Biomechanical properties of the calcaneal tendon in vivo assessed by transient shear wave elastography

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Purpose

Tendons adapt dynamically to mechanical stress, increasing their resistance to rupture when in use [1 on page __] . Conversely, a change in their elastic properties is found in immobilization and in aging [2 on page __] . Tendinopathies occur frequently, and have increased over the last thirty years due to the rise in sporting activity [3 on page __ , 4 on page __] . The calcaneal tendon (or Achilles tendon) is subjected to the greatest mechanical stress and is the most frequently injured tendon : calcaneal tendon injury rate is estimated to 12 in 100,000 individual [5 on page __] . This presents a diagnostic and therapeutic challenge in which imaging plays a crucial role.

Current gold standard imaging techniques for tendon injury assessment are ultrasound (US) and MRI. They allow precise morphological analysis of normal and damaged calcaneal tendon, but do not quantitatively evaluate biomechanical properties such as viscoelasticity and anisotropy.

Transient shear wave elastography (SWE) is a recent non invasive ultrasonographic imaging technique introduced in 2002 [6 on page __] which can evaluate soft tissue stiffness [6-8 on page __] . SWE has the advantage of being able to measure the speed of shear stress wave propagation in tissue, allowing Young's modulus to be calculated [8 on page __ , 9 on page __] . The first applications for SWE were the characterization of mammary nodules [10 on page __] and the evaluation of hepatic fibrosis [6 on page __ , 11 on page __] . Only two studies of normal calcaneal tendon in SWE have been published to our knowledge : the first was carried out using a prototype with an upper elasticity modulus measurement limit of 600 kPa on 30 healthy volunteers [12 on page __] . The second studied the calcaneal tendon in only one position [13 on page __] .

The main objective of our study was to quantify the elastic properties of normal calcaneal tendon with SWE in vivo, and to estimate anisotropy. The secondary objectives were to study the interobserver reproducibility of the measurements and to look for factors in the variation of shear modulus such as age, sex, body mass index, sporting activity and dominant leg.
Methods and Materials

a. Study population

Institutional review board and written informed consent from all volunteers were obtained. Eighty healthy volunteers were included in this prospective study from January 2011 to September 2011. The inclusion criterion was healthy volunteers over 18 years of age. The exclusion criteria were pregnant women, history of calcaneal tendinopathy or calcaneal tendon surgery, pain in the calcaneal tendon and morphological anomaly on ultrasound (B mode and power Doppler). Volunteers with a history of systemic, metabolic or endocrine diseases, psoriasis or those treated with corticosteroids, estrogens, quinolones and cholesterol drugs were also excluded due to the association between these factors and tendinopathies [14, 15].

The following data were collected by the principal investigator (S.A) : inclusion date, date of birth, weight (kg), height (m), sex, number of hours spent exercising per week, and dominant leg. Patients’ age was calculated using the difference between their inclusion date and date of birth. The body mass index (BMI) of each volunteer was calculated using the formula BMI = Weight (kg) / Size (m)^2. The volunteers were identified as "sporty" if they claimed to spend one hour or more exercising per week. Otherwise they were considered "non-sporty".

b. Procedure

All ultrasounds were bilateral according to a standardized protocol using the Aixplorer® machine (SuperSonic Imagine®, Aix-En-Provence, France) equipped with a 12 MHz superficial linear transducer. Patients were placed in a prone position, legs extended. The examination began with grayscale B mode and power Doppler ultrasound to eliminate any sign of tendinopathy. The width (mm) and thickness (mm) of each tendon were measured with axial (i.e. perpendicular to the direction of the fibers) grayscale ultrasound 5 cm from the end of the tendon. The cross-sectional area (mm^2) of each tendon was calculated using the following formula : cross-sectional area = # * width/2 * thickness/2.

Measurements in elastographic mode were made successively for four passively mobilized ankle positions : Position N°1 : maximal plantar flexion; position N°2 : 45° plantar flexion; position N°3 : 0° flexion; position N°4 : 45° dorsiflexion ou maximal dorsiflexion for patients who did not sustained 45° dorsiflexion.
Fig. 1: Calcaneal tendon was examined at 5cm from the end of the tendon consecutively for four degrees of ankle flexion. Position N°1: maximal plantar flexion; position N°2: 45° plantar flexion; position N°3: 0° flexion; position N°4: 45° dorsiflexion. As it may have increased tissue stiffness, pre compression was avoided by interposition of a gel pad between the probe and the skin. Position was maintained and controlled by fastening feet on an articulated board.

