

Quantitative elastography of Achilles tendon using Shear Wave Elastography (SWE): correlation with zonal anatomy

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Summary

Introduction: To evaluate the feasibility and reproducibility of quantitative ultrasonic measurement of normal Achilles tendon (AT) stiffness, using supersonic shear wave elastography (SWE) in correlation with its zonal anatomy.

Materials and methods: Thirty tendons (8 women, 7 men) (mean age, 29,5 years; age range, 24-51 years) underwent morphologic and SWE measurements. The quantitative measurements of the tendon in four points (musculo-tendinous junction, tendinous body, pre-insertional area and enthesis) according to zonal anatomy were performed by two MSK radiologists and respectively expressed in terms of mm and Young's modulus (kPa). Inter-observer reproducibility was also assessed.

Results: The SWE measures show higher stiffness for the sagittal position of the US than in axial plane in all four AT levels ($p < 0.0382$). Moreover, SWE measurements were significantly higher in dorsal flexion than in plantar flexion in all four AT levels ($p < 0.0317$). Last, SWE visco-elasticity increases significantly from the musculo-tendinous junction to the pre-insertional and enthesis area ($p < 0.001$) in plantar flexion. There was no significant interobserver difference for morphologic measurements and for stiffness measure-

ments in plantar and dorsal flexions ($p > 0.075$).

Conclusion: Quantitative measurement of normal AT using SWE is reproducible almost in plantar flexion, and increase from musculo-tendinous junction to enthesis and could now be integrated in our routine AT ultrasound exploration.

Level of evidence: II.

KEY WORDS: achilles, tendon, elastography, shear-wave-elastography (SWE), ultrasound.

Introduction

Achilles tendinopathy has recently risen because of the over-use of this tendon in recreational but also sporting activities, in intermediate sport level and athletes population^{1,2}. Beside the necessary load X-rays, ultrasonography (US) is the first examination to explore this anatomical structure because of the superficiality of the Achilles tendon (AT) and the availability of this technique.

Nowadays, the US exploration is usually based on the B-mode and Power Doppler-mode to assess tendon lesions, with better sensitivity but lower specificity than MRI³. Indeed, US is the indirect reflection of the healthiness of the tendon through evaluation of peri-tendinopathy, tendinopathy, tear, hyperhematoma or calcification. This modality provides an anatomic precise imaging. However, it looks sometimes difficult to correlate tissue disorganization and clinical pain, especially in very previous symptoms. To go further in US assessment, elastography appeared and tried to provide functional characteristics of the stiffness behavior of the tendon. On the top of that, elastography software are more and more present on US system in clinical practice^{4,5}.

Three main different elastography techniques have been developed. First, the strain elastography (SE) needs external manual compression from the operator which is efficient for superficial organs or used the compression generate by internal physiologic motion and permits a qualitative assessment⁶. Second, Acoustic Radiation Force Impulse (ARFI) strain imaging is based on the tissues displacements perpendicular to the surface by a short duration high intensity acoustic pushing pulse and permits quantitative assessment^{7,8}. Last, the most recent technic is called Shear Wave Elastography (SWE) and is based on the creation of dynamic stress (with 2 pushing pulse)

to create shear waves into the tissue and their measurement^{9,10}. Since 2012, to our best knowledge, there have been many studies (around 45 publications) so far evaluating AT elastography, and discordant results have been reported. Kind of qualitative or quantitative data in elastography, in different ankle positions, in not the same clinical conditions, make the results difficult to interpret and then compare. Among them, 21 focused about healthy tendons and showed that elastography is feasible and reproducible in healthy volunteers¹¹⁻¹⁴. Twelve studies used SWE with same conclusion on feasibility in normal AT, with a softer pathologic AT and lower shear wave speed in case of tendinopathy¹⁵.

Moreover, to our knowledge, except one cadaveric series¹⁶, all these SWE series considerate AT as one unique entity and didn't takes in consideration AT anatomic regions and then biomechanical function and histology¹⁷.

