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Muscle-tendon morphomechanical properties of non-surgically treated Achilles tendon 1-year post-rupture

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A R T I C L E I N F O

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A B S T R A C T

Background: Achilles tendon rupture appears to alter stiffness and length of the tendon. These alterations may affect the function of tendon in force transmission and in energy storage and recovery. We studied the mechanical properties of the Achilles' tendon post-rupture and their association with function.

Methods: Twenty-four (20 males, 4 females) participants (mean age: 43 y, 176 cm, 81 kg) were recruited. Ultrasonography and dynamometry were used to assess the muscle-tendon unit morphological and mechanical properties of non-surgically treated patients 1-year post rupture.

Findings: Injured tendons were longer with difference of 1.8 cm (95%CI: 0.5–1.9 cm; $P < 0.001$), and thicker by 0.2 mm (0.2–0.3 mm; $P < 0.01$). Medial gastrocnemius cross-sectional area was 1.0 cm^2 smaller (0.8–1.1 cm^2; $P < 0.001$), fascicles were 0.6 cm shorter (0.5–0.7 cm; $P < 0.001$) and pennation angle was 2.5° higher (1.3–3.6°; $P < 0.001$) when compared to the uninjured limb. We found no differences between injured and uninjured tendon stiffness 1-year post-rupture (mean difference: 29.8 N/mm, −7.7–67.3 N/mm; $P = 0.170$). The injured tendon showed 1.8 mm (1.2–2.4 mm; $P < 0.01$) lower elongation during maximal voluntary isometric contractions. Patient-reported functional outcome was related to the tendon resting length ($\beta = 0.68$, $r(10) = 4.079$, $P = 0.002$). Inter-limb differences in the medial gastrocnemius fascicle length were related to inter-limb differences in maximum contractions ($\beta = 1.17$, $r(14) = 2.808$, $P = 0.014$).

Interpretation: Longer Achilles tendon resting length was associated with poorer self-evaluated functional outcome. Although the stiffness of non-surgically treated and uninjured tendons was similar 1-year post rupture, plantar flexion strength deficit was still present, possibly due to shorter medial gastrocnemius fascicle length.

1. Introduction

The incidence of Achilles tendon rupture (ATR) is rising (Lantto et al., 2015). The recovery of ATR is a long process (Holm et al., 2015), muscle strength decrements persist for several years and seem to be permanent (Heikkinen et al., 2017a). Although non-surgical treatment of ATR is considered safe, assessing biomechanical recovery of the ruptured tendon is important (Deng et al., 2017; Khair et al., 2021; Reda et al., 2020; Reito et al., 2018).

Studies have shown that tendon length increases within the first 4 months post-rupture (Kangas et al., 2007; Silbernagel et al., 2012a) regardless of treatment approach, and that additional tendon slack seems to alter the calf muscles' ability to generate force (Brorsson et al., 2017; Mullaney et al., 2006). Increased AT length and immobilization post-rupture lead to sudden changes in muscle-tendon tension and stimulate changes in plantar flexor muscles (Hullfish et al., 2019). Previous studies found that medial gastrocnemius (MG) fascicles were shorter and more pennate in the first weeks after injury, as well as several months later (Hullfish et al., 2019; Peng et al., 2019).

In vivo human ultrasonography studies performed 2-years post-ATR found lower tendon stiffness in the injured compared to the uninjured tendon (Chen et al., 2013; Geremia et al., 2015; Mcnair et al., 2013; Wang et al., 2013). Conversely, a study performed 2–6 years post-rupture found higher stiffness in the injured tendon (Agres et al.,

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2015). While the majority of long-term follow-ups are done after surgical treatment, understanding how the mechanical properties of the AT change post-rupture is also important after non-surgical treatment.

The purpose of this study was to evaluate alterations in mechanical and structural properties of non-surgically treated muscle-tendon units (MTU) 1-year post-ATR, and to examine their associations with force production capacity and functional outcomes. The following hypotheses were tested: 1) compared to the uninjured limb, the injured AT would be thicker and have a longer resting length, and MG would have smaller cross-sectional area (CSA), and shorter and more pennate fascicles; 2) AT stiffness and maximum elongation would be statistically lower during maximal voluntary isometric contractions (MVC) in the injured limb; 3) inter-limb differences in MTU morphomechanical parameters would be predictive of MVC, walking speed and self-reported clinical outcomes.

2. Methods

2.1. Participants

Twenty-four (20M, 4F) participants (means ± SD age: 43.2 ± 8.9 years, height: 176.1 ± 8.1 cm, mass: 80.9 ± 13.1 kg) in Central Finland were recruited within a clinical cohort study "Non-operative treatment of Achilles tendon Rupture in Central Finland: a prospective cohort study – NoARC" (trial registration: NCT03704532). The Ethics Committee approved the study (2U/2018). Participants were diagnosed within 14 days of the rupture using guidelines by the American Academy of Orthopaedic Surgeons and received non-surgical treatment. Inclusion criteria were a minimum of 2 of the following 4 criteria: a positive Thompson test, decreased plantarflexion strength, presence of a palpable gap, and increased passive ankle dorsiflexion with gentle manipulation (Surgeons AA of O, 2009). The exclusion criteria were avulsion fracture of the calcaneus or a re-rupture. Participants signed an informed consent explaining the details of the study, possible risks, and gave permission to use data for research purposes. Participants were tested 1-year ±3.5 months after rupture.

