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Assessing non-uniform stiffening of the achilles tendon noninvasively using surface wave

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ABSTRACT

Currently, noninvasive cost-effective techniques capable of quantifying non-uniform degradation of tendon's mechanical and structural properties associated with localized tendon injuries are not readily available. This study demonstrates the applicability of a simple surface-wave elastography (SURF-E) method for assessing the stiffness of the Achilles Tendon by measuring the propagation velocity of surface waves along the tendon in a much broader range of values than currently available Ultrasound-based or MRI-based elastography methods do. Results from this study confirm the non-uniform stiffening of the AT during passive ankle dorsiflexions.

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1. Introduction

The Achilles tendon (AT) is the most commonly injured ankle tendon and the major causation factor is overuse (excessive loading) although it is the strongest tendon in the human body Maffulli et al. (2004). The number of AT injuries, such as tendinopathy and rupture, has been increasing exponentially in Western countries with an incidence rate of 2.5 per 1000, and is often related to athletic activity Jarvinen et al. (2005) and Hoffer and Maffulli (2007). Tendinopathies are typically associated with localized degradations of the AT structure, such as abnormal collagen-fiber structure, fatty infiltrations, hypercellularity, nerve ingrowth, neovascularization, and increased glycosaminoglycans between the tendon fibrils Maffulli et al. (2004) and Jarvinen et al. (2005). These degradations, commonly occurring at mid-portion of AT but also at the distal heel bone-tendon junction (calcaneal enthesis), have been linked to decreased mechanical properties such as localized AT softening Maffulli et al. (2004) and Jarvinen et al. (2005). Since tendon structure and composition are difficult to quantify non-invasively, changes in AT mechanical properties (e.g. stiffness) can be used as equivalent biomarkers of tendon health and function. However, clinical practitioners can only assess the morphology of symptomatic AT using B-mode US or MR imaging alone Paavola et al. (1998), Hoffer and Maffulli (2007) and Åström et al. (1996). Hence, quantitative measurements of the spatial variations of AT mechanical properties, such as AT stiffness, would provide more relevant and reliable information for guiding treatment strategies that is not provided by morphologic assessment alone.

One promising approach for non-invasively measuring stiffness distribution of soft-tissues in vivo is elastography Greenleaf et al. (2003). Clinical applicability and significance of various elastography modalities (e.g. MR-based, US-based) has been explored and discussed for the detection of breast cancer Tanter et al. (2008), liver fibrosis Foucher et al. (2006), and musculoskeletal activity Yoshitake et al. (2014), Shinohara et al. (2010) among others. However, AT can be several orders of magnitude stiffer compared to muscles and other softer tissues (breast, liver) when loaded Greenleaf et al. (2003), Hoffer and Maffulli (2007) and Maganaris and Paul (2002). Furthermore, the slender AT has a very small cross-section (only a few mm) Maffulli et al. (2004) and Jarvinen et al. (2005). Consequently, simple biomechanical model assuming free space propagation of elastic shear waves are not applicable for this geometry; instead assuming propagating waves along a thin rod model is more realistic to invert for actual stiffness parameters Martin et al. (2018). Hence this brings unique challenges for existing elastography methods. We also find limitations in the clinical applicability of existing US-based elastography for quantitative diagnosis of AT stiffness variations Klauser et al. (2013) and DeWall et al. (2014). Studies on patients with lateral epicondylitis and Achilles tendinopathy have revealed tendon softening in symptomatic ATs relative to healthy control ATs De Zordo et al. (2010), Turan et al. (2013) and Zordo et al. (2009), but their proposed static elastography approach had repeatability limitations due to user-dependent variations and could not provide absolute measurement of local stiffness but only relative changes. A pilot