The aim of this publication was 1) to assess the stiffness properties of the 4 different regions of normal AT by using SWE, in plantar and dorsal flexion; 2) to study its interobserver reproducibility and 3) try to propose an optimal anatomical and functional US protocol (within a reasonable time) in clinical practice.

Materials and methods

Study Population

Our study was submitted to the local institutional review board (CPP: Comité de Protection des Personnes du Sud-Ouest et d'Outre-Mer). None of the Authors received any support from any industry. All patients were volunteers and gave their written permission for anonymized use of their medical data for scientific purposes before the imaging examinations. They were prospectively included between February 2016 and May 2016.

The inclusion criteria for volunteers were age of 18 years or older. The exclusion criteria for volunteers were pregnancy, history of Achilles tendinopathy or AT surgery, pain in the AT. Volunteers with a history of systemic, metabolic, or endocrine diseases, psoriasis and those received corticosteroids, estrogens, quinolones, and cholesterol drugs were excluded because of known associations between those factors and tendinopathy^{18,19}. Volunteers with a VISA-A score < 90, were also excluded because of high risk of Achilles tendinopathy²⁰.

The age of AT was calculated by using the difference between inclusion date and birthdate.

US Procedure

All examinations were performed bilaterally in the same time procedure to a standardized protocol (described below) with the same US system (SuperSonic Imagine®, Aix-en-Provence, France) equipped with a 4-15 MHz superficial linear transducer. All measurements were realized by 2 (Musculo-skeletal)

MSK radiologists (respectively with 3 and 6 years post residency experience), at the same room temperature (20°C), the same day for each patient.

The tendon was divided in 4 anatomical regions: musculo-tendinous junction, body area, pre-insertional area (1 cm upwards the enthesis) and enthesis¹⁵.

First, pathologic AT characteristics were searched: enlargement (tendon thickness >5 millimeters)²¹, tendinosis, tear, calcification or hyperemia. Second, morphologic measurements were realized in dorsal flexion with the evaluation of the tendon thickness at the 4 AT levels described above and expressed in millimeters (mm).

Third, SWE quantitative measurement were obtained by placing a 1 mm diameter ROI in the tendon, on the most homogenous area of the elastogram, determined by the operator over the color qualitative cartography of the AT stiffness. One ROI was placed on the axial slice at each AT level, in each 4 quarter of the slide (supero-medial, supero-lateral, infero-medial, infero-lateral). Then a ROI was placed on the sagittal medial and lateral slice, also in the 4 AT portions (Figs. 1, 2).

No gel pad was used but a minimum 5 mm thickness of US gel (measured on the B mode) was necessary in order to make SWE measurements, to compensate the ankle curve with the linear probe²².

All measurements were realized in dorsal flexion with tiptoes on the examination bed (ankle at 90°, Fig. 3A) and repeated in plantar flexion with the back of the foot on the examination bed (ankle at 160°, Fig. 3B).

The mean and standard deviation (SD) of stiffness in kilo-Pascal (kPa) were recorded for each ROI.

Statistical analysis

The software SAS (SAS for Windows version 9.3; SAS Institute, Cary, NC) was used to support the data sets.

Continuous variables were expressed as mean and SD in millimeters for morphologic assessment and in kPa for stiffness values.

SWE sagittal and axial variables were compared between the 4 different AT regions, in plantar and dorsal AT flexion, for the 2 MSK radiologists, using Student t test. Interobserver reproducibility was also assessed. An overall *P* value of less than 0.05 was considered to indicate a significant difference.

Results

Population and morphologic US measurements

Fifteen healthy volunteers (i.e., 30 normal ATs) were included. Mean age was 29,5 years old (SD: 6,93). There were 7 males (47%) and 8 females (53%). There were as many left tendons as right because all subjects were analyzed both sides.

First, no pathologic AT characteristics were founded. No significant difference was noticed between all AT morphologic measurements between the 2 readers (*p*>0,42).