2.2. Non-surgical treatment protocol

Participants were treated non-surgically in combination with early mobilization. Immediately after ATR, the ankle was cast in full equinus for two weeks. After two weeks, the physician clinically assessed tendon uniformity. If uniformity was confirmed, the foot was moved into plantarflexion using a 20° equinus open sole cast allowing toe movement. Patients were encouraged to bear full weight by treatment week 4 if possible, with a custom-made functional walking orthosis with 1 cm thick heel wedge. At week 8, the orthosis was removed, and progressive physiotherapy began. Walking, swimming, underwater running, and cycling were recommended after 8 weeks. The aim was to gradually increase loading to enable pain-free walking, after which more intense activities could be included. Light jogging was permitted when the patient exhibited ankle mobility close to that of the uninjured limb, was able to walk and could perform heel raises without pain (Reito et al., 2018).

2.3. Laboratory test protocol

Participants were first prepared for the measurements, whereby both malleoli and first and fifth metatarsal heads were marked with a pen, and photos of the foot were taken to approximate the moment arm of the forefoot. AT resting length, MG fascicle length and MG CSA were then assessed using ultrasonography. Participants then sat in a custom-made ankle dynamometer (University of Jyväskylä, Finland) with the hip at 120°, knee at 0° (fully extended), and the ankle and first metatarsophalangeal joints fixed at 90° and 0° respectively. The foot was strapped to the dynamometer pedal and the thigh was strapped to the seat above the knee to minimize alignment changes within and between trials. Data were collected from both legs in one session, starting with the uninjured limb. A series of submaximal voluntary isometric contractions were performed at torque levels ranging from 50% up to maximum. This served as a warm-up and familiarization, and lasted approximately 5 min. Subsequently, MVCs were performed, where participants were asked to reach maximum torque in 2–3 s and decrease torque back to zero in a gradual manner within 2–3 s, resulting in an overall contraction time of 6 s. During these contractions, tendon length changes were quantified using ultrasound imaging. Subjects received verbal encouragement to ensure maximal effort, and visual feedback of the torque trace was also provided. The trial with the highest torque was used for further analysis. Lastly, participants were asked to walk at their preferred speed with the instruction "walk at the speed you normally walk freely down the street" for 6 m with photocells at both ends. Preferred walking speed was defined as the average of three trials.

2.3.1. Force and torque

Force data were collected via a transducer in the foot pedal of the ankle dynamometer. A potentiometer placed under the heel was used to detect heel lift during contractions. Data were sampled at 1KHz via a 16-bit A/D board (Power 1401, Cambridge Electronic Design, Cambridge, UK) connected to the lab computer, and signals were recorded using Spike2 software (Cambridge Electronic Design, Cambridge, UK). To synchronize data, a TTL-pulse was sent manually via Spike2 to trigger the recording of the US device.

AT moment arm length was calculated from photos taken in the sagittal plane from both medial and lateral sides of the foot with a ruler beneath them as a reference and pen marks on the malleoli. The moment arm was measured as the horizontal distance from the estimated centre of rotation (axis through the tip of the medial and lateral malleoli) to the midpoint of the AT (Kongsgaard et al., 2011). First, the horizontal distance from the ankle joint centre to the posterior aspect of the AT skin (M1) was measured with a custom MATLAB (R2018a) script. Then, the distance from the skin to the midpoint of the tendon (M2) was measured from a sagittal plane ultrasound image taken from the AT (see below), and subtracted from the ankle centre of rotation to AT distance, AT moment arm: MA = M1-M2 (Kongsgaard et al., 2011; Zhao et al., 2009).

Plantar flexion torque was calculated by multiplying the dynamometer force by foot moment arm which is the distance between the foot centre of pressure estimated from the pen marks on both 1st and 5th metatarsal, and the strain gauge attachment site on the foot plate (Arampatzis et al., 2005). AT force was calculated as the plantar flexion torque divided by the respective AT moment arm (MA) of each subject. A small joint rotation (heel lift) usually occurs during isometric plantarflexion tasks, resulting in an overestimation of muscle-tendon junction (MTJ) displacement. This displacement was recorded and corrected using the potentiometer under the heel (Ackermans et al., 2016). The mean (SD) magnitude of heel lift during MVCs was 1.4 mm (4.4).

