Journal of Biomechanics 47 (2014) 2831–2835

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading

Laura Chernak Slane [a,*], Darryl G. Thelen [a,b,c]

[a] Department of Biomedical Engineering, University of Wisconsin-Madison, WI, USA
[b] Department of Mechanical Engineering, University of Wisconsin-Madison, WI, USA
[c] Department of Orthopedics and Rehabilitation, University of Wisconsin-Madison, WI, USA

ARTICLE INFO

Article history:
Accepted 31 July 2014

Keywords:
Achilles tendon
Non-uniform motion
Ultrasound elastography

ABSTRACT

The goal of this study was to investigate Achilles tendon tissue displacement patterns under passive and eccentric loading conditions. Nine healthy young adults were positioned prone on an examination table with their foot secured to a rotating footplate aligned with the ankle. Subjects cyclically rotated their ankle over a 25° range of motion at 0.5 Hz. An inertial load geared to the footplate induced eccentric plantarflexor contractions with dorsiflexion. Passive cyclic ankle motion was also performed over the same angular range of motion. An ultrasound transducer positioned over the distal Achilles tendon was used to collect radiofrequency (RF) images at 70 frames/s. Two-dimensional ultrasound elastographic analysis of the RF data was used to track tendon tissue displacements throughout the cyclic motion. Non-uniform tissue displacement patterns were observed in all trials, with the deeper portions of the Achilles tendon consistently exhibiting larger displacements than the superficial tendon (average of 0.9–2.6 mm larger). Relative to the passive condition, eccentric loading consistently induced smaller tissue displacements in all tendon regions, except for the superficial tendon in a flexed knee posture. Significantly greater overall tissue displacement was observed in a more extended knee posture (30°) relative to a flexed knee posture (90°). These spatial- and posture-dependent displacement patterns suggest that the tendon undergoes non-uniform deformation under in vivo loading conditions. Such behavior could reflect relative sliding between the distinct tendon fascicles that arise from the gastrocnemius and soleus muscles.

1. Introduction

The frequency and type of tendon loading is an important determinant of injury potential and mechanobiological responses. For example, Achilles tendinopathies are most commonly observed in individuals involved in activities that subject the tendon to repetitive loading (e.g., running) (Maffulli et al., 2003). It has been hypothesized that this repetitive loading gives rise to the localized fibrillar damage and tissue degeneration that develops in tendinopathies (Riley, 2008). However, somewhat paradoxically, exercises involving repeat eccentric loading of the injured tendon have shown effectiveness in treating some individuals with mid-substance tendinopathies (Alfredson, 2003; Fahlstrom et al., 2003; Maffulli et al., 2008). Although the underlying mechanism of this conservative treatment is not well understood, it is believed that the shear loading induced via eccentric exercises may stimulate the tenocytes to induce anabolic responses (Fong et al., 2005; Maeda et al., 2011). These observations highlight the importance of understanding tissue deformation patterns that arise from different in vivo loading paradigms.

There is increasing recognition that architectural features can give rise to complex deformation patterns within tendons. For example, micromechanical studies have demonstrated that tendon tissue stretch likely involves a combination of fascicle stretch and inter-fascicle sliding (Thorpe et al., 2013, 2012). These observations are highly relevant to the Achilles tendon, which consists of distinct fascicles arising from the soleus, medial gastrocnemius and lateral gastrocnemius muscles (Szaro et al., 2009). Distally, the architecture of the Achilles tendon is characterized by a helical twist which causes the relative positioning of these fascicles to vary along the Achilles length. In the mid-substance of the free Achilles tendon, the fascicles from the medial gastrocnemius are located in the superficial portion of the tendon, and fascicles from the soleus are primarily in the mid and deep portions of the tendon (Szaro et al., 2009). This complex architecture, paired with independent loading from the soleus and gastrocnemius muscles (Arndt et al., 1999; Ivanenko et al., 2004; Winter and Yack, 1987), contributes to the potential for development of non-uniform deformation in the free Achilles tendon.

---

* Correspondence to: Department of Biomedical Engineering, 1513 University Ave, Madison, WI 53705, USA. Tel.: +1 608 603 6692; fax: +1 608 265 2316.
E-mail address: laura.c.slane@gmail.com (L.C. Slane).

http://dx.doi.org/10.1016/j.jbiomech.2014.07.032
0021-9290/© 2014 Elsevier Ltd. All rights reserved.

Quantitative ultrasound techniques have recently emerged that allow for the assessment of in vivo behavior of the Achilles tendon. For example, prior studies have used ultrasound-based manual tracking of anatomical landmarks to show that different amounts of strains are taken up by the free tendon and aponeurosis (Arampatzis et al., 2005; Magnusson et al., 2001, 2003, 2001). Along-tendon non-uniform deformation could arise from variations in loading along the aponeurosis (Finni et al., 2003) as well as spatially varying tendinous tissue stiffness (DeWall et al., 2014). However, much less is known about spatial variations in tendon deformation across the tendon thickness. A prior study using ultrasound speckle tracking discovered variations in tissue displacement between the superficial, mid and deep layers of the Achilles tendon during passive stretch (Arndt et al., 2012), which suggested the existence of differential stretch in tendon fascicles that originate in the soleus and gastrocnemius muscles. It is likely that such behavior could vary with active muscle loading and limb posture, given that knee flexion shortens gastrocnemius muscle-tendon operating lengths. Indeed, prior studies have shown that gastrocnemius contributions to ankle plantarflexor strength are greatly reduced in flexed knee postures (Arampatzis et al., 2006; Cresswell et al., 1995).

