Original article

Side-to-side differences in Achilles tendon geometry and mechanical properties following achilles tendon rupture

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Summary

***Background*: Recovery of tendon structure has been suggested to play a role in clinical success following Achilles tendon rupture. The purpose of this study was to identify side-to-side differences in tendon geometry and mechanical properties following Achilles tendon rupture and investigate the relationship of tendon structure with clinical outcomes.**
***Methods*: Participants within 1 year post complete rupture were included. Tendon geometry and mechanical properties were quantified using B-mode ultrasound imaging and continuous shear wave elastography (cSWE). Clinical outcomes included the heel-rise test. Participant self-reported function was measured using the Achilles tendon Total Rupture Score, Foot and Ankle Outcome Score - quality of life subscale, and the Physical Activity Scale.**
***Results*: Twenty participants [mean (SD) age: 42.7(13.6) years, 13 managed surgically] were included. Tendon thickness was greater on the ruptured side (p <0.001) [median (IQR) rupture: 1.38(1.21-1.56) cm, non-rupture: 0.49(0.40-0.52)]. Tendon length to the gastrocnemius was longer (p <0.001) on ruptured [22.8 (21.71-24.31) cm] than non-ruptured [21.66(20.74-23.62) cm] sides. Viscosity was lower on the ruptured side (p <0.001) [median (IQR) rupture: 37.7(30.6-43.3) Pa*s, non-rupture: 53.5(48.4-59.6) Pa*s]. Shear modulus was not different between sides. Tendon thickness (rho = 0.675, p = 0.002) and shear modulus (rho = -0.791, p = 0.001) related to total work on the heel-rise test.**
***Conclusion*: Ultrasound imaging, including cSWE, can be used to detect side-to-side differences in tendon structure in individuals with Achilles tendon rupture and tendon structure relates to clinical performance.**
Level of evidence: III b.

KEY WORDS: ankle, elastography, imaging, rehabilitation, ultrasound, viscoelastic.

Introduction

Outcomes following Achilles tendon rupture are highly variable. For instance, a prior study reported some patients being unable to perform a hopping task on their injured side at one year post-injury, while other patients were able to regain over 100% of their hopping capacity compared to the uninjured side[1]. Body mass index (BMI) and sex[2] have been associated with patient outcomes, but much of the variability between individuals remains unaccounted for even when treatment regimens are standardized[3]. Differences in outcomes appear within the first 3 months after rupture and remain throughout recovery. Prior studies have identified significant functional recovery 3 to 6 months post-injury, with smaller functional gains between 6 and 12 months[3,4]. No functional improvements and continued side-to-side deficits have been reported 1 to 2 years post-injury[1]. Detecting individual differences early in recovery requires the clinician to rely on objective, measurable outcomes to identify patients at risk for poor outcomes. Being able to identify patients with a poor prognosis within the first 3 months post-injury would provide the health-care professional the opportunity to intervene and hopefully improve a patient's potential for full functional recovery.
There are few objective tools to guide clinical decision-making at this key, early phase of recovery. Functional testing, such as the heel-rise test and jump testing[5] have been used in the mid to late stages (5+ months) of recovery. Performance of

these tests can be problematic in the early (0-4 months) stages of rehabilitation due to floor effects as they rely on unilateral lower extremity tasks. For example, at three months post-rupture, only 50% of individuals are able to complete a single, unilateral heel-rise[6]. Assessing tendon structure – including both geometrical and mechanical properties – following rupture has been suggested to fill this void[7-9].

Animal studies have identified differences in tendon structure throughout the healing course[10,11]. Tendon stiffness and ultimate stress, but not elastic modulus, was found to respond to different tendon loading protocols in rats[10]. A study by Freedman, et al., identified differences in mechanical properties with regard to surgically *versus* non-surgically managed tendons as well as with timing of activity[11]. Tendon cross-sectional area has been found to increase with healing post-tendon transection in rats, particularly with increasing amounts of tendon load[10-12]. Differences in tendon geometry and mechanical properties between treatment groups points to the importance of quantifying these properties to guide clinical decision-making.