2.3.2. Ultrasonography

AT resting length, MG CSA, and AT thickness were measured using a 3.6-cm linear probe (UST-5411; 7.5 MHz) and an Aloka Alpha-10 device (Aloka, Tokyo, Japan). Images were acquired with subjects in prone position with the feet at the end of the table, with a natural relaxed resting joint angle. Thickness was analysed 1 cm above the calcaneal insertion. Two images per subject and limb were analysed for tendon thickness and the mean values were used for further analysis. Typical repeated measures error for tendon thickness was 4.1%. To measure AT resting length, ultrasound was used to find the most distal point of the MG-MTJ and the tendon insertion on the calcaneus, both of which were marked on the skin. The distance between the points was then measured with a measuring tape (Barfod et al., 2015). MG fascicle length and pennation angle (PA) were acquired in prone position described above using a 6-cm linear probe (UST-5712; 7.5 MHz). Images were taken from the central portion of the muscle belly halfway between the MTJ and the crease of the knee where the deep and superficial aponeuroses of the muscle were parallel (Bolsterlee et al., 2016). Average values from two images were used for further analysis. Repeated measures typical error was 6.2% for MG fascicle length and 6.5% for pennation angle.

CSA images were taken at 50% of MG muscle length at rest in prone position with the knee flexed to 90°. A guiding frame was attached to the skin to ensure that the image was taken in the transverse plane. The extended field of view function was used to visualize CSA. All structural image analysis was done using ImageJ (1.44b, National Institutes of Health).

During maximal isometric contractions, MG-MTJ displacement was imaged with the 6-cm linear probe in B-mode. The ultrasound probe was strapped over the most distal part of MG, as elongation measured at MTJ represents tendon elongation with the possible heel lift accounted for (Fig. 1). Ultrasound videos were sampled at 70 Hz for 8-s per contraction using the same Aloka device as for the resting measurements. MTJ displacement was tracked manually with Tracker 5.1.3 Software (https://physlets.org/tracker/) using a 4 cm calibration bar and an oval-shaped feature template (length: 0.3–1 cm, height: 0.25–0.50 cm).

2.3.3. AT mechanical properties

Tendon elongation and force recordings were synchronized, allowing AT force-elongation relations to be constructed for each subject and fitted to a second order polynomial forced through zero (Magnusson et al., 2001). In some cases, mostly injured limbs, a second order polynomial fit was applied only up to 80% of MVC or below (Fig. 2). This was done because AT length reached a plateau while plantarflexion force was still increasing, resulting in poorly fitting polynomials when using data up to 100% of MVC (Fig. 2).

The second order polynomial described the force-elongation behaviour of the tendon well as evidenced by R^2 values that always exceeded 0.90. From the polynomial, tendon stiffness was taken as a tangent at 50% MVC of the injured limb (Fig. 2C). In this way, the stiffness of both limbs was calculated at the same absolute force level. We also report normalised stiffness because AT elongation at a given force depends on the resting length of the tendon (Arampatzis et al., 2007). Normalised stiffness was defined as the slope of the tendon force-AT strain relationship.

2.3.4. Patient-reported outcome

Upon 1-year follow up at the hospital, patients filled out Achilles tendon rupture score (ATRS) surveys ($N = 19$, 5 non-responders). The survey consists of 10 questions that assess self-reported limitations in different aspects of AT function with a 0–100 linear score, where 0 indicates no symptoms and a fully functioning AT (Carmont et al., 2013).

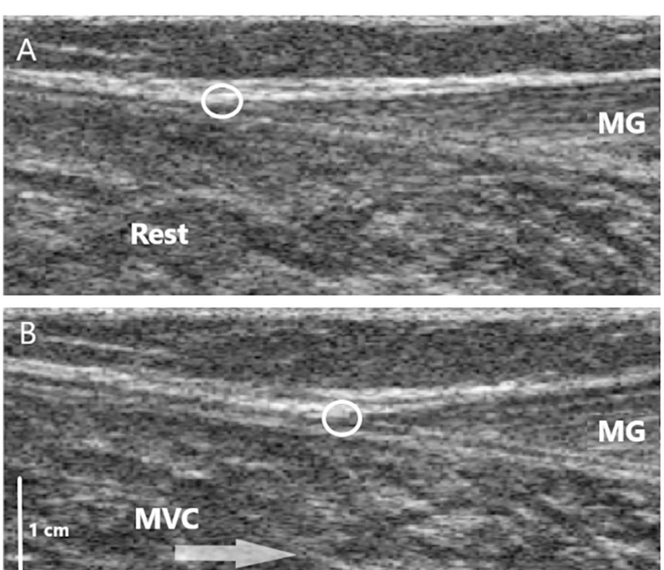

Fig. 1. B-mode ultrasound images of the MG-MTJ (A) at rest and (B) during MVC. Circles indicate the position of the tracked MTJ.

2.4. Statistical analysis

Statistical analysis was performed using JASP (JASP version 0.14.1, Amsterdam, Netherlands). Differences between limbs were compared with adjusted analysis using linear mixed models and unadjusted analysis using pairwise *t*-test. Linear mixed model with random intercepts was built using limb condition (injured vs uninjured) and age as fixed factors, and patient ID as a random factor. Model terms were tested using the Satterthwaite method for each variable independently. Restricted maximum likelihood with Satterthwaite approximation was used since it produces acceptable type 1 error for small sample sizes (Luke, 2017). Descriptive data are presented as fixed effect estimates 95% CI and adjusted *p* values. $P < 0.05$ were considered significant.