The goal of this study was to use ultrasound elastography (Chernak and Thelen, 2012; Slane and Thelen, 2014) to measure Achilles tendon displacement patterns under both passive and eccentric loading conditions in two knee postures. We hypothesized that eccentric loading would induce more non-uniform tendon motion than observed under passive stretch. We also hypothesized that knee posture would alter relative tendon tissue motion between the soleus and gastrocnemius portions of the Achilles tendon, due to a posture-induced change in loading sharing between gastrocnemius and soleus fascicles. Specifically, we hypothesized that when the knee is extended, distal tendon tissue motion would increase in the more taut gastrocnemius muscle-tendon unit.

2. Methods

Nine healthy young adults (5 F/4 M; 24 ± 1 yrs) with no self-reported history of Achilles tendon injury were recruited for this study. Written consent was obtained from each subject as per our Institutional Review Board requirements prior to testing. Subjects were first asked to walk at a comfortable pace for six minutes to pre-condition the plantarflexor muscle-tendon units (Hawkins et al., 2009). Subjects were then positioned prone on an examination table with their foot secured in a rigid shoe, which was then attached to a rotating footplate (Fig. 1). Care was taken to adjust the axis of the footplate to ensure that it aligned well with the sagittal ankle axis of rotation. The footplate was coupled via a stiff belt and gear-train to rotating inertial disks. Eccentric plantarflexor activity was used to decelerate the rotating disks as the ankle moved toward peak ankle dorsiflexion. Loads were recorded using two load cells (LCM300 Futek, Irvine, CA) mounted on the belts of the loading assembly and recorded at 1000 Hz. Ankle angle was simultaneously recorded using an encoder mounted on the foot-plate rotation shaft. Load cell and encoder data were subsequently used in post-hoc inverse dynamic analyses to compute the internal sagittal ankle moment.

Subjects performed eccentric and passive ankle trials at fixed knee flexion angles of 30° and 90°, referred to as extended and flexed knee postures, respectively. In eccentric trials, subjects were asked to cyclically dorsi- and plantarflex their ankle between 0 and 30° of plantarflexion at a rate of 0.5 Hz. Assuming the subject performs the task sinusoidally, the task induces a peak angular speed of ~90 °/s in the middle of the range of motion. A metronome was used to guide the cyclic rate, and subjects were provided real-time angular feedback to maintain the desired range of motion. Inertial disks on the loading device induced eccentric ankle plantarflexor moments, with the peak load of ~30 Nm occurring when the subject was near their most dorsiflexed position. For both knee angles, inactive passive trials were also conducted in which a researcher guided the ankle through the same range of motion at the same cyclic rate as in the eccentric loading trials. Subjects were instructed to remain relaxed in the passive trials and the researcher monitored the footplate loading to ensure compliance. Trial order was randomized, and subjects were given one minute of practice with each loading condition prior to data collection.

Rectangular ultrasound standoff pads ($178 \times 127\ \text{mm}^2$, 16 mm thick) were created by heating a commercial pad (Aquaflex, Parker Laboratories, Fairfield, NJ) and letting it settle in a mold. The standoff pad was placed over the Achilles tendon and secured with an elastic ankle brace. A 10 MHz linear array transducer was then manually positioned to image the Achilles tendon, with the inferior edge of the transducer positioned just superior to the superior edge of the calcaneus (Fig. 1b). For each test condition, three eight-second trials of cine ultrasound radiofrequency (RF) data were collected of the Achilles tendon at 70 frames/sec. All trials were then visually reviewed to ensure that out-of-plane motion was small and that tendon fascicles remained in view throughout loading. At least one trial for each of the subjects and for each of the loading conditions met the required criteria and was included in the analysis.

Tissue displacements were computed retrospectively from the RF data. Tissue tracking was performed using a 2D cross-correlation based elastography technique that has been described previously (Chernak and Thelen, 2012), and validated in phantom and *ex vivo* experiments (Chernak and Thelen, 2012; Slane and Thelen, 2014). Briefly, ankle angle data were used to define each cycle of motion, with the most plantarflexed position designated as the cycle start. To ensure that only tendinous tissue was

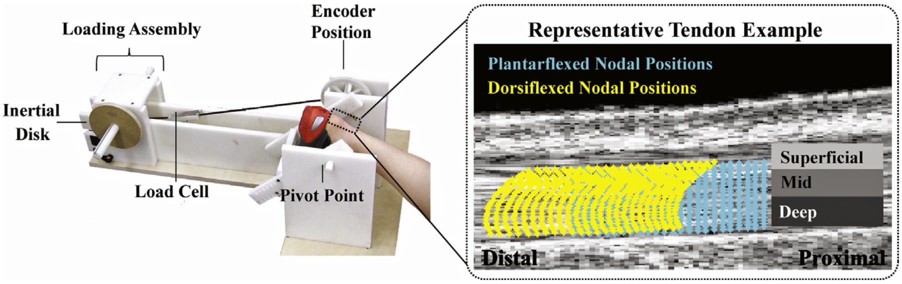

Fig. 1. An overview of the experimental setup and image analysis. Inertial disks were used to induce eccentric plantarflexor contractions when moving from a plantarflexed to dorsiflexed position. An ultrasound transducer placed over the distal Achilles tendon was used to collect RF data throughout the cyclic trials. In post-hoc analysis, initial nodal positions were defined within the tendon from an image collected in the most plantarflexed position. Two-dimensional elastography was then used to track the subsequent motion of nodes located in superficial, mid and deep portions of the tendon.