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# Evaluation of Elastic Stiffness in Healing Achilles Tendon After Surgical Repair of a Tendon Rupture Using *In Vivo* Ultrasound Shear Wave Elastography

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Statistical Analysis C  
Data Interpretation D  
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**Background:** There has been no published report assessing the mechanical properties of a repaired Achilles tendon after surgery using shear wave elastography (SWE). The aim of this study was to investigate the changes in mechanical properties of the healing Achilles tendon after surgical repair of a tendon rupture using ultrasound SWE and how these changes correlate with tendon function.





**Material/Methods:** Twenty-six patients who underwent surgical repair for Achilles tendon rupture were examined with ultrasound SWE coupled with a linear array transducer (4–15 MHz). The elasticity values of the repaired Achilles tendon in a longitudinal view were measured at 12, 24, and 48 weeks postoperatively. Functional outcomes were assessed with the American Orthopedic Foot and Ankle Society (AOFAS) rating system at 12, 24, and 48 weeks postoperatively. General linear regression analysis and correlation coefficients were used to analyze the relationship between elasticity and the AOFAS score.

**Results:** There were significant differences with respect to the mean elasticity values and functional scores of the repaired Achilles tendon at 12, 24, and 48 weeks postoperatively (all  $P < 0.05$ ). Tendon function was positively correlated with the elasticity of the repaired Achilles tendon ( $P = 0.0003$ ).

**Conclusions:** Our findings suggest that SWE can provide biomechanical information for evaluating the mechanical properties of healing Achilles tendon and predict Achilles tendon function.

**MeSH Keywords:** **Achilles Tendon • Elasticity Imaging Techniques • Foot Injuries • Ultrasonography**

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## Background

The Achilles tendon is the most commonly ruptured tendon in the body [1]. Rupture of the Achilles tendon, a debilitating injury, often requires surgical repair and extended immobilization, which may lead to prolonged rehabilitation [2]. In addition, the ruptured Achilles tendon heals slowly due to the limited blood supply and slow cell turnover [3]. Damaged and then healed Achilles tendon is composed of a curved pattern of thin collagen fibers with decreased type I and a greater proportion of weaker type III collagen [4]. Changes in tendon structure may also affect its biomechanical properties, which in turn affect its performance and patient's coordination in daily life. Normally, the Achilles tendon absorbs energy of motion in life activities such as walking, running, and jumping [5]. The tendon can be extended because of its viscoelastic properties, which are critical for storing elastic energy. However, its viscoelasticity may be affected by rupture, repair, and subsequent remodeling during the healing process, thus resulting in changes in tendon stiffness (the resistance of tendons to lengthening). If repaired tendons are too stiff and hence not being able to absorb sufficient energy during the motion, they are more likely to be injured again [6]. Therefore, it is important to evaluate the tendon stiffness following repair of Achilles tendon rupture.

Prior studies showed that the mechanical properties of a repaired tendon, such as stiffness, provide information on the material properties of the tendon tissue and its function [7–9]. However, measuring such properties via histological and biomechanical methods is invasive and thus is not suitable in a clinical setting. Currently, clinical questionnaires containing items about pain, functional activity level assessments, and muscle strength testing have been established to assess the recovery of injured tendons *in vivo*. However, the correlation between functional outcomes and tendon stiffness remains unclear.

Ultrasound shear wave elastography (SWE) is a non-invasive ultrasonographic imaging technique introduced in 2002 [10], which has the advantage of being operator-independent, reproducible, and quantitative [11]. Currently, the SWE method has been used to detect quantitative and qualitative information in the normal and pathologic Achilles tendon [12,13]. However, to the best of our knowledge, there has been no report assessing the mechanical properties of a repaired Achilles tendon after surgery. The main objective of our study was to investigate the changes in mechanical properties of the healing Achilles tendon after surgical repair of a tendon rupture with SWE *in vivo* during the various stages of rehabilitation. We hypothesized that stiffness of the repaired Achilles tendon would increase 2–6 months postoperatively, and that SWE could detect the increase. The secondary objective was to investigate whether these changes correlate with tendon

function. We hypothesized that stiffness of the repaired Achilles tendon, as estimated by SWE, would be associated with the function outcome.