In humans, quality of tendon tissue – evidenced by characteristics of tendon structure and mechanical properties – have been found to contribute to regaining function in later phases. Structurally, tendon elongation occurs within 3 months post-rupture[13] and is associated with deficits in heel-rise height on the heel-rise test at 6 and 12 months post-rupture[8]. From a mechanical property standpoint, early recovery of elastic modulus measured by Roentgen stereophotogrammetric analysis (RSA) at 7 weeks post-injury correlated with performance on the heel-rise test at 19 weeks[9]. However, assessment of mechanical properties of tendon tissue has not been without its challenges. Techniques to measure mechanical properties often require loading of the tendon with muscle contraction[14] or invasive techniques[9], limiting their clinical application particularly early post-injury.

To overcome these obstacles, non-invasive ultrasound techniques have been proposed to measure tendon mechanical properties *in vivo*. Shear wave elastography has been applied to the Achilles tendon rupture population in one study[7], and has been found to relate to elastic modulus with tensile testing[15]. Continuous shear wave elastography (cSWE) has been developed[16] and utilized in assessment of Achilles tendons in a healthy population[17], and has been applied to Achilles tendon rupture in a case study[18]. This technique uses an external actuator to generate a vibration in the tendon. As the vibration travels down the tendon, linear displacement of tendon tissue is recorded using ultrasound imaging. From this information, the speed of shear wave propagation is calculated and used in a biomechanical model to estimate tendon shear modulus and viscosity. Therefore, the purpose of this study is two-fold. First, we aim to identify side-to-side differences in tendon shear modulus and viscosity following Achilles tendon rupture using cSWE. Second, we aim to investigate the relationship of tendon mechanical properties measured using cSWE to tendon geometry as well as clinical and functional outcomes in individuals following Achilles tendon rupture.

Materials and methods

Study Design and Subject Selection

This cross-sectional study included data from a subgroup of participants included in a larger, prospective study of individuals with Achilles tendon pathology between November 2014 and June 2016. Data from individuals within 12 months following unilateral Achilles tendon rupture were included. Data were excluded for participants with tendon laceration (n=2), repair complicated by deep wound infection (n=1), or history of contralateral Achilles tendon rupture (n=1). This study was conducted with the approval of the Universal of Delaware institutional review board. This study meets the ethical standards of this Journal[19].

Quantification of Tendon Structure

Tendon structure was measured using B-mode ultrasound imaging. The participant was positioned in prone with feet hanging off the side of a plinth in resting position. To measure Achilles tendon length, a mark was made on the skin between the medial and lateral gastrocnemius. The probe was positioned in long axis to the Achilles tendon over the midpoint of the calcaneus and then moved to the mark between gastrocnemius heads. Achilles tendon length from insertion to the gastrocnemius myotendinous junction was measured using extended field of view settings (GE LOGIQ e, GE Healthcare, Chicago, IL[20]. Tendon thickness was measured in long axis at the region of interest – either the rupture site or the anatomical equivalent on the uninjured side – by drawing a line from the superficial to deep fascial lines. For both tendon length and thickness, an average of three measures was used for analysis.

Tendon shear modulus and viscosity were quantified using cSWE as described in detail by Cortes et al[16,17] using an ultrasound scanner (MDP, Ultrasonix, Vancouver, Canada) with a L14-5/38 transducer and external data acquisition unit (DAQ). This technique uses an external actuator to propagate a shear wave along the length of the Achilles tendon. The participant is positioned in prone with their feet secured against a footplate set at 10° dorsiflexion. An ultrasound probe is placed at the region of interest, either the rupture site or the anatomical equivalent of the rupture site on the uninjured side, and linear displacement of the tissue is captured using ultrasound imaging. From this data, speed of shear wave propagation is calculated and then used in the Voigt model to approximate tendon shear modulus and viscosity. The average values for shear modulus and viscosity within the region of interest were used in data analysis.

cSWE Test-retest Reliability Study

Nineteen individuals with healthy Achilles tendons were included in this test-retest reliability study. Three trials of cSWE were performed for both the test and re-test conditions and the average of these measures was used for data analysis. For the re-test condition, cSWE was repeated at the same location on the tendon after a break of no longer than 10 minutes. The mean (SD) for shear modulus was 94.8 (16.4) kPa for the test and 95.0 (16.1) kPa for the re-test condition. The mean (SD) for viscosity was 57.8 (13.6) Pa*s for the test and 55.4 (12.7) Pa*s for the re-test condition. Intraclass correlation coefficients (ICC) and standard error of measurement (SEM) were calculated[21]. The ICC was found to be 0.67 for shear modulus and 0.80 for viscosity. The SEM was found to be 9.4 kPa for shear modulus and 6.04 Pa*s for viscosity.