Limb asymmetry index (LSI) was calculated for all parameters as percentage (%) difference between limbs: $-\frac{Injured - Uninjured}{Un-injured} * 100$ (Carabello et al., 2010). Multiple regression was used to predict functional outcomes including walking speed, inter-limb difference in MVC and patient-reported outcomes with age and gender as confounding factors, and mechanical and structural parameters as predictors. All assumptions were found to be met and no outliers were found. Correlations within predictors were examined using Pearson's correlation. If a high correlation (> 0.7) was found, one of the correlated variables was removed to ensure collinearity. Relationships between mechanical and structural parameters were examined using Pearson's correlation. Correlations were interpreted as 0.1 (weak), 0.4 (moderate), and 0.70 (strong) (Schober et al., 2018).

3. Results

3.1. Muscle-tendon structural properties

AT resting length was significantly longer in the injured compared to the uninjured limb with a mean difference (95%CI) of 1.8 cm (0.5–1.9 cm; $P < 0.001$). The injured tendons were also thicker by 0.2 mm (0.2–0.3 mm; $P < 0.001$). In the injured limb at rest, MG had a smaller cross-sectional area (1.0 cm^2, 0.8–1.1 cm^2; $P < 0.001$), as well as shorter fascicles (0.6 cm, 0.5–0.7 cm; $P < 0.001$) that were more pennate (2.5°, 1.3–3.6°; $P < 0.001$). Descriptive data are shown in Table 1.

3.2. AT mechanical properties

We found no statistical difference in AT stiffness between limbs 1-year post-rupture, with a mean difference (95%CI) of 29.8 N/mm (−7.7–67.3 N/mm; $P = 0.170$). Similarly, normalised stiffness did not differ between limbs (1.7 kN/strain, −4.9–8.3 kN/strain; $P = 0.633$). The injured tendons displayed lower AT elongation during MVC with a mean difference (95%CI) of 1.8 mm (1.2–2.4 mm; $P < 0.01$). Plantar flexion MVC torque was lower in the injured limb, with an inter-limb difference of 24.1 Nm (17.5–30.7 Nm; $P < 0.001$; Fig. 3).

3.3. Relationship between functional and morphological outcomes

Multiple regression analysis including all variables except normalised stiffness with age and gender as covariates was used to predict MVC, preferred walking speed (mean (SD) 1.2 (0.1) m/s) and ATRS (mean (SD), median (interquartiles) 14.7 (11.8), 12 (Agres et al., 2015; Arampatzis et al., 2005; Brorsson et al., 2017; Chen et al., 2013; Geremia et al., 2015; Hullfish et al., 2019; Kangas et al., 2007; Khair et al., 2021; Kongsgaard et al., 2011; Mcnair et al., 2013; Mullaney et al., 2006; Peng et al., 2019; Silbernagel et al., 2012a; Surgeons AA of O, 2009; Wang

