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Sonoelastography of the Achilles tendon: a review

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ABSTRACT

Sonoelastography (SE) is a method that evaluates the mechanical properties of tissue by detecting tissue displacement and strain after stress applied to the tissue. There are various sonoelastography techniques used in clinical practice. Strain elastography, which allows real-time visualization of the tissue elastography map, is the most widely used technique. There is increasing evidence that SE can be used to measure the mechanical properties of musculoskeletal tissue in clinical practice. It is thought to have the potential to guide both early diagnosis and treatment monitoring and therapy in the future. This review describes various Achilles tendon SE techniques and published evidence for clinical use and includes discussions on the use and limitations of SE in the musculoskeletal system and future perspectives.

Keywords: Ultrasound, elastography, shear wave, strain, Achilles tendon, tendinopathy

INTRODUCTION

Sonoelastography (SE) is a new and promising non-invasive method based on ultrasound that evaluates the elastic properties of tissues based on the physical principles produced by tissue compression. This technique was introduced in vitro in the early 1990s and has since been used in real-time in vivo. In addition to B-mode and Doppler imaging, which provide acoustic impedance and vascular flow information in diagnostic imaging, SE provides information about tissue stiffness, opening a new window.[1-5]

SE is based on showing the change in the elastic properties of the stressed tissue. Over the years, studies on elasticity have used different methods to measure the displacement of stressed tissue. Strain elastography is one of the most widely used techniques that allows real-time visualization of the image in different tissues and organs and can detect and characterize lesions.[1-3]

Changes in tissue and cell biomechanics occur because of many diseases. SE examination is currently used in the diagnosis of breast, thyroid, cervix, and liver pathologies.[6-9] In the musculoskeletal system, it is used to evaluate tendons, muscles, fascia, and subcutaneous tissue. The Achilles tendon is the first area to be evaluated using SE. Achilles tendon SE provides most of the clinical data in musculoskeletal applications available so far.[9-11]

The aim of this review is to describe the various published elastographic applications on the Achilles tendon and to discuss limitations and future perspectives.

ELASTOGRAPHY PHYSICS AND SONOELASTOGRAPHY METHODS

Elastography assesses tissue elasticity, which is the tendency of tissue to resist deformation by an applied force or to return to its original shape after removal of the force. Hooke's law is defined as the law of elasticity, where a material is completely elastic and its deformation does not depend on time. An equation for linear elastic materials ($\sigma=E \cdot \varepsilon$) was proposed by the English mathematician Robert Hooke (1653-1703) and is known as Hooke's Law. Under the effect of any pressure or stress, a shortening of the length of the object occurs. While the change in length is called deformation, the amount of length change per unit length is called strain (ε - epsilon). During this deformation, there is a direct proportional relationship between stress (σ) and strain (ε) ratio.[12] Strain imaging uses the direct Hooke's Law relationship where σ represents the externally applied stress and ε represents the strain.[13]

Elastography is a set of techniques in which tissue stiffness is estimated as a physical property called Young's modulus (E). Young's modulus is defined as the ratio of the stress (force per unit area) applied to the object and the resulting axial strain (displacement or deformation) in the linear elastic region of the material.

SE methods can be divided into two categories: strain-based (**Figure 1**) and shear-wave-based (**Figure 2**). In strain-based elastography, force is applied through the application of probe pressure or endogenous mechanical force (e.g., carotid pulsation). In shear wave-based elastography, the imaging system induces a tissue shear wave. In both approaches,