Measurement of Clinical Outcomes

Achilles tendon resting angle was measured using an inclinometer on the plantar aspect of the participant's foot, with the knee flexed to 90°[22]. Maximum calf circumference was measured using a tape measure. Lower leg function was assessed using the heel-rise test as described by Silbernagel et al.[23]. In this test, unilateral heel-rises are performed at a rate of 30 per minute on a 10° incline until fatigue (Fig. 1). Participant self-reported level of function was evaluated using the Achilles tendon total rupture score (ATRS)[24], the Foot and Ankle Outcome Score - quality of life subscale[25], and activity level was assessed using the Physical Activity Scale (PAS)[26].

Figure 1. Set-up for the heel-rise test.

Statistical analysis

Due to the nonparametric nature of the data and small sample size, statistical analysis was performed using nonparametric tests. For quantitative variables, the median and interquartile range (IQR) are reported. The Spearman correlation coefficient was used for correlation analyses. The difference between rupture and non-rupture sides and the difference between pre and post activity levels were evaluated with Wilcoxon Signed Rank test. Effect sizes were calculated by dividing the Z-score from the Wilcoxon Signed Rank test by the square root of the number of samples. To determine the difference in time since injury and thickness for participants grouped by nominal variable, an independent samples Mann-Whitney U Test was used. Limb symmetry indexes (LSI) were calculated by dividing the value for the ruptured side by the value of the non-ruptured side (ruptured side/non-ruptured side * 100).

Results

Subject Demographics

Data from 20 participants (15 males, 5 females) were included. Participants had a mean (SD) age of 42.7 (13.6) years with the left side injured in 16 and the right side injured in 4 participants. All participants were between 2 and 12 months post complete Achilles tendon rupture [median (IQR) of 4.6 (3.1-6.6) months]. Seven participants had non-surgical and 13 had surgical treatment. Participants rated their activity prior to injury as a median (IQR) of 5.5 (4.5-6.0) prior to injury and 3.5 (3.0-4.5) on the Physical Activity Scale at the time of evaluation. There were no statistically significant differences between surgically and non-surgically managed participants for any measurement on the ruptured side or any change score.

Tendon Structure

Tendon thickness was significantly greater on the ruptured side ($p < 0.001$) with a median (IQR) of 1.38 (1.21-1.56) cm on ruptured and 0.49 (0.40-0.52) cm on healthy sides (Fig. 2). Tendon length to the gastrocnemius myotendinous junction was also significantly longer ($p < 0.001$) on ruptured [median (IQR) 22.85 (21.71-24.31) cm] than non-ruptured [21.66 (20.74-23.62) cm] sides.

Viscosity was significantly lower on the ruptured side ($p = 0.001$), with a median (IQR) of 37.7 (30.6-43.3) Pa*s on ruptured and 53.5 (48.4-59.6) Pa*s on non-ruptured sides, with a large effect size of 0.691. The difference in viscosity between sides surpassed the SEM in 17 individuals, with the ruptured side being lower than the non-ruptured side in 15 of the 17 cases. Shear modulus was not significantly different between sides with a median (IQR) of 94.3 (82.4-106.1) kPa on ruptured and 94.2 (90.6-113.2) kPa on non-ruptured sides, with a small effect size of 0.042. The