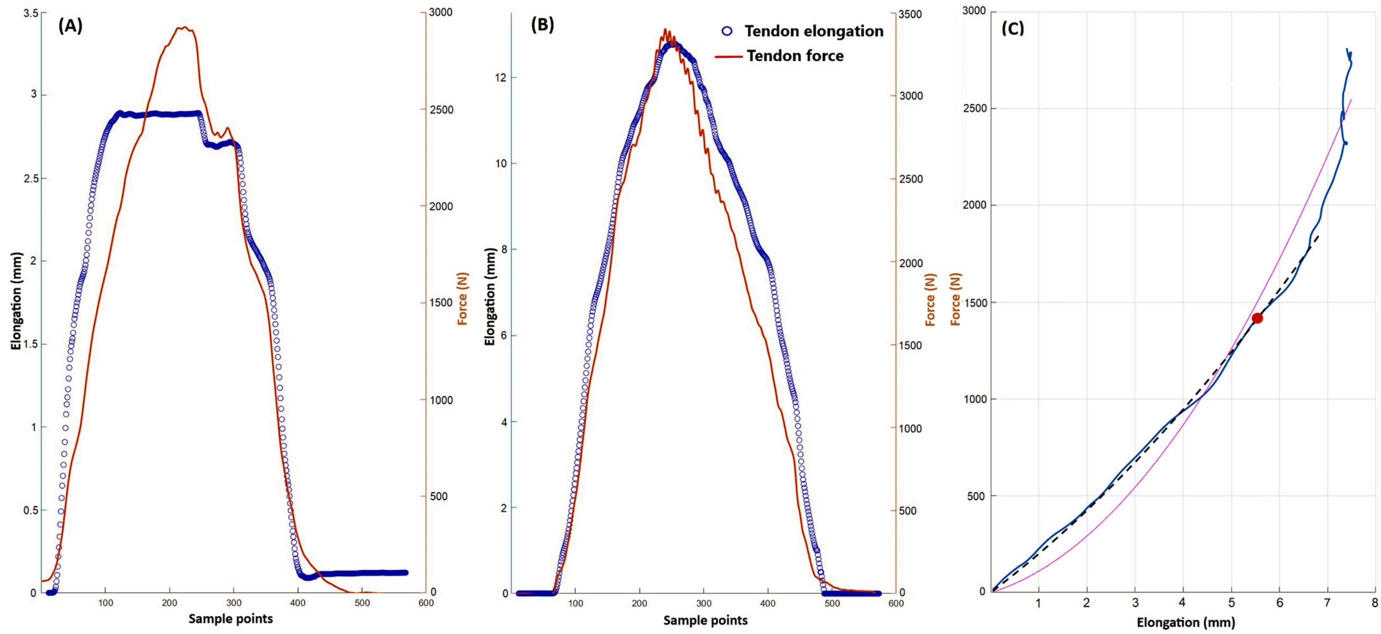

Fig. 2. Example of synchronized raw tendon force and elongation data for both limbs of one subject. (A) Injured limb, where AT elongation reached a plateau while force was still increasing. (B) Data from the same subject's uninjured limb. (C) The elongation plateau in some subjects (as in example in A) causes the force-elongation curve to rise vertically at high forces, resulting in a poor 0–100% polynomial fit (solid pink line). In this case, a polynomial fit to 80% of MVC (black dashed line) yielded a better curve fit. Stiffness was defined as the slope of the fitted curve at 50% MVC of the injured limb (red dot). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Descriptive data and mean differences in muscle-tendon morphomechanical parameters.

	Injured	Uninjured	Mean difference (95%CI)	% difference (LSI)
Thickness mm (SD)	9.3 (2.0)	4.9 (1.1)	4.4 (3.5 to 5.1)	93.2%
AT resting length cm (SD)	21.3 (2.9)	18.8 (1.8)	2.5 (1.5 to 3.5)	13.5%
MG fascicle length cm (SD)	3.6 (0.6)	4.7 (0.6)	1.1 (0.9 to 1.4)	−23.8%
MG pennation angle ° (SD)	26.7 (5.9)	22.1 (4.4)	4.5 (2.6 to 6.4)	21.7%
MG CSA cm^2 (SD)	11.7 (2.6)	13.7 (2.2)	2.0 (1.2 to 2.8)	−14.6%
MVC Nm (SD)	127.4 (38.7)	173.9 (41.1)	45.8 (32.4 to 59.2)	−25.1%
Elongation mm (SD)	7.5 (5.0)	11.0 (5.7)	3.5 (1.9 to 5.1)	−26.7%
Stiffness N/mm (SD)	413.4 (186.6)	486.5 (210.2)	73.1 (−12.2 to 158.4)	−7.2%
Normalised stiffness kN/strain (SD)	89.8 (40.2)	85.1 (35.7)	4.7 (−11.0 to 20.5)	4.3%

Un-adjusted pairwise T-test.

et al., 2013; Zhao et al., 2009)). The ATRS model explained 69% of the variance (F(8,9) = 2.51, P = 0.096) with a Root mean square error (RMSE) of 9.02. Only resting length was significantly related to ATRS (β = 0.61 (0.22–1.00), r(9) = 3.548, P = 0.006). As for MVC LSI, the model explained 46% of the variance (F(8,13) = 1.38, P = 0.292) with RMSE of 15.83. MG fascicle length LSI positively predicted MVC LSI (β = 1.22 (0.24–2.20), r(13) = 2.688, P = 0.019). The preferred walking speed model explained 41% of the variance (F(8,12) =1.052, P = 0.452) with RMSE of 0.11. None of the above-mentioned parameters were significantly related to preferred walking speed.

AT resting length LSI was inversely correlated with stiffness LSI (rs = −0.41, 95%CI [−0.7–0.0], P = 0.045). MG fascicle length LSI was negatively correlated with AT resting length LSI (rs = −0.43, 95%CI [−0.7–0.0]), P = 0.037), and pennation angle LSI (rs = −0.5, 95%CI [−0.8–0.2], P = 0.04). MG CSA LSI was positively correlated with normalised stiffness LSI (rs = −0.46, 95%CI [0.1–0.7], P = 0.26).

4. Discussion

In the present study we examined the MTU morphomechanical properties of non-surgically treated patients 1-year post rupture. In the injured limb, plantar flexor muscle strength was lower, AT resting length was longer and MG had smaller CSA with shorter and more pennate fascicles. AT stiffness did not differ between limbs. Poor self-evaluated functional outcome was associated with longer AT resting length. MG fascicle length LSI was related to MVC LSI. This study shows that non-surgical treatment may result in restoration of AT mechanical properties, but longer AT resting length was observed and is probably a contributing factor to the observed changes in morphomechanical properties and self-evaluated function.