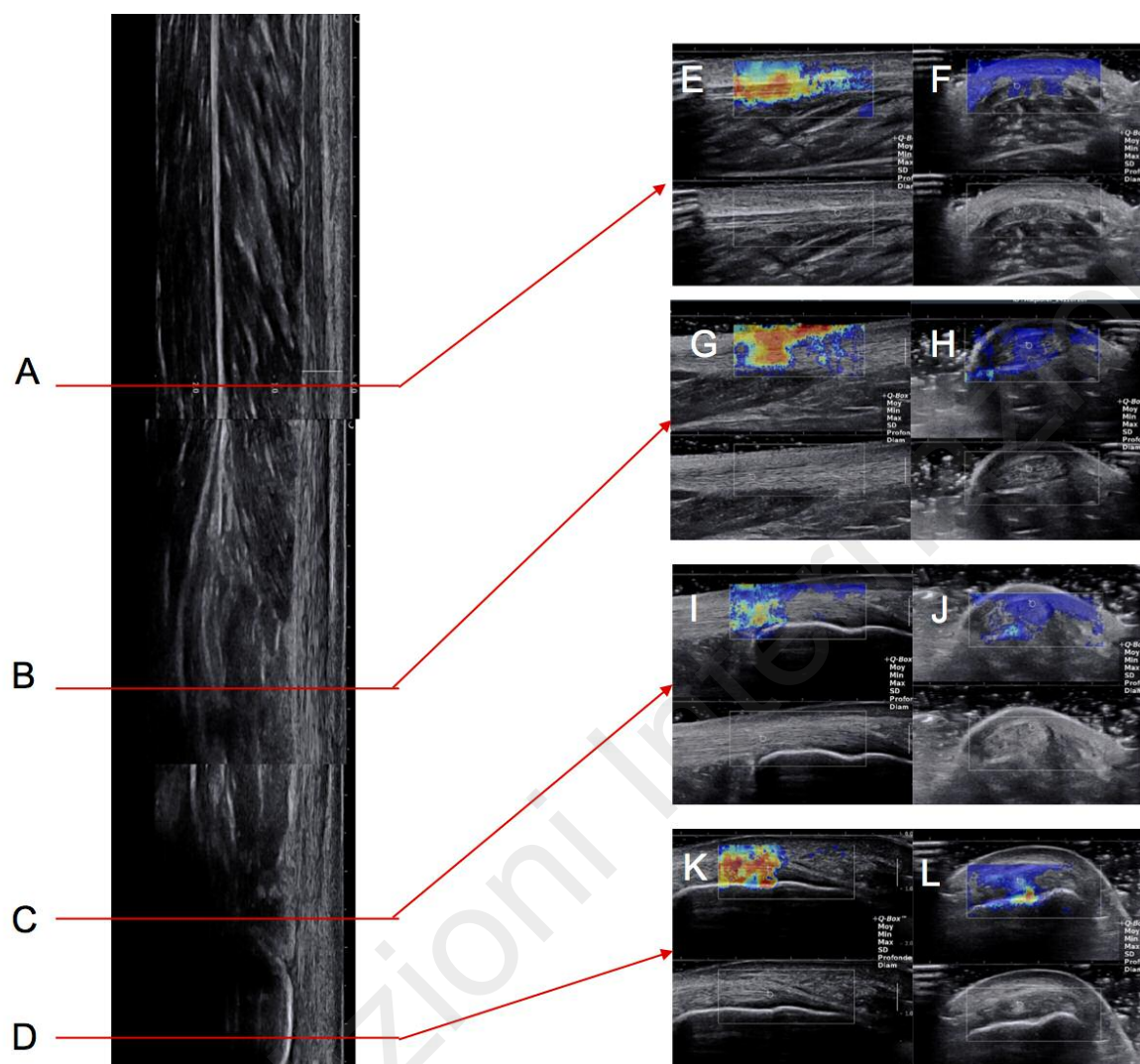


Figure 1. Panoramic reconstruction sonographic sagittal view of the AT in dorsal flexion with correspondent SWE acquisition of the 4 regions in sagittal and axial plane.