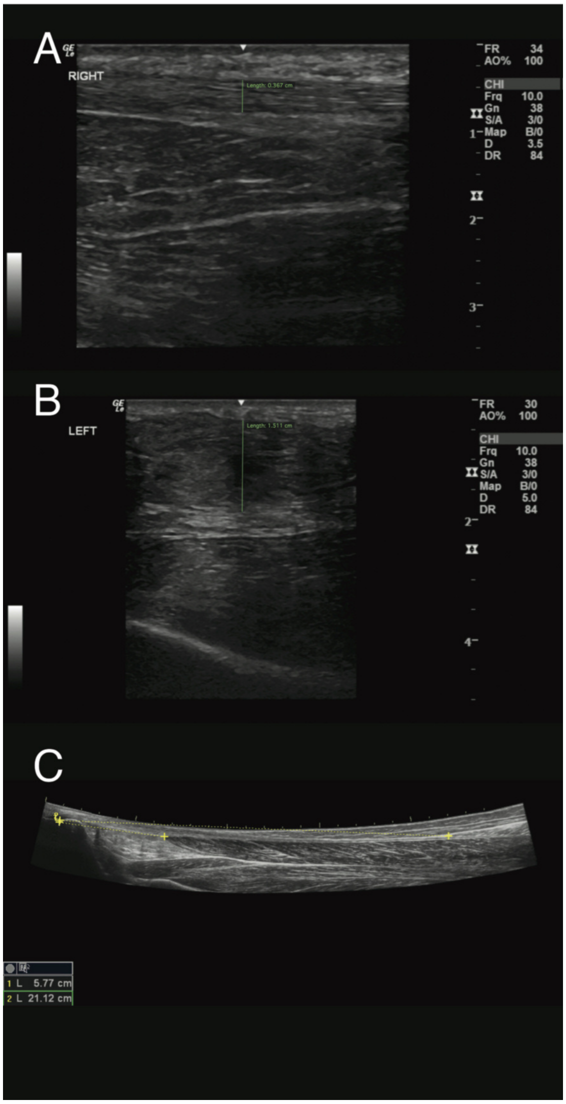

Figure 2. B-mode ultrasound images with measurement lines for A. tendon thickness in a non-ruptured tendon, B. tendon thickness in a ruptured tendon, and C. tendon length to gastrocnemius myotendinous junction.

difference in shear modulus between sides surpassed the SEM in 15 of 20 individuals. In 8 individuals (40% of total participants), shear modulus was lower on the ruptured side, and in 7 individuals (35% of total participants), the shear modulus was higher on the ruptured side.

Clinical Outcomes

The participants demonstrated significantly smaller calf circumference, increased tendon length, decreased Achilles tendon resting angle, and decreased heel-rise performance on the ruptured *versus* non-ruptured side (Tab. I). Two participants were not permitted to perform the heel-rise test on their ruptured side due to early phase of healing, and five participants were unable to complete a unilateral heel-rise on their ruptured side. Heel-rise test performance was the only clinical or structural measurement that related to time since injury. With increasing time from injury, participants demonstrated improved heel-rise height LSI (rho=0.487, p=0.04), repetitions LSI (rho=0.515, p=0.003), and total work LSI (rho=0.493, p=0.04). Participants' current physical activity level [median (IQR) 3.5 (3-4.5)] was significantly lower compared to before injury [median (IQR) 5.5 (4.5-6.0)] (p <0.001). Participants scored a median (IQR) of 65.5 (29.5-75.5) of 100 total points on the ATRS.

Relationship Between Tendon Structure and Clinical Tests

Shear modulus correlated with age on the ruptured side only (rho = -0.481, p = 0.037). Shear modulus LSI correlated with side-to-side difference in tendon thickness (rho = 0.492, p = 0.028). Tendon thickness on the ruptured side was found to relate to ATRS score (rho=0.488, p=0.029) and FAOS score (rho = 0.536, p = 0.018). The relative difference in thickness was also significantly related to ATRS score (rho=0.498, p=0.025) and FAOS score (rho=0.561, p=0.013).

In all individuals who were able to attempt the heel-rise test (n=18), tendon thickness on the ruptured side was related to heel-rise test repetitions (rho =

Table I. Results of clinical measures.