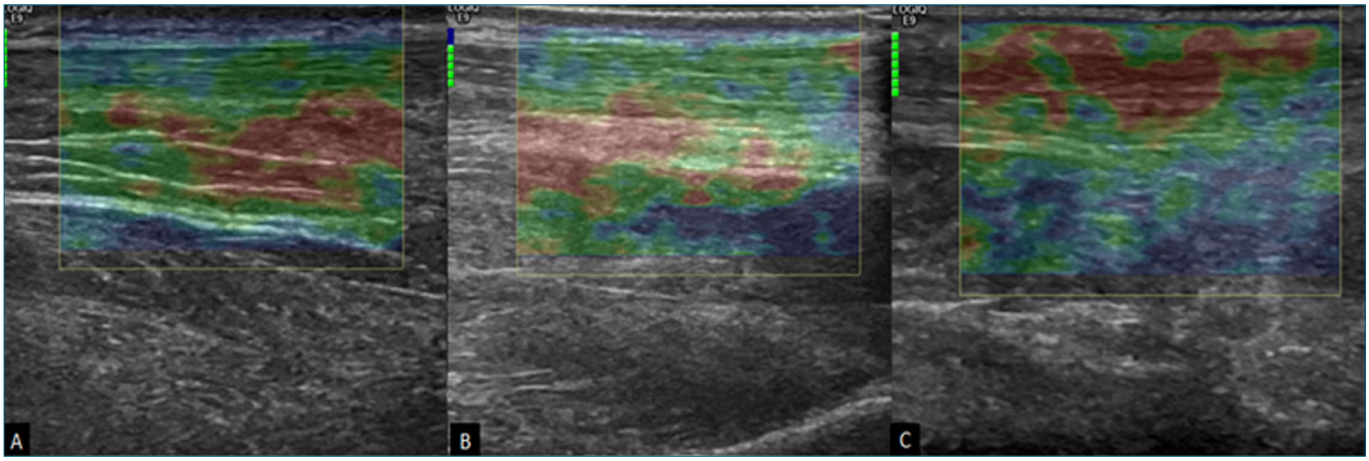

Figure 1. Strain elastography image of the Achilles tendon with different stiffness. Ultrasound probe was placed in a longitudinal scan at the level of the medial malleolus.

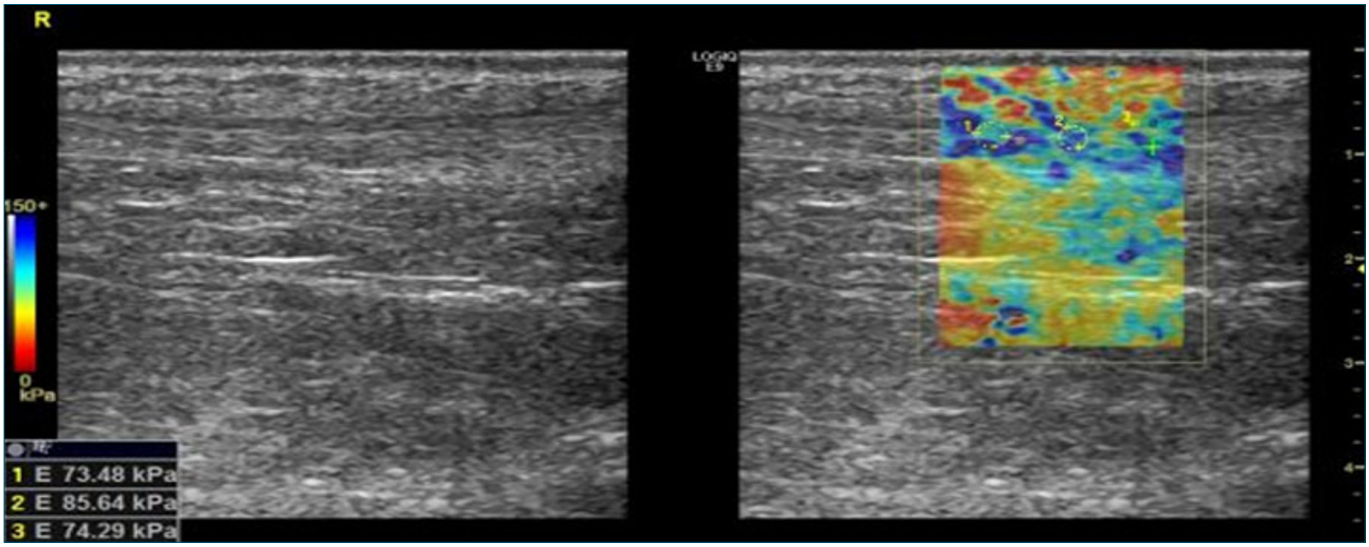

Figure 2. SWE measurements(kPa) of Achilles tendon in a longitudinal scan

the tissue response to these mechanical stimuli is used to estimate the mechanical properties of the tissue.[12]

Young's modulus is not calculated with clinical strain imaging systems, as the force applied to the tissue of interest is usually unknown. Shear wave imaging systems calculate Young's modulus using the relationship E=3ρcs2, where ρ represents the tissue density and cs represents the shear wave velocity.