Table I resumed the morphologic antero-posterior diameter (in mm) of the 30 studied AT for both operators.

SWE US measurements

The measurements show higher stiffness for the sagittal position of the US than in axial plane in all four AT levels ($p < 0.0382$). Moreover, SWE measurements were significantly higher in dorsal flexion than in plantar flexion in all four AT levels ($p < 0.0317$). Last, SWE stiffness increases significantly from the musculo-tendinous junction to the pre-insertional and entheses area ($p < 0.001$) in plantar flexion ankle position.

These results were independent of the AT side: indeed, there was no significant difference according to the AT side ($p > 0.8$).

Table II resumed the stiffness (in kPa) of the 4 different portions of the tendon in axial and sagittal for both operators, in dorsal and plantar position.

Interobserver reproducibility

There was no significant difference between the two radiologists for all the measurements in plantar and dorsal flexions ($p > 0.075$).

Table III resumed the inter observer reliability of SWE stiffness of the 4 different portions of the tendon in axial and sagittal for both operators and both side, in dorsal and plantar position.

According to Table III, perfect interobserver correlation was obtained for the plantar flexion and lower interobserver reproducibility was obtained for the dorsal flexion, especially for the entheses region.

Discussion

Our study confirmed that AT stiffness is more important in sagittal plane than in axial plane and in dorsal flexion than in plantar flexion. Moreover, our results also showed that SWE stiffness increases significant-