Clinical Measure	Ruptured Side	Non-ruptured Side	p-value
Calf circumference (cm)	37.2 (35.0-39.5)	38.5 (36.2-41.0)	0.003**
Achilles tendon length to gastrocnemius (cm)	22.85 (21.71-24.31)	21.66 (20.74-23.62)	< 0.001*
Achilles tendon resting angle	4.90 (2.60-12.30)	16.0 (12.4-21.0)	< 0.001**
Heel-rise Test			
Maximum heel-rise height (cm)	6.65 (0-8.10)	12.30 (11.40-13.00)	< 0.001*
Number repetitions	13.5 (0-25)	24 (20-31)	< 0.001*
Total work (Joules)	593 (0-1294)	2049 (1556-2517)	< 0.001*

Displayed values are Median (IQR) * p-value from Wilcoxon Signed Rank test (test for a median difference significantly different from 0) ** p-value from Wilcoxon Signed Rank test (test for a median limb symmetry index significantly different from 100%)

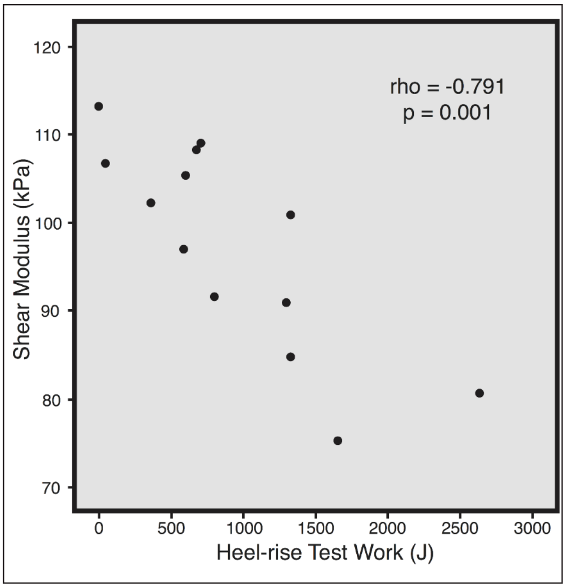

Figure 3. The inverse relationship between total work performed on the heel-rise test (J) and shear modulus (kPa).

0.684, p = 0.002), maximum height (rho = 0.616, p = 0.007), and total work (rho = 0.675, p = 0.002). Furthermore, tendon thickness was significantly larger in individuals who were compared with those who were not able to complete a unilateral heel-rise on the ruptured side (p = 0.014). When looking at individuals able to complete the heel-rise test (n = 13), shear modulus on the ruptured side was found to inversely relate to heel-rise test repetitions (rho = -0.798, p = 0.001), maximum height (rho = -0.564, p = 0.045), and total work (rho = -0.791, p = 0.001) (Fig. 3). The difference in tendon length to the gastrocnemius on ruptured compared to healthy sides was found to relate to heel-rise test repetitions LSI (rho = -0.567, p = 0.043). There was no significant relationship between viscoelastic properties and heel-rise test performance on the healthy side. Viscosity did not relate to self-reported function or heel-rise test performance.

Discussion

The results of this study show side-to-side differences in tendon geometry and viscosity in individuals following Achilles tendon rupture. Achilles tendon geometry, but not viscosity, was also found to significantly relate to clinical outcomes. While no significant differences between ruptured and non-ruptured sides was observed, shear modulus was found to relate to clinical outcomes on the ruptured side.