References: Musculoskeletal Imaging, CHRU Besancon - Besancon/FR

The mean shear wave velocity ($V_{\text{mean}, \text{m.s}^{-1}}$) was measured in elastographic mode (SWE) by placing a region of interest (ROI) with the following requirements: constant round size (3mm in diameter) situated in the center of the tendon 5 cm from it's end, both in sagittal (i.e. parallel to the direction of the fibers) and in axial SWE.
Fig. 2: Young's modulus map (SWE) of the calcaneal tendon in position N°2 parallel (a) and perpendicular (b) to the direction of the fibers.

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Young's modulus $E_{\text{mean}}$ (kPa) was calculated from $E_{\text{mean}} = 3 \# V_{\text{mean}}^2 [7]$ where density $#$ is assumed to be constant (1000 kg.m$^{-3}$), under the assumption of a purely elastic model. The relative anisotropy coefficient (A) was calculated using the following formula: $A = (\text{sagittal } V_{\text{mean}} - \text{axial } V_{\text{mean}}) / \text{axial } V_{\text{mean}}$.

In accordance with the protocol, the examinations of the 80 included healthy volunteers were performed by the main investigator (S.A). However, in 30 of these cases, volunteers also underwent examinations of two other investigators, (JRR, BBB). These 30 subjects were examined independently by the three investigators, such that the ankle positioning and imaging were repeated 3 times.

c. Statistical analysis

Continuous variables are expressed as mean ± SD. A mixed model was used to evaluate the elastic and anisotropic variations for the four ankle positions.

An overall p-value of less than 0.05 was considered statistically significant.

An univariate analysis was performed to show whether the following variables influenced elastic and anisotropic tendon properties: age, sex, physical exercise, dominant leg, weight, height, BMI and the thickness, width and cross-sectional area of the calcaneal tendon.
Interobserver reproducibility was evaluated using the intraclass correlation coefficient (ICC). An ICC between 0.8 and 1 was considered to be very reproducible, between 0.6 to 0.79 was considered moderately reproducible and less than 0.6 was considered not very reproducible. Statistical analysis was performed using SAS for Windows version 9.1.3 (SAS Institute Inc., Cary NC).
Fig. 1: Calcaneal tendon was examined at 5cm from the end of the tendon consecutively for four degrees of ankle flexion. Position N°1: maximal plantar flexion; position N°2: 45° plantar flexion; position N°3: 0° flexion; position N°4: 45° dorsiflexion. As it may have increased tissue stiffness, pre compression was avoided by interposition of a gel pad between the probe and the skin. Position was maintained and controlled by fastening feet on an articulated board.

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Fig. 2: Young's modulus map (SWE) of the calcaneal tendon in position N°2 parallel (a) and perpendicular (b) to the direction of the fibers.

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Results

a. Patients:

Forty-three women and 37 men with a mean age of 45.4 (range: 20-83) were included. Their mean weight was 68.6±12.6 kg, mean height was 168.6±9.1 cm and mean BMI was 24.1±3.8. The mean exercise time per week was 1.7±2.4 hours. Forty-three volunteers were considered "sporty" (53.7%, 43/80) and 37 "non-sporty" (46.3%, 37/80). In 66.2% of cases (53/80), dominant leg was the right leg.

b. Ultrasound and elastographic variables:

Data of the right and left tendons were grouped together so that 160 tendons were studied. In the axial ultrasound, the thickness of the calcaneal tendon was 4.4±0.6mm, the width was 15.1±1.9mm and the cross-sectional area was 53.1±11.7mm². The results of the elastographic analysis are shown in table 1.

<table>
<thead>
<tr>
<th>Position N°1</th>
<th>Position N°2</th>
<th>Position N°3</th>
<th>Position N°4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal (mean ±SD)</td>
<td>Sagittal (mean ±SD)</td>
<td>Sagittal (mean ±SD)</td>
<td>Sagittal (mean ±SD)</td>
</tr>
<tr>
<td>Axial (mean ±SD)</td>
<td>Axial (mean ±SD)</td>
<td>Axial (mean ±SD)</td>
<td>Axial (mean ±SD)</td>
</tr>
<tr>
<td>(V_{\text{mean}})</td>
<td>6.8±1.4</td>
<td>5.1±0.8</td>
<td>10.7±2.4</td>
</tr>
<tr>
<td>(E_{\text{mean}})</td>
<td>147.6±62.7</td>
<td>78.7±26.9</td>
<td>359.1±160</td>
</tr>
<tr>
<td>(A)</td>
<td>0.38±0.31</td>
<td>0.87±0.43</td>
<td>1.87±0.72</td>
</tr>
</tbody>
</table>

\(V_{\text{mean}}\) : Mean velocity (m.s\(^{-1}\)) of shear wave in the ROI
\(E_{\text{mean}}\) : Mean elasticity (kPa) of tendon in the ROI
\(A\) : Relative anisotropy coefficient

Table 1: Elastic and anisotropic values of the calcaneal tendon as a function of the position of the ankle on sagittal and axial SWE