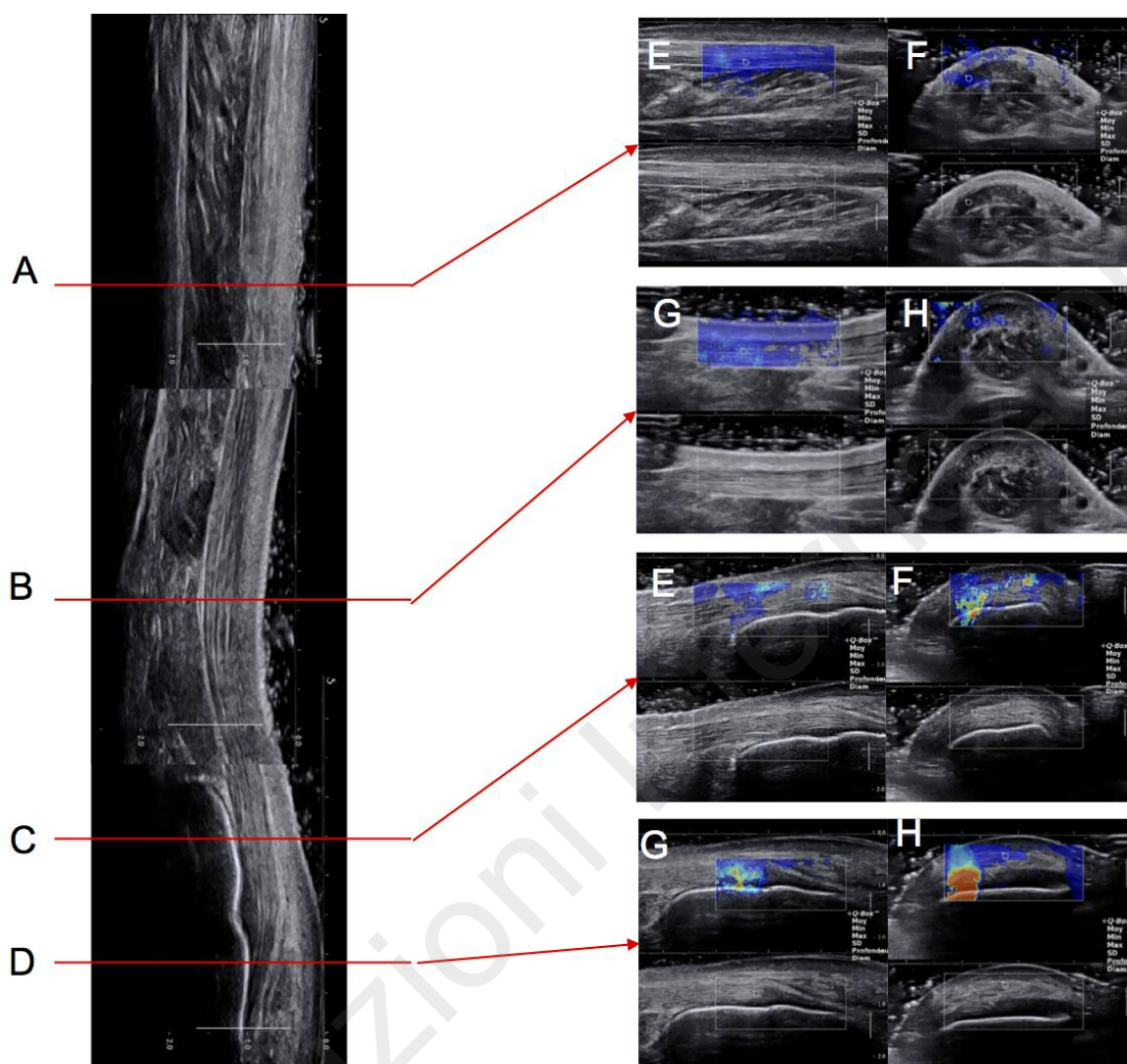


Figure 2. Panoramic reconstruction sonographic sagittal view of the AT in plantar flexion with correspondent SWE acquisition of the 4 regions in sagittal and axial plane.

Table I. Morphologic antero-posterior diameter (mm) of the 30 studied Achilles tendons for the 2 readers. Mtj: Myo-tendinous junction.

	Operator 1	Operator 2	p
Mtj	1,77	1,65	0.4212
Body	4,00	4,01	0.5889
Pre insertional	3,61	3,39	0.5491
Enthesis	2,89	2,68	0.7043

ly from the musculo-tendinous junction to the enthesis area in plantar flexion with a perfect interobserver correlation.

Our results are concordant with most part of recent SWE literature, despite controversial conclusions concerning elastography.

On one hand, in 2011, Aubry et al. studied the AT of 30 healthy subjects in 3 positions and demonstrated good intra individual correlation with interobserver reproducibility assessment in a unique measure on AT body¹². Then, they explored healthy and pathologic tendon stiffness by SWE but with only one operator. This study showed a softening of the mid portion of the tendon for pathologic tendons, with a high specificity and low sensitivity. The mean stiffness was higher in the sagittal position than in the axial because the strong anisotropy of the tendon. Shear waves propagate slower perpendicularly to the tendon¹⁵. Our results are consistent with these series concerning AT healthy body assessment but show also the same difference between axial and sagittal measurements^{12,15}.

In the same way, Suydam et al. studied 29 healthy volunteers and showed that there was no difference between right and left AT assessment²³. One single