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study recently explored the clinical utility of the shear-wave elastography method in the assessment of asymptomatic and ruptured Achilles tendon Chen et al. (2013), but due to implementation choices, the upper stiffness measurement limit of this shear-wave elastography method is too low for measuring AT stiffness during stretching and even at rest (e.g. dorsiflexed position), thus limiting its diagnosis capability Aubry et al. (2013), Chen et al. (2013), Aubry et al. (2014) and DeWall et al. (2014). To address these limitations, this paper demonstrates the capability of the surface-wave elastography (SURF-E) method to provide quantitative baseline measurements of the non-uniform stiffening of the AT occurring from the musculotendon junction to the calcaneus insertion over a significantly wider range of stiffness for various ankle joint positions when compared to previously tested elastography methods. Based on transient elastography principles Greenleaf et al. (2003), DeWall et al. (2014) and Martin et al. (2018), actual AT stiffness could be inferred from velocity for a given biomechanical model, but strong simplifying assumptions must be made regarding the mechanical behavior of the tested tendon and the nature of propagating waves (e.g. surface waves vs. bulk shear waves). Practically speaking, however and based on previous elastography studies Salman et al. (2014), DeWall et al. (2014) and Aubry et al. (2013), we assume here that measuring relative variations of the surface wave propagation velocity provides a simple means to quantify relative changes of the mechanical state of the AT across various conditions within individuals. We have recently demonstrated the applicability of the SURF-E method for contracting muscle Salman et al. (2014). This letter is

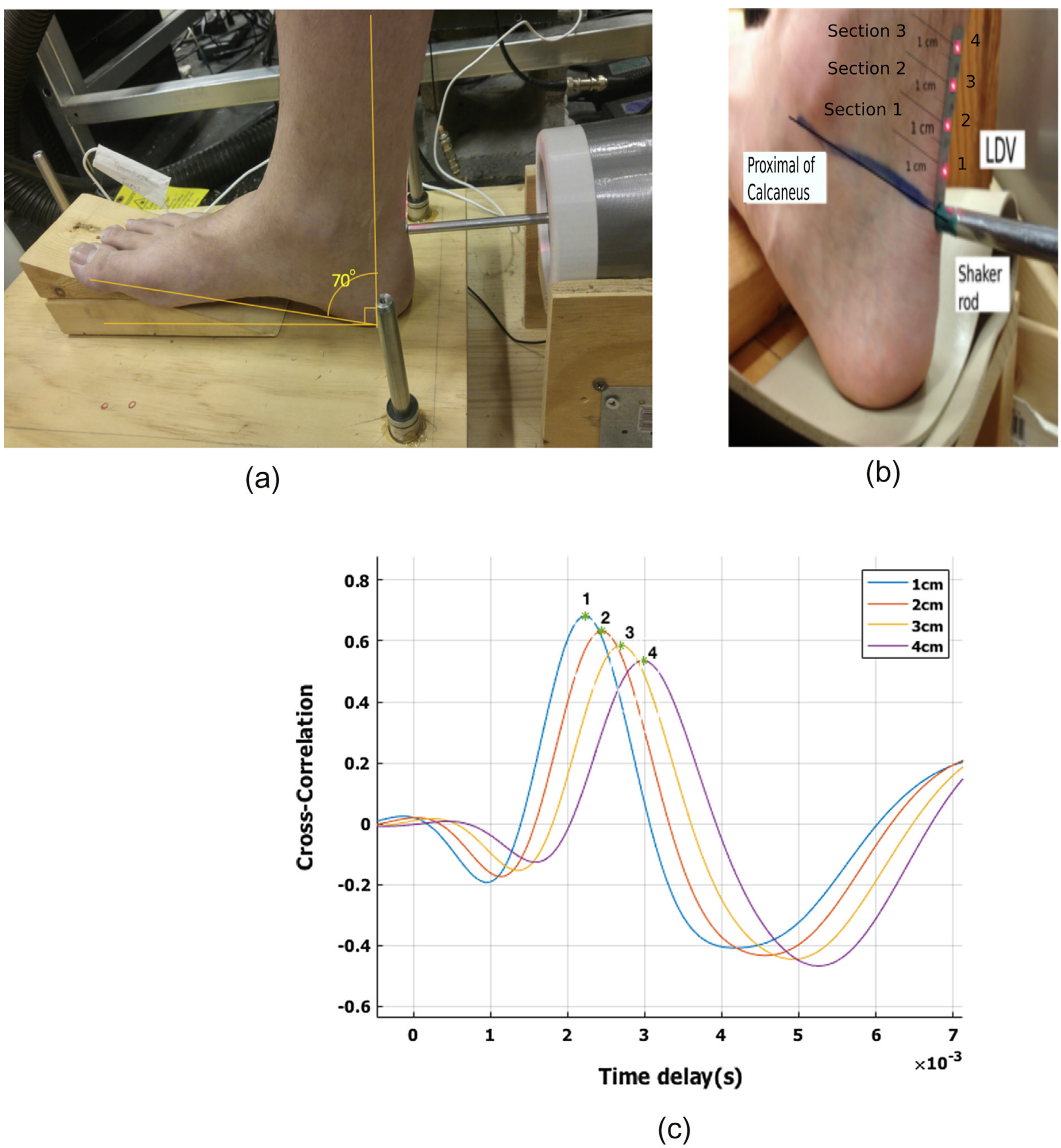

Fig. 1. (a) Experimental set-up. (b) Sections of the AT used in this study. (c) Measured surface-wave pulse with the LDV as it successively propagates away from the distal end along the four positions marked on the AT line as shown in (b).

