.

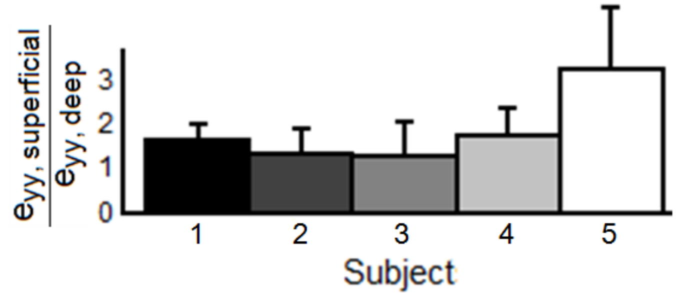

Figure 4. Ratio of the average superficial strain normalized to the average deep tissue strain.

RESULTS

Highly consistent measures of tissue motion were obtained across repeat cycles in both the along-fiber and transverse directions (Fig. 2). The resulting spatial strain distributions exhibited greater strain along the superficial edge of the tendon at the time of peak dorsiflexion (Fig. 3). When the tendon was equally divided into superficial and deep regions, the average superficial strains were from 1.3 to 3.3 times higher than the average strains in the deeper tissue (Fig. 4).

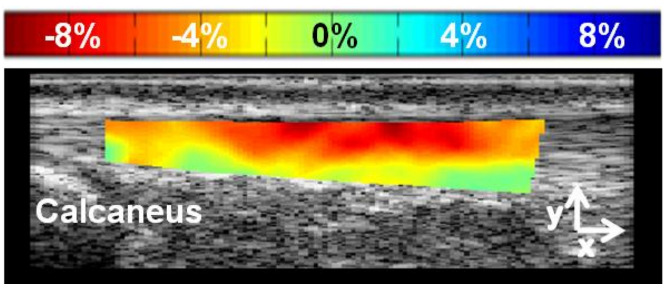

Figure 3. Sample image of transverse (y) strain distributions within the Achilles tendon at the time of peak dorsiflexion.

DISCUSSION

Ultrasound elastography is traditionally used to track tissue motion along the transducer beam direction [4]. High resolution measures of tissue displacement can be obtained by utilizing the phase of raw RF signals to track the movement of speckle patterns. In this study, we leveraged this capability to assess regional variations in tendon strain during cyclic loading of the plantarflexors. As hypothesized, the largest strains were observed along the superficial edge of the tendon. This result could reflect the slightly greater moment arm of the superficial tissue, which requires greater length excursion during dorsiflexion than the deeper tissue. Another potential contributing factor to the strain variations is the relative loading of the gastrocnemius and soleus muscles, which insert onto the superficial and deep portions of the tendon respectively. Varying knee angles would theoretically modulate the relative loading of the gastrocnemius, and provide a mechanism to assess the possible bimuscular loading contributions to nonuniform strains in the Achilles tendon.

Ultrasound elastography may be useful for assessing biomechanical aspects of tendon damage. For example, Achilles tendinosis is often reported to originate on the deep edge of the tendon [6], proximal to the calcaneal insertion. In our study, this region actually exhibited relatively low strains (Fig. 3). While counter-intuitive, it has recently been suggested that localized tendon tissue damage could arise from a stress shielding phenomenon in which under-loaded tissue is insufficiently conditioned to handle overload conditions [3]. Elastographic analysis provides an innovative means to investigate this conjecture. Further, this quantitative imaging technique may enable the tracking of tissue strain variations that occur with remodeling and treatment following injury.

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