Side-to-side differences in tendon mechanical properties have been identified in prior studies using advanced ultrasound imaging[27,28]. Shear modulus, measured by supersonic shear wave imaging, was found to be lower in damaged porcine tendons (tendons treated with collagenase) compared to healthy tendons and was also found to strongly relate to Young's modulus[28]. Similarly, shear modulus was found to be lower in individuals with tendon pain compared to the asymptomatic side[27]. When looking over time using shear wave elastography, shear modulus has been reported to increase following Achilles tendon repair, however, side-to-side comparisons have not been reported[7]. The lack of side-to-side comparison may be due to concerns regarding saturation of stiff tissue using commercially available shear wave elastography. Saturation does not appear to be an issue with use of cSWE, allowing for side-to-side comparison between limbs. A prior study in individuals with healthy Achilles tendons demonstrated no side-to-side differences in shear modulus or viscosity when measured with cSWE[17]. When applied to the Achilles tendon rupture population, cSWE was able to detect side-to-side differences in tendon viscosity, however, we did not identify differences in shear modulus at the group level. There are several reasons why prior studies using similar ultrasound techniques identified differences in shear modulus and we did not. First, cSWE and supersonic shear-wave imaging (SSI) measure different mechanical properties. cSWE separates the mechanical response of the tendon into a 'static' shear modulus and a viscosity parameter characterizing the loading rate dependency. In the case of SSI, both static and rate dependent effects are combined into a single measurement of shear modulus. Therefore, the changes in viscosity reported in this study may be related to the changes in shear modulus reported in other studies using SSI. Second, it is possible that due to a relatively small sample size included in this study, we were not powered to see differences in shear modulus. Third, participants in this study were placed in a standardized foot position with their foot against a foot plate. This is different than the above studies, which placed the foot in a resting position. Finally, participants included individuals at varied stages of healing, which may have resulted in differences in shear modulus between sides going in different directions. Future studies in a more homogenous population (controlled for variables such as surgical/non-surgical management, rehabilitation, and time from injury) may help in identifying differences between sides with regard to shear modulus.

Increased tendon cross sectional area following Achilles tendon rupture has been reported previously in animal and human studies[10,11,29,30]. Furthermore, level of activity and surgical *versus* non-surgical intervention has been found to affect tendon cross sectional area[11]. Prior studies in rats have reported a relationship between increased tendon cross sectional area and lower elastic modulus, which was suggested to relate to formation of a tendon callus[10]. In the present study, a moderate relationship was seen between shear modulus and tendon thickness. The underlying cause of the observed relationships between tendon geometry and mechanical properties warrants further study[31], however, based on animal studies investigating the role of tendon loading[11], these parameters seem potentially modifiable.

Previous studies have related clinical outcomes to tendon structural characteristics. Heel rise height has been associated with Achilles tendon length in the context of tendon elongation following rupture[8]. In the present study, heel-rise height was found to relate to repetitions completed during the heel-rise test but not maximum heel-rise height. The results of this study suggest that in addition to considering tendon length with these tests, tendon mechanical properties also seem to contribute to these outcomes. Prior studies using cSWE in individuals with healthy Achilles tendons found no relationship between tendon mechanical properties and strength[17]. Our findings in a population of individuals following Achilles tendon rupture support prior findings as we did not see a relationship between mechanical properties and clinical outcomes in relatively healthy tendons (non-ruptured side), however, these relationships are observed with pathology (ruptured side). It may be that in a healthy condition there is a ceiling effect; with a highly efficient tendon, muscular contributions are so great that tendon contribution is indistinguishable.

Several animal studies have reported a relationship between age and tendon mechanical properties, suggesting that tendon mechanical properties decline with increasing age[32-34]. In humans, age has further been reported to change the mechanical properties of healthy tendons in response to loading[35]. In the present study, age was found to be inversely related to shear modulus only in ruptured tendons. While this relationship was not seen on the healthy side, lower values with increasing age fits the trends previously reported in the literature[33-36].

There are several limitations to this study. First, it utilizes a cross-sectional study design, so the effect of time from injury cannot be well-discerned and would be better addressed in future, longitudinal studies. The participants in this study were heterogeneous in medical management (included individuals managed with and without surgery) as well as in rehabilitation protocol. Group heterogeneity, combined with small sample size, may make relationships between tendon structural and patient functional outcomes difficult to detect. The benefit of a heterogeneous group, however, lies in increasing the generalizability of study findings.

The strength and novelty of this study is the use of advanced imaging techniques along with well-established, Achilles tendon-specific patient outcomes to evaluate the relationship between tendon structure and clinical outcomes. Future, longitudinal studies will help elucidate the responsiveness of these properties to changes in the tendon as well as whether cSWE findings early following Achilles tendon rupture are predictive of long-term outcomes. The findings of this study indicate that tendon mechanical properties measured within the first 12 months following Achilles tendon rupture relate both to presence of pathology as well as clinical outcomes. This supports the continued investigation of the early recovery of mechanical properties following tendon injury in a research setting to better understand the process of tendon healing as well to potentially guide patient treatment in the future.

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