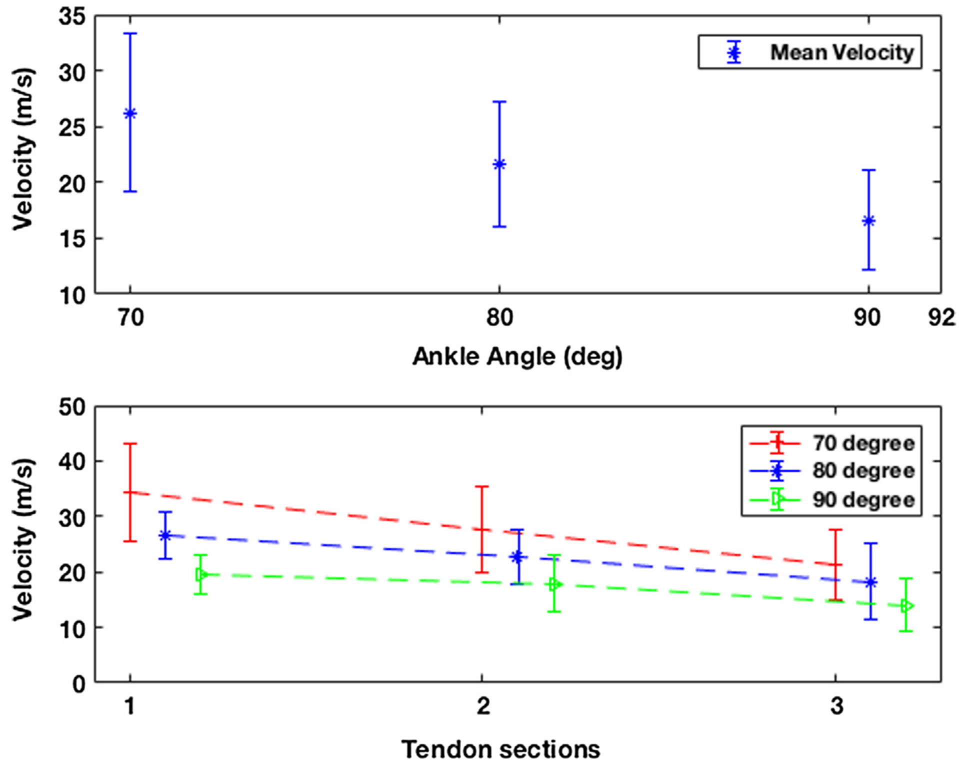

Fig. 2. For 10 subjects. (a) (Top) Mean velocity measurements along the AT at three ankle joint's angles. (b) (Bottom) Spatial velocity variations at three sections along the AT.

the first attempt to systematically examine the applicability of SURF-E to AT for an order of magnitude higher stiffness values (up to Young's Modulus of 100 MPa). This method could provide a fundamental understanding of how stiffness measurements can be used to differentiate healthy vs. symptomatic ATs and could be applicable to diagnose other tendons. Furthermore, developing a low-cost, single LDV-based SURF-E modality as an alternative to using expensive US scanner could broaden the acceptance and clinical usage of elastography for AT's diagnosis and monitoring of AT's mechanical recovery post-surgery.

2. Method

Ten healthy volunteers (Men and women; age: 22 ± 5 years, height: 175 ± 9 cm, body mass: 72 ± 8 kg) with no signs of neuromuscular diseases volunteered for this study approved by the Institutional Review Board (IRB) of the Georgia Institute of Technology. The ankle joint's angle was set to three different values 70°, 80° and 90° using various wedges (Fig. 1a), and the actual angles were verified with a goniometer. Furthermore, in order to limit motion artifacts, the subject's leg was restrained in a fixture around the calf by the help of a strap and a clamp.