Tendons in the injured limb were thicker, as reported previously in surgically treated patients (Wang et al., 2013). Animal models have shown that non-surgical treatment leads to higher grade organization of collagen fibres, and a more healthy tendon-like appearance compared with a greater proportion of scar tissue in the operative group (Krapf et al., 2012). Given that non-surgical treatment may be associated with less scar tissue formation than surgical treatment, the increase in tendon thickness in the current study may be a compensation for impaired material properties in the ruptured tendon resulting from compositional changes or changes in the internal organization of the material (Freedman et al., 2014).

In this study, injured AT resting length was on average 13.5% longer than in the contralateral limb, this results are in accordance with Heikkinen et al. 2017 (Heikkinen et al., 2017b). Previously, a longer AT resting length has been reported up to 2 years post-rupture, and has been shown to be associated with impaired walking performance and heel raise performance in the injured limb (Agres et al., 2015; Baxter et al., 2019; Silbernagel et al., 2012b). Since MTU length stays constant, the

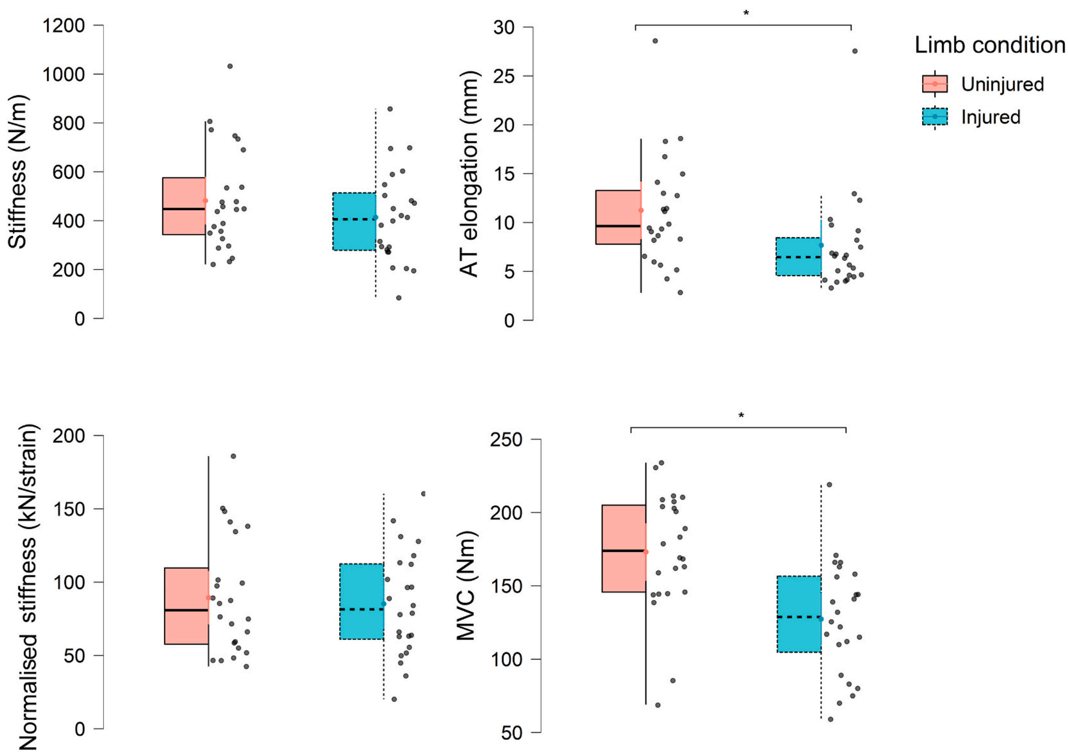

Fig. 3. Box plots illustrating estimated means ± SD for AT mechanical properties during MVC for both limbs. *Significant difference between limbs ($P < 0.001$).

increase in tendon length is presumably associated with decreased MG fascicle length. Indeed, we found an inverse correlation between resting length LSI and MG fascicle length LSI. The functional consequences of tendon elongation and the associated muscle shortening depend on sarcomere level adaptations. If there was no change in serial sarcomere number, the sarcomeres would be shorter for a given joint angle post-rupture, which would negatively affect force production capacity as TS muscles operate mostly on the ascending limb of the force-length relationship (Holzer et al., 2020). On the other hand, reduced sarcomere number can restore the sarcomere operating length at a specific joint angle. However, force production capacity would still be compromised as the sarcomeres would be forced to operate over a larger operating range for a given joint movement.