In the axial SWE, there was a significant increase in the \(V_{\text{mean}}\) and \(E_{\text{mean}}\) between positions N°1 and N°2 (p<0.001), and between N°3 and N°4 (p<0.001), but there was no significant difference in these variables between positions N°2 and N°3 (respectively \(V_{\text{mean}}\)p=0.62 and \(E_{\text{mean}}\)p=0.7). In the sagittal SWE, there was a significant increase in
\(V_{mean}\) and \(E_{mean}\) between positions N°1 and N°2, N°2 and N°3 and between N°3 and N°4 (\(p<0.001\)). The relative anisotropy ratio \(A\) was 0.38±0.31 in position N°1. It increased significantly between positions N°1 and N°2 (\(p<0.001\)), and between positions N°2 and N°3 (\(p<0.001\)). However, there was a statistically significant drop between positions N°3 and N°4 (\(p<0.001\)).

The univariate analysis found that \(V_{mean}\) was significantly reduced with age on the axial SWE acquisitions in position N°1 (\(p<0.001\)) and N°2 (\(p=0.0015\)), and in the sagittal SWE in position N°2 (\(p=0.004\)). \(V_{mean}\) was significantly higher in men in axial acquisitions in position N°1 (\(p=0.005\)) and in sagittal acquisitions in position N°1 (\(p=0.03\)), N°2 (\(p<0.001\)) and N°3 (\(p=0.017\)). However, exercise, dominant leg, weight, height, BMI and the thickness, width and cross-sectional area of the calcaneal tendon did not have a significant influence on \(V_{mean}\) regardless of the orientation of the transducer and the position of the ankle.

c. Interobserver reproducibility

The different intraclass correlation coefficients are shown in table 2.
Conclusion

Biomechanical properties of tendons are difficult to assess because tendons are highly complex and are made of dense fibrous connective tissue that transmit the mechanical force of muscle contraction to the bones. Although the role of viscoelasticity in tendon biomechanics is well recognized, methods of measuring viscoelasticity in vivo are currently limited. The recent development of a new quantitative elastography technique has made it possible to explore elastic properties of the tendon depending on whether it is stretched.

Our study confirms that SWE enables us to evaluate the elastic properties of the calcaneal tendon in vivo. At rest in full extension, the values obtained (Sagittal $E_{\text{mean}}$ 147±62kPa, Axial $E_{\text{mean}}$ 78±26kPa) (Table 1) are similar to those of the earliest studies published in the literature (Figure 3): the first results (Sagittal $E_{\text{mean}}$ 104±46kPa, Axial $E_{\text{mean}}$ 64±22kPa [12]) were obtained using a prototype. Those published by Arda (Sagittal $E_{\text{mean}}$ 74±45kPa, Axial $E_{\text{mean}}$ 54±25kPa [13]) are of the same order of magnitude. The four studies on the elastic properties of the calcaneal tendon published previously [16-19] were all carried out with static elastography which do not provide quantitative data on tendon stiffness and anisotropy.

![Fig. 3](image)

Fig. 3: Mean Young's modulus ±SD over the calcaneal tendon along (a) and perpendicularly (b) to the tendon fibers as a function of the ankle flexion from position N°1 to N°4. Comparison with the results of previously published series.

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The calcaneal tendon has tendinous fibers that lie parallel to each other. There is therefore an axis of symmetry along the fibers that relates to a hexagonal system (transverse isotropy) according to the viscoelasticity theory [20]; This enables to define two main axes: one parallel and one perpendicular to the fibers. Our results on the calcaneal tendon are similar and we estimate the relative anisotropy coefficient $A$ of the calcaneal tendon at rest at 0.38±0.31. This confirms that, much like muscle [21],
tendon is anisotropic, and that the orientation of the transducer axis in relation to the
tendon fiber axis must be known in order to accurately interpret the quantitative values
provided by the device. Anisotropy is almost five times higher for a stretched tendon
(position N°3) than at rest (position N°1). This result is consistent with previous work on
muscle anisotropy [21].

Our results also confirm the increase in $E_{\text{mean}}$, $V_{\text{mean}}$, and $A$ when the calcaneal tendon
was stretched [12] (Figure 4), regardless of whether the measurements were made in
the sagittal SWE or in the axial SWE (Figure 3).