The ultrasound operator can convert kPa to m/s and m/s to kPa. At the end of the US examination, most US systems display a table showing hardness values in both kPa and m/s.[13]

THE ROLE OF SONOELASTOGRAPHY IN TENDON EVALUATION

B-mode ultrasonography (US) is usually the first imaging modality used to evaluate tendon abnormalities because it is easily accessible, fast, safe, and inexpensive. With conventional B-mode US, the diagnosis of tendinopathy is often based on the presence of morphologic changes of the relevant tendon, such as focal or diffuse thickening, intra-tendon hypoechoic areas. Beyond the morphological information obtained with US, power doppler (PD) can show pathologically increased vascularization.[14-16] Currently, current imaging of tendon pathologies is mainly based on magnetic resonance imaging (MRI) in addition to traditional B-mode and PD sonography. However, it is well known that US and MRI show a "limited correlation between structural irregularity and pain," i.e., various tendons of asymptomatic patients may have abnormal imaging on MRI but not on B-US and PD-US. In addition, there is thought to be a lack of current imaging modalities (B-US, PD-US, and MRI) in defining the smooth transition process from "asymptomatic" to "symptomatic" (or vice versa) during the incipient disease or healing process in the tendon. Therefore, so far, the interpretation of tendon structure analyzed by B-US, PD-US, and MRI with additional examinations such as SE could benefit the clinic.[17,18]

Recently, shear wave elastography (SWE) has been recognized as a technique that provides quantitative information about tissue stiffness and thus the mechanical properties of a tendon. SWE is a real-time diagnostic imaging technique that provides quantitative information on tissue elasticity (in kilopascals (kPa) or meters per second (m/s). Real-time ultrafast SWE calculates the US pulse's generated shear wave velocity (in meters per second). Further studies are needed to fully correlate SWE with the reference standard. However, SWE provides diagnostic information complementary to B-mode US and PD-US. SWE has been shown to be able to detect and grade tendinopathies and can significantly improve diagnostic accuracy. Quantitative and semi-quantitative SWE measurements of Achilles, patellar, and wrist extensor tendons have been found to correlate better with patient symptoms than traditional ultrasound findings.[19,20] SWE allows repeated intra-individual as well as inter-individual measurements and comparisons and is therefore suitable for diagnosis and treatment monitoring.

In general, symptomatic tendons exhibit lower SWE values than asymptomatic tendons, but so far there are no universally accepted or applicable reference values for healthy Achilles tendons. Little is known about factors that influence tendon stiffness, such as patient age, weight, pre-existing diseases, or strengthening of a tendon due to exercise.

ACHILLES TENDON SONOELASTOGRAPHY

The Achilles tendon is the thickest, largest, and strongest tendon in the human body and is loaded 3.9 times the body weight during walking and 7.7 times the body weight during running. With these tensile loads, the tendon structure is exposed to the highest stress in the body. Especially if there is a biomechanical incompatibility, it is exposed to significant stress when running uphill and downhill.[21]

Many factors contribute to the development of tendinopathy in the general population and among athletes. The exact mechanisms leading to tendinopathy are complex and poorly understood. However, overuse of the tendon has an important role in the onset of tendinopathy. Tendinopathy can occur in any tendon, especially in the adhesion zone where the greatest stresses occur. Any activity or condition that increases the load to which the tendon is subjected (e.g., increased activity, weight gain, age) can lead to tendinopathy.[22]

Risk factors for tendinopathy can be divided into intrinsic and extrinsic factors; intrinsic factors originate from the body itself, such as age, gender, obesity, and genetics, while extrinsic factors originate from outside the body, such as excessive activity or intensity, occupation, footwear, and environmental conditions.[22] Although the etiology of tendinopathy is known to be multifactorial, there are many studies in the literature on risk factors.

In a study by Timm Dirrichs et al.[23] Achilles tendon SWE was assessed by taking measurements of both Achilles tendons from 33 semi-professional athletes and 35 non-athletes, totaling 68 individuals with a training history of at least 5 years of weekly running. Two radiologists with 6 and 7 years of experience took the measurements without knowing whether the participants were "athletes" or "non-athletes." The mean SWE value in athletes was 187.2 kPa (±45.2 kPa) on the right and 180.4 kPa (±39.7 kPa) on the left; in non-athletes, it was 105.4 kPa (±34.9 kPa) on the right and 101.8 kPa (±28.9) on the left. Dirrichs found a significant increase in tendon stiffness in athletes compared to non-athletes.