Our findings demonstrate inter-limb differences in MG morphology at rest. In the injured limb MG had a smaller CSA, with shorter, more pennate fascicles. Muscles are able to sense changes in mechanical tension and regulate their architectural configuration (de Boer et al., 2008) by adding or removing sarcomeres, as shown in animal studies (Williams and Goldspink, 1973). Post-rupture, a sudden loss of muscle-tendon tension due to the increase in AT length probably elicits plantar flexor muscle remodelling and a removal of serial sarcomeres. Hullfish et al. (2019) showed higher pennation angle in the injured limb and

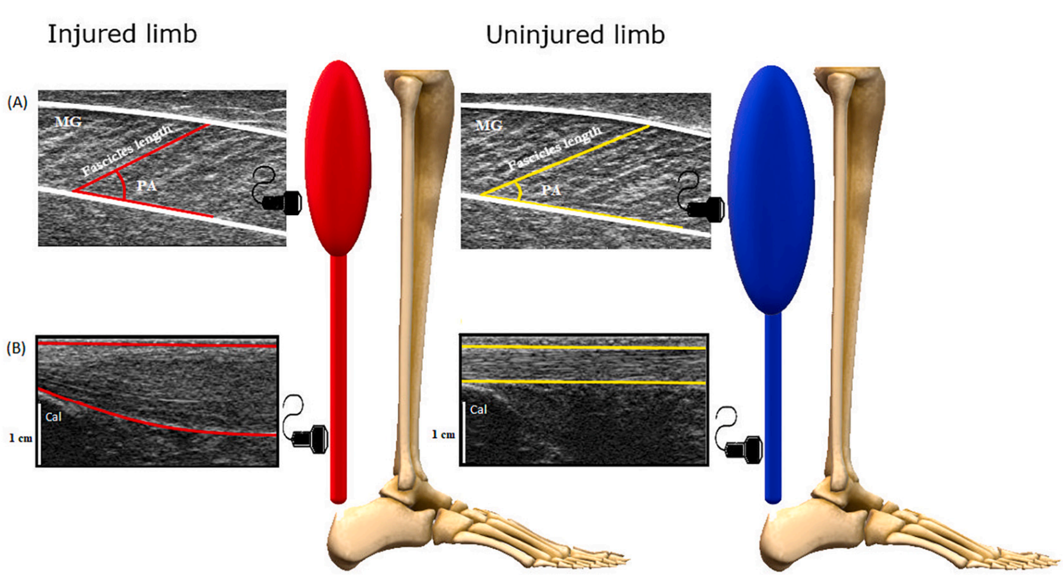

Fig. 4. Ultrasonographic images of muscle-tendon unit structural properties 1-year post-rupture in both limbs. (A) images of MG muscle where pennation angle and fascicle length were analysed. (B) Images where AT thickness was measured 1 cm away from the calcaneal insertion. Injured limb AT was longer and thicker than the uninjured AT. At rest, MG had a smaller CSA with longer and more pennate fascicles.

shorter fascicle length in the first 4 weeks of conservative treatment (Hullfish et al., 2019), but no change in muscle thickness. In the present study performed 1-year post rupture, higher pennation angle and shorter fascicles were accompanied with smaller CSA in the injured versus the contralateral limb (Fig. 4). Therefore, the acute alterations in MG muscle architecture seem to persist after one-year post-rupture, with an additional loss of muscle mass. We also observed that a greater difference in MG CSA between limbs was associated with a greater inter-limb difference in normalised AT stiffness. This may indicate that increased AT length leads to remodelling in MG structure. Change in MG structure change the muscle force production capacity effecting the tendon stiffness and influencing the mechanical loading environment of the tendon.

After rupture, MG muscle probably adapts by resetting fascicle length (dictated by serial sarcomere number) and pennation angle to a new optimum for force production at a joint angle at which the force requirement during normal locomotion is largest. This still leads to reductions in the range of motion at which force can be produced (Stäudle et al., 2020) and the ability of the plantar flexors to perform work (Baxter et al., 2019). We found that the reduction in MG fascicle length was inversely correlated with increased pennation angle, as shown previously (Hullfish et al., 2019). This morphological adaptation has functional consequences, as the increase in pennation angle increases muscle belly gearing (Lichtwark and Wilson, 2007). Muscle belly gearing reduces muscle fiber shortening for a given muscle belly shortening, so the increase in pennation angle helps to preserve force production due to the force-velocity and force-length relationships. The downside of increased pennation angle is that a lower proportion of the fiber force is transmitted in the direction of the tendon and thus to the skeleton. Therefore, the increase in pennation angle likely preserves the muscle's force production and work generation capability in concentric muscle actions but negatively affects force production in isometric conditions.