![Figure 4: Young's modulus map (SWE) of the calcaneal tendon, parallel to the direction
of the fibers, in position N°1 (a) and in position N°3 (b).](image)

References: Musculoskeletal Imaging, CHRU Besancon - Besancon/FR

Values in the sagittal SWE at 0° and in complete dorsiflexion are probably under-
estimated because the upper limit of our device (800kPa) is often reached for these two
positions in the sagittal SWE. In vitro studies based on methods other than elastography
(uniaxial contraction test) report variable Young’s modulus values for the tendons studied,
between 1 and 2 GPa [22]. The differences in values found seem to be linked mainly to
the experimental conditions (changes in the tendon on its support system) but also to
the methods used for preserving tendon samples (fixation) [23]. We should therefore be
cautious when extrapolating in vivo experimental data [12, 13, 24]. The results of previous
quantitative studies [12, 13, 24] are compared in figure 3. These studies are consistent
in terms of the increase of the absolute values of $E_{\text{mean}}$ when the tendon is stretched.
The differences are however relatively large when stress is applied, particularly for the
highest position. Because stress is considered to be non-existent at rest, quantitative
comparison with our results is possible. On the other hand, comparison with intermediate
and highest positions in which degree of stress is unknown must remain qualitative.
Of the factors that may influence the elastic properties of the calcaneal tendon, we found significantly higher $E_{\text{mean}}$ and $V_{\text{mean}}$ values in position N°1 in men compared with women, similarly to Arda [13]. In position N°1 and N°2, we showed a significant reduction in $E_{\text{mean}}$ and $V_{\text{mean}}$ according to age. Although they have not been found before [12, 13], this association suggests tendon senescence and should be confirmed in further studies. Unlike previous study [12], we found that physical activity made no difference to the elastic properties of the calcaneal tendon. These inconsistent results should be regarded with caution and should be compared to the results of future studies on higher numbers of subjects.

In the sagittal SWE and at rest (N°1), there is a statistically significant interobserver correlation for $E_{\text{mean}}$ and $V_{\text{mean}}$ measurements. Such reproducibility is questionable ($E_{\text{mean}}$ ICC = 0.43, $V_{\text{mean}}$ ICC = 0.46) but better than in the axial SWE ($E_{\text{mean}}$ ICC = 0.16, $V_{\text{mean}}$ ICC = 0.15). In position 2, the interobserver reproducibility of $E_{\text{mean}}$ and $V_{\text{mean}}$ measurements is poor. The interobserver reproducibility in positions N°3 and N°4, although questionable, is better in axial SWE than in sagittal SWE, perhaps because the upper limits of the measurement device are reached in the sagittal SWE (Table 2). Due to this poor reproducibility of $E_{\text{mean}}$ and $V_{\text{mean}}$, interobserver reproducibility of A is also questionable regardless of the position. Quantitative values measured in positions other than at rest should be interpreted with great caution.

The pathogenesis of tendinopathies is a complex biomechanical and biochemical change which might be better understood through elastography. The first studies to have included symptomatic patients are inconsistent and were carried out with static elastography. One showed stiffer tendons in symptomatic subjects [19], while the other showed softer tendons [17]. According to Khoury's study in tennis elbow [25], "tenomalacia" could be a new sign of tendinopathy. This might be better described as tendon-softening (or tenosoftening) and should be confirmed by additional studies with a higher number of tendinopathies. It would also be interesting to see whether elastographic anisotropy is modified in calcaneal tendinopathy. Because shear wave do not propagate in liquids, tendon tears may appear with no signal on Young’s modulus map (Figure 5).
**Fig. 5:** Grayscale ultrasound and SWE of a partial tear of calcaneal tendon close to its osseous insertion. Young's modulus of calcaneal tendon increases when it is stretched by ankle dorsiflexion, whereas tear remains with no SWE signal.

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However, because of moderate to low inter-observer reproducibility of the measures of tendon elasticity, any further study on this topic should be performed taking into account several bias. First, a bias related to the possible contraction of the subjects’ calf. Second, measurement bias related to positioning or direction of the transducer or positioning of the ROI. Finally, a possible measurement bias may be due to the device itself.

Despite these limitations, **transient shear wave elastography enables to quantify the elastic properties of normal calcaneal tendon in vivo and to follow the variations in these properties when the tendon is stretched.** Further studies are necessary in order to validate the benefit of this technique in tendon pathologies.
Fig. 2: Young's modulus map (SWE) of the calcaneal tendon in position N°2 parallel (a) and perpendicular (b) to the direction of the fibers.

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Fig. 3: Mean Young's modulus ±SD over the calcaneal tendon along (a) and perpendicularly (b) to the tendon fibers as a function of the ankle flexion from position N°1 to N°4. Comparison with the results of previously published series.

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**Fig. 4:** Young's modulus map (SWE) of the calcaneal tendon, parallel to the direction of the fibers, in position N°1 (a) and in position N°3 (b).

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Fig. 5: Grayscale ultrasound and SWE of a partial tear of calcaneal tendon close to its osseous insertion. Young’s modulus of calcaneal tendon increases when it is stretched by ankle dorsiflexion, whereas tear remains with no SWE signal.

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