The Achilles tendon was marked at five position, each 1 cm apart starting from the datum line parallel to the proximal of calcaneus bone as shown in Fig. 1b. The measurement line along the AT was divided into 3 sections starting from 1 cm above the datum line in order to assess the spatial variations of the AT stiffness. The SURF-E method uses a skin-mounted vibrating probe to excite superficial tissues with a transient mechanical impulse and simultaneously measure its propagation velocity along the tendon fiber direction externally above the AT along the skin-surface using a non-contact laser Doppler vibrometer (LDV). Specifically, to do so the rod of electrodynamic mini-shaker (model 4810, Bruel & Kjaer, Naerum, Denmark) was placed on the first position, nearest to the calcaneus bone and was actuated to generate band pass filtered frequency (5–1000 Hz) sine sweep signal for one second long duration. The data was acquired using the LabVIEW program sampled at 100 kHz and processed in MATLAB. The SURF-E measurements were performed on these ten subjects using the similar SURF-E procedure as described in detail in Salman & Sabra Salman et al. (2014) and previously validated using soft gel samples Salman and Sabra (2013, 2012) using a Laser Doppler Vibrometer (PDV 100, Polytec, Irvine, CA, USA) illuminating a long thin retro-reflective adhesive tape (3 M) placed along the measurement line to ensure sufficient laser light reflectivity. LDV beam was aimed perpendicular to the skin-surface. Measurements of the surface wave velocity along the ATs were performed for each subject for three different ankle joint position (70°, 80° and 90°). The measurements were made in a randomized order.

3. Results and discussion

Fig. 1(c) displays the measured surface-wave pulse with the LDV as it successively propagates away from the distal end along the four positions marked on the AT line (see Fig. 1b). The slope of a linear fitting of the four peak arrival times yields the average surface-wave velocity value along the overall AT section. Furthermore, measuring the differential arrival times between each adjacent position yields an estimate of the individual velocity values for each of the three sections in Fig. 1(b) and thus provide a means to assess the spatial velocity variations along the AT.

Fig. 2(a) shows the mean and standard deviation values over the 10 subjects for the average surface-wave velocities as a function of the ankle joint's angle. The measured velocity values in Fig. 2(a) for three ankle joint's angles range from (10–40 m/s) which is in agreement with previously reported results Brum et al. (2014), Ooi et al. (2014), Gibbon et al. (2000), Aubry et al. (2014), DeWall et al. (2014) and Martin et al. (2018). Higher standard deviation in Fig. 2(a) at 70° ankle position as compared to the other two flexion positions may be due to the inherent variability of stiffness of AT including skin, subcutaneous fat and the complexity of the internal transverse isotropic structure at stiffer level. Fig. 2(a) verifies that as the ankle joint's angle decreases, the AT becomes stiffer due to passive dorsiflexion and the surface wave velocity increases accordingly.

Fig. 2(b) indicates that, for each ankle joint's angle, the shear wave velocity gradually decreases along the axis of the AT. Section 1, near the calcaneus bone, has a higher velocity as compared to the Sections 2 and 3 towards the calf muscle. Furthermore, Fig. 2 (b) shows that the SURF-E technique is sensitive enough to measure slight spatial variations of the AT stiffening.

4. Conclusion

Developing a low-cost, LDV-based SURF-E could provide an alternative elastography modality that could broaden the acceptance and clinical usage of transient elastography methods for AT's diagnosis and monitoring the mechanical recovery of injured ATs. This method appears as a potentially robust, repeatable and reliable technique in young healthy volunteers. Besides, it uses a less complex setup compared to other US-based or MRI-based elastography modalities. Hence, this SURF-E method could assist the injury risk assessment and patient-specific selection of treatment plans for tendinopathy as well as the monitoring the efficiency of therapeutic exercise programs which could diminish health care costs associated with the exponentially increasing number of AT injuries. As another advantage of the SURF-E method is that it can be performed in near real-time (< 5 s) and thus could readily be used to monitor the evolution of the AT stiffness before and after short exercise or loading conditions of the AT for instance, in order to better understand the instantaneous AT response and its stiffness variations caused by brief acute loading. One limitation of the SURF-E method compared to US-based or MRI-based elastography is that it is one-dimensional and can only assess the overall stiffness of the tendon across its-cross section with no depth discrimination; but this is likely to not be a significant factor as the skin and fat layer above the AT is very thin and thus not significantly affect the wave propagation at those low frequencies (<1 kHz).

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication.

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