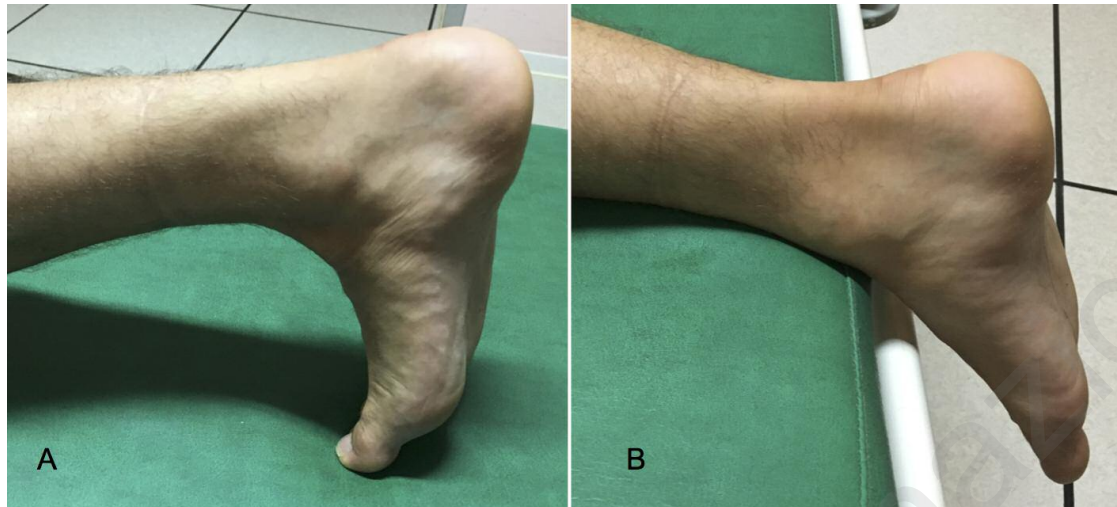


Figure 3. Picture of patient ankle position during examination with dorsal flexion (A) and plantar flexion (B).

Table II. SWE stiffness (kPA) of the 4 different portions of the Achilles tendon in axial and sagittal plane, for both operators (op1: operator1; op2: operator2), in dorsal and plantar position. Mtj: Myo-tendinous junction.

DORSAL FLEXION					
	Axial	mean	SD	min	max
OP 1	Mtj	54,6	27,3	2,2	150,6
	body	79,5	111,9	2,2	752
	pre insertional	57,8	50,0	1,3	250,2
	enthesis	40,5	44,1	1,2	261,9
OP 2	Mtj	38,5	26,9	2,1	170
	body	45,5	35,8	1,3	287
	pre insertional	47,7	44,9	1,1	182,8
	enthesis	60,1	51,6	3,2	305,5
	Sagittal	mean	SD	min	max
OP 1	Mtj	96,7	107,8	1,8	641,4
	body	80,4	73,6	2	281
	pre insertional	82,9	77,2	4,4	377,9
	enthesis	53,8	41,2	3,9	207,6
OP 2	Mtj	106,3	104,9	0,8	512
	body	94,6	80,1	1,4	306,4
	pre insertional	95,4	83,8	1,4	371,7
	enthesis	67,0	76,9	1,7	475
PLANTAR FLEXION					
	Axial	mean	SD	min	max
OP 1	Mtj	39,1	31,8	1	254,8
	body	48,8	33,6	2,1	165
	pre insertional	62,9	37,8	1,4	259,2
	enthesis	66,5	51,1	1,9	281,8

To be continued

Continue from **Table II.**

OP 2	Mtj	32,8	17,8	1,6	89,3
	body	42,9	27,1	1,9	167,3
	pre insertional	75,2	52,8	1,7	244
	enthesis	61,2	57,3	0,6	258,4
	Sagittal	mean	SD	min	max
OP 1	Mtj	72,4	44,8	7,2	280,6
	body	86,1	49,5	10,3	243,4
	pre insertional	65,4	54,5	1,2	296,8
	enthesis	62,3	46,8	3,7	197,2
OP 2	Mtj	85,8	46,4	8,3	209,2
	body	95,3	61,6	7,8	269,5
	pre insertional	59,8	39,9	2,5	211,3
	enthesis	73,4	58,7	1,4	241,3

Table III. Inter observer reliability of SWE stiffness (kPa) of the 4 different portions of the tendon in axial and sagittal for both operators (op1: operator1; op2: operator2), in dorsal and plantar position. Mtj: Myo-tendinous junction.