Coombes et al.[24] In a study of 40 patients (33 study patients and 7 control patients), they investigated the effects of diabetes on tendons. In their study, they also evaluated Achilles tendon thickness with B-mode US and tendon elasticity with shear wave velocity (SWV) in patients with and without statin use. They found lower SWV values and increased thickness values in the Achilles tendon of participants with diabetes on statins compared to participants without statins. They found that SWV of the Achilles tendon was moderately negatively correlated with total cholesterol and LDL cholesterol in statin-treated diabetic patients, whereas no correlation was found with serum lipids in non-statin-treated patients. The relationship between Achilles tendon thickness, elasticity, and body mass index (BMI) was also evaluated in this study by Coombes et al.[24] A negative correlation was observed between SWV of the Achilles tendon and BMI. A minimal positive correlation was observed between Achilles tendon thickness and BMI. They thought that this was due to the pathologic effects of lipids and cholesterol causing subcutaneous fat accumulation in and around the tendon. Long-term statin use was thought to cause microdamage to the tendon and decrease tendon elasticity. It is thought that these changes in the extracellular matrix of tendons after treatment with statins probably cause microdamage and micro ruptures in the tendon, and that these factors are the pathophysiology causing the loss of elasticity in the tendon.

Wen Cao et al.[25] conducted a large multicenter study with a total of 1165 adult participants in 17 Chinese hospitals using SE to determine Achilles tendon visco-elasticity in healthy humans and to determine normal values. Measurements were made in the middle 1/3 of the Achilles tendon with the foot in a relaxed, neutral position. Tendon circumference measurements were taken simultaneously from the section where tendon thickness measurements were taken. The data were obtained using these two measurements, the SWE value, and the elastic modulus (Young's modulus), which is the resistance of a substance to elastic deformation. In the study, BMI values were calculated from the height and weight data of the patients. The mean BMI value was found to be 22.75 (±3.22). In another study conducted in Chinese patients, both Achilles tendon thicknesses were found to be 0.48 cm (±0.27 cm) on the left and 0.47 cm (±0.07 cm) on the right. Wen Cao et al.[25] obtained Young's modulus SWE kPa values with tendon circumference, diameter, and SWE multiplier when the Achilles tendon was in its natural position and found 381.41 kPa (±106.50 kPa) on the right and 374.24 kPa (±106.12 kPa) on the left for both Achilles tendons.

Alessandro Schneebeli et al.[26] used elastography to look at the Achilles tendon's mechanical properties and elasticity while it was being stretched isometrically. 20 healthy participants underwent repeated measurements with SE and SWE by 2 radiologists with 7 years of musculoskeletal SE experience. The examination was performed longitudinally along the Achilles tendon by evaluating B mode, SE, and SWE. Measurements were taken at the level of the medial malleus and not at the Achilles tendon calcaneal attachment to avoid the effect of stiffening artifacts that may occur near the bone. Participants were instructed to perform contractions of different intensities (0 kg, 0.5 kg, 1 kg, 2 kg, 5 kg, and 10 kg) from the plantar flexion position using a wrist ergometer. Measurements were made on each tendon each time. Both practitioners obtained similar results in SE evaluations. They found a decrease in the strain rate in the Achilles tendon as the contraction intensity increased. However, in SWE measurements with increasing contraction intensity, the first practitioner found a decrease in the strain value, while the other practitioner's measurement showed an increase in the strain value with increasing contraction intensity.

SE probably represents the most important technical development in the field of ultrasonography since Doppler imaging. It has many advantages over other tissue elasticity estimation methods, such as MR elastography, as it is a low-cost, non-invasive, and rapid system and has the potential for wider clinical availability. The evidence so far seems very promising that SE can be used to assess the mechanical properties of musculoskeletal tissues in a clinical setting. It suggests that SE may be even more sensitive than MRI or gray-scale ultrasound in detecting subclinical changes in muscle and tendon and may therefore be valuable in early diagnosis

and rehabilitation. SE can be used as a research tool to provide information on the biomechanics and pathophysiology of musculotendinous diseases. However, despite the great interest in the technique, published literature information is still very limited and is mainly based on case reports or studies with small study populations using various EUS techniques and scoring systems. The lack of measurement methods, which limits the reproducibility of the method, and various technical issues, such as artifacts and differences in the application of the technique by different users, cast doubt on its potential clinical utility. In addition, it has been found that in most pathologic conditions, the changes detected on SE are those that are evident on B-mode US and PD examinations. The clinical significance of changes that are not seen in conventional B-mode US and PD but can be seen in SE is controversial.

For all these reasons, it is obvious that there is a need for standardization and consensus for elastogram window size, adapter/pad/gel usage, and scoring in soft tissue applications for SE. It is very important to ensure this consistency in the future, and this will only be possible by applying the technique to many studies performed today and making comparisons between studies.

CONCLUSION

SE in its current form remains highly subjective due to a lack of standardization and limited research data in terms of its clinical value. With more research and appropriate standardization, SE could become a valuable complementary tool in the study of musculoskeletal disorders.

ETHICAL DECLARATIONS

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

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Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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