We found no difference in stiffness between ruptured and contralateral tendons. This contrasts with previous studies where AT stiffness was lower in the injured limb 3–12 months after surgical treatment (Chen et al., 2013; Geremia et al., 2015; Mcnair et al., 2013; Wang et al., 2013), but higher when investigated 2–6 years post-rupture (Agres et al., 2015). Initially, the healing tendon has lower stiffness, which gradually increases towards normal values in the remodelling stage, at least in mice (Palmes et al., 2002). Similarly, in humans, after an initial drop post-rupture, stiffness increases to eventually match or even exceed that of the uninjured tendon (Agres et al., 2015; Karamanidis and Epro, 2020). These changes in tendon stiffness have functional consequences via their effects on the muscle's force-length and force-velocity relationships. As TS muscles operate mostly on the ascending limb of the force-length relationship (Holzer et al., 2020), a higher AT stiffness helps to preserve favourable sarcomere lengths during force generation by reducing muscle shortening. Higher tendon stiffness may also help to minimize the impairments in force production caused by the increased AT resting length, albeit incompletely (Stäudle et al., 2020). AT stiffness is also positively correlated with TS rate of force development (Monte and Zignoli, 2021; Muraoka et al., 2005; Peng et al., 2019). Hence, from the viewpoint of isometric force production, it may be beneficial if the injured tendon remodels to have higher stiffness than the contralateral tendon. However, this may negatively affect locomotion efficiency and performance as there seems to be an optimal stiffness for cyclically generating force and power (Lichtwark and Wilson, 2007; Orselli et al., 2017). In the present study, the observed increase in AT thickness may have contributed to the restoration of AT stiffness. We also observed a negative correlation between stiffness LSI and AT resting length LSI indicating that more AT lengthening is associated with lower stiffness, which negatively affects isometric force production capacity. Thus, minimizing tendon lengthening after rupture may help to restore tendon mechanical properties.

The combination of a ~ 25% plantar flexion strength deficit in the injured limb with no difference in AT stiffness led to the reduction in maximal tendon elongation. Reduced maximal elongation may negatively affect movement economy due to a reduced capacity to store elastic potential energy in the tendon. This may also predispose the muscle to eccentrically-induced muscle damage or strain as the tendon cannot work as efficiently to dissipate energy and reduce the power of the negative work done by the muscle (Roberts and Azizi, 2010). However, there may be benefits associated with the reduced maximal tendon elongation related to tendon injury risk. Lower maximal elongation coupled with an increase in tendon length greatly reduces tendon strain, which has been speculated to be important for reducing the risk of tendon injury (Karamanidis and Epro, 2020) and fatigue damage (Wren et al., 2003).

During stiffness assessments we observed a plateau in MG-MTJ displacement while plantarflexion force continued to increase at the end of an isometric contraction. This phenomenon was more pronounced in the injured limb (Fig. 2) and may have been due to changes in MTU structure post-rupture. The shortened MG fascicles may have led to a relatively quick saturation of MG force generation due to the muscle's force-length properties. Furthermore, deep flexors such as flexor hallucis longus (FHL) may make a larger contribution to plantar flexion torque in the ruptured limb (Finni et al., 2006). Along with the potential contribution of the soleus muscle, these factors may result in increased plantar flexion torque that would not be detectable when tracking the MG-MTJ. This novel observation highlights the role of synergistic muscles in compensating plantarflexion torque after AT rupture (Heikkinen et al., 2017a), and warrants careful examination of data and decision making in relation to stiffness assessments. We decided to compare stiffness at 50% of MVC of the injured limb to get valid data from all participants. Therefore, direct comparisons to previous studies with different methodologies are not advisable.

When examining the significance of morphomechanical variables in relation to the self-reported functional outcomes we found that AT resting length LSI positively predicted ATRS (Kangas et al., 2007; Pajala et al., 2009; Silbernagel et al., 2012b). Our sample had a relatively good ATRS (mean 14.7). The patient with the worst outcome (47/100) also had the most elongated tendon when compared to the contralateral limb. Preferred walking speed was not related to any morphomechanical tendon parameter. The preferred walking speed was close to the values reported for healthy individuals (Stenroth et al., 2017), indicating recovery of daily function in situations where TS muscles operate submaximally. However, during maximal effort tasks (MVC), we observed deficits. The deficits can be long-lasting, even after returning to pre-injury activities. Karamanidis & Epro (2020) reported that two elite athletes had significant plantar flexion force deficits in the injured limb 2.5 years post-ATR, despite high training volumes with high loads (Karamanidis and Epro, 2020). Moreover, Trofa et al. (Trofa et al., 2017) reported that for about 30% of professional athletes, ATR is a career ending injury. Thus, although daily function returns after ATR, it may lead to irreversible MTU deficits, preventing participation in some pre-injury activities.

One of the study limitations is the assumption that the axes of ankle joint rotation and dynamometer are aligned. This may not be always valid and may have affected the stiffness values. However, the error is likely similar in both limbs within an individual level. During ultrasound imaging, the applied pressure may influence the measures of fascicle length and pennation angle. From the two sequential images, we evaluated that the typical error in these measures was ~6% while the mean value was reported.

5. Conclusion

One-year post-rupture, non-surgically treated tendons seem to heal to an elongated length, accompanied with MG remodelling to shorter, more pennate fascicles along with a decrease in muscle mass. Although the stiffness of non-surgically treated tendons was similar to that of the contralateral limb, plantar flexion strength deficit was still present.

Thus, the observed remodelling of the MG muscle, seems to be one of the main causes of lower force production capacity in the ruptured limb. AT resting length was associated with clinical outcome scores. As the increase in AT length seems to be responsible for the observed objectively measured and self-reported functional deficits.

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Declaration of Competing Interest

None.

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