PLANTAR FLEXION			DORSAL FLEXION		
Axial	Mtj	0.30526	Axial	Mtj	0.13377
	Body	0.30449		Body	0.095516
	Pre insertional	-		Pre insertional	-
	Enthesis	0.27311		Enthesis	0.16907
Sagittal	Mtj	0.16376	Sagittal	Mtj	-
	Body	-		Body	0.23587
	Pre insertional	0.15332		Pre insertional	0.070272
	Enthesis	0.075153		Enthesis	0.095756

operator measured the stiffness at 10° of dorsi-flexion, in AT body, on a dynamometer in order to have a constant strength on the tendon with a mean stiffness of 83,2 kPa. Considering the 4 AT levels, we made the same statement and found no difference between both AT side. Considering AT body in plantar flexion, our values were respectively 45,9 kPa and 90,7 kPa in axial and sagittal position and are linkable with this SWE literature.

Then, in the most important cohort, Fu et al. measured SWE in AT body on 326 healthy volunteers in axial and sagittal in relaxed position of the ankle²⁴. They showed a good interobserver reproducibility (0,923 for axial measurement and 0,870 for sagittal) in this plantar flexion, with no significant difference with age. Considering AT body in plantar flexion, our values also correlates with these previous data.

In our series, we divided AT in 4 portions based on

Del Buono et al. functional description. Del Buono et al. divided the tendon and have taken in consideration AT anatomic regions and then biomechanical function to class AT in non-insertional and insertional parts, with muscular fibers for the non-insertional and different management between these two main regions¹⁷. In literature and in our personal experience, this could be explained by the histologic structure of the tendon which is different between AT musculo-tendinous junction, body and insertional parts with different biomechanical functions. Physiologically, a tendon is formed by collagen fibers, associated with striated muscle cells in smaller quantities than in muscle in its myo-tendinous junction²⁵. The healthy body and the pre-insertional tendon are principally composed of type 1 collagen and a few elastic fibers, within a ground substance containing cells (tenocytes and tenoblastes) and water. Concerning the enthesitis,

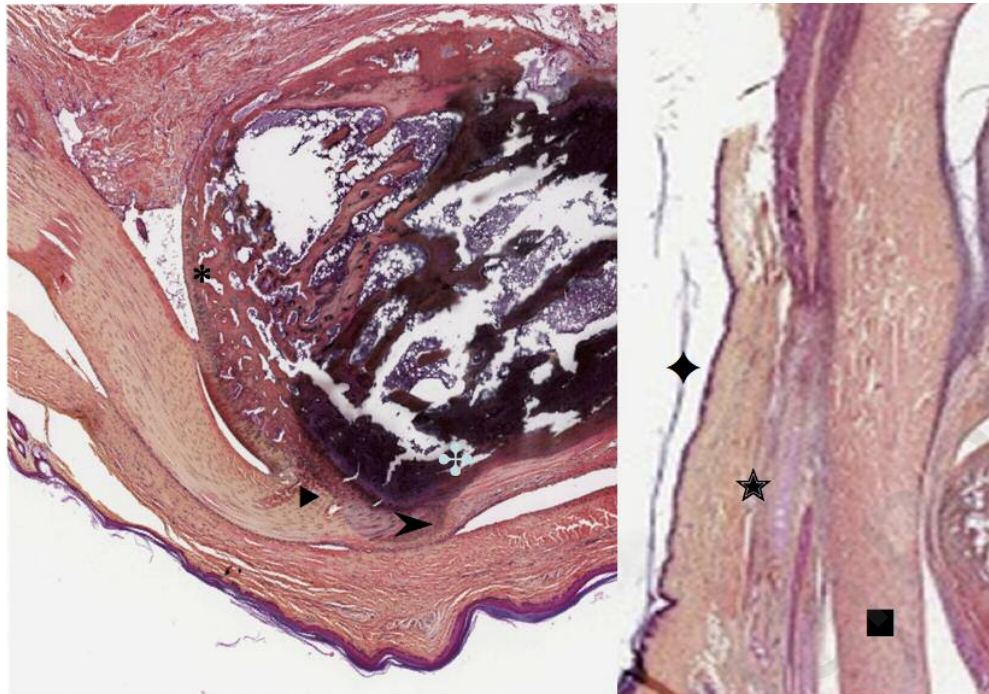


Figure 4. Sagittal histological section of a rat tendon showing the three insertional tendinous structures (▶ sesamoido-fibrocartilage, ► entheso-fibrocartilage and ✕ periostofibrocartilage) and musculo-tendinous structures (■ body tendon, ★ muscle, ◆ skin).

three parts can be distinguished: sesamoido-fibrocartilage, entheso-fibrocartilage and periostofibrocartilage (Fig. 4)²⁶. This could explain our results with a stiffer tendon near the enthesis.

On the other hand, a former qualitative SE study, by De Zordo et al., divided the tendon in 3 portions (1: musculo-tendinous junction; 2: 2-6 cm above insertion of the calcaneus and 3: the insertion of the calcaneus) founded also the same differences than ours concerning AT stiffness with SE¹¹. In a more recent cadaveric study, Haen et al. divided tendon in 3 portions and showed a significant difference in quantitative SWE values in function of the strain of the tendon but, unfortunately, they didn't analyze the difference between these 3 portions¹⁶. However, they focused, like in our own experience, about an increase of the AT stiffness in maximal dorsal flexion.

In the same way, a recent study of Payne et al. presented also contradictory results with SE elastography (on the tendon's body in one unique site) with poor reproducibility of compression elastography in AT, considering same day and consecutive day measurements²⁷.

With SWE elastography, the same ward team found, in a very recent series, that reproducible SWE measures were obtained over a 1-h period as well as a period of 5 consecutive days with more reliable measures obtained using a relaxed foot position²⁸. These very recent results are concordant with ours. Indeed, our results are less reproducible concerning SWE measurements in the dorsal flexion, and the SD are

much larger in this position. This should make us think that the most interesting value is the plantar flexion SWE measurement.

Our study has however 2 main limitations. First, this study was constrained by the small size of patients (n=15) but to our knowledge, it is the largest homogeneous series, with a prospective design, focusing on AT healthy tendon quantitative SWE, not considering AT as a unique tube entity. Second, neither intra-observer agreement was calculated. However, our goal was to evaluate, in clinical practice, SWE quantitative assessment in AT and not intraobserver MSK radiologist reproducibility. Last, we didn't use any pad like previous studies, but we proceed like this to be as close as possible to the daily practice.

Our study is a great amount of data collected on few normal AT with 2 MSK operators in the same exact conditions of SWE measurements, considering its zonal anatomy and trying to explain SWE differences in correlation with biomechanical and histology aspects. According to these results, we propose a reliable and simplified AT US dynamic protocol, in a reasonable time, with a 2-time cluster: 1) Dorsal Flexion with anatomic measurements and tendinopathy assessment in B-mode - 2) Plantar Flexion with vascular and functional stiffness assessment in Power-Doppler and SWE mode. Indeed, the perspective of our study is to detect pre-morphological changes in very early or tenuous AT symptomatic tendinopathy, due to the SWE analysis, such as Dirrichs et al. considering SWE for the evaluation of patients with

tendinopathies with increased sensitivity from 67.1 to 94.3% using SWE or for monitoring of treatment of these tendinopathies^{29,30}.

Conclusion

Our study investigated the SWE quantitative variable stiffness value in all the 4 parts of AT, in correlation with its zonal anatomy. According to these results, we propose a reliable and simplified AT US protocol with a 2-times cluster: 1) Dorsal Flexion with anatomic measurements and tendinopathy assessment in B-mode - 2) Plantar Flexion with vascular and functional stiffness assessment in Power-Doppler and SWE mode, in a reasonable time. Further series should be leaded using a prospective design and a large included cohort to confirm our results.

Conflict of interest

No potential conflict of interest relevant to this article was reported.

Ethics

The Authors declare that this research was conducted following basic ethical aspects and international standards as required by the Journal and recently update in³¹.

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