## Material and Methods

### Patients

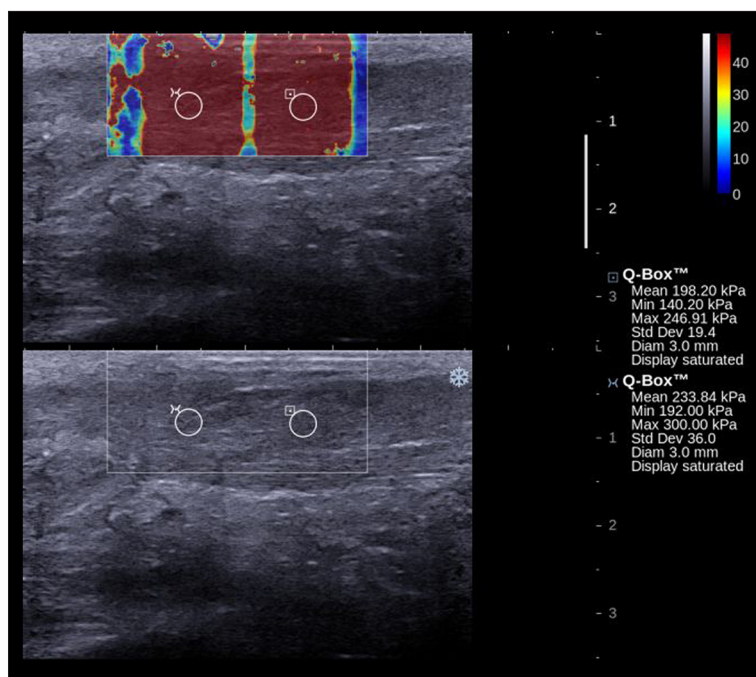
This study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of the Chinese PLA General Hospital. Written informed consent was obtained from all subjects.

From May 2009 to April 2011, a total of 26 patients who underwent surgical treatment of acute and complete Achilles tendon rupture at the Chinese PLA General Hospital were included in this study. The patients were 5 females and 21 males with a median age of  $38.1 \pm 10.6$  years (range 18–65). The causes of injury in all of the 26 patients were sports or sports-related injury. In all cases, the rupture was located in the middle third of the tendon and was treated with open surgery. Of the patients studied, 10 had ruptures on the right side and 16 on the left side). Patients with diabetes mellitus, cancer, lung and heart diseases, rheumatoid arthritis, spondyloarthropathy, and hypercholesterolemia were excluded due to the association between these factors and tendon abnormalities [14]. At enrollment, clinical details were obtained from each patient, and radiological and functional assessments were performed.

Patients received a modified rehabilitation program [15] supervised by the physiotherapist at our hospital's rehabilitation center. The rehabilitation program included non-weight-bearing cast immobilization with reduced equinus and toe motion for 6 weeks and a short leg cast with neutral ankle dorsiflexion from 6 to 8 weeks postoperatively. After fitting with a partial weight-bearing, removable cast boot or night splint from 8 to 12 weeks postoperatively, patients completed a physical therapy program, including proprioceptive and functional ankle recovery, and cross-training. The cast boot was discontinued at 12 weeks postoperatively. Then patients sustained full weight-bearing followed by a physical therapy program, including return to sport, road running, and cross-training.

### Ultrasound examinations

A commercially available Aixplorer® system (Supersonic Imaging, Aix-en-Provence, France) coupled with a linear array transducer (4–15 MHz) was used to assess the elasticity of the Achilles tendons. Each tendon was scanned in a prone position with the foot hanging over the edge of the examination bed in a neutral position to avoid tendon stress [16]. At 12, 24, and 48 weeks postoperatively, the tendons were examined in longitudinal



**Figure 1.** Conventional ultrasound and SWE images of surgically repaired Achilles tendon at 12 weeks postoperatively. The boxes are the regions of interest for quantitative measurement.

planes by the same radiologist with 13 years of experience in musculoskeletal ultrasound. SWE measurements were obtained by applying light repetitive compression [17] with a handheld transducer to avoid strain-stiffening effect. The color SWE map suspended on the B-mode image was placed at the upper part of the screen with the B-mode image at the lower part. The color scale of elasticity values displayed on right of the image ranged from 0 to 160 kPa, with red representing hardness and blue softness. Using the B-mode ultrasound display for guidance, an ROI was selected in the repaired part of the Achilles tendon, and quantitative data (elastographic index) in kPa (mean, maximum, and minimum) were determined. SWE scans were repeated at least 4 times to obtain a mean value of the elastic modulus.

### Functional outcomes

Tendon function was assessed at 12, 24, and 48 weeks postoperatively using the American Orthopedic Foot and Ankle Society (AOFAS) rating system [18].

### Statistical analysis

Continuous variables are expressed as means±standard deviations (SD). STATA software (version 11.0; Stata Corp., TX) was used for data analysis. Repeated ANOVA was used to compare differences in elastic modulus values and AOFAS scores at the 3 postoperative time points. General linear regression analysis and correlation coefficients were used to investigate the relationship between elasticity and functional scores. Differences were considered statistically significant when  $P < 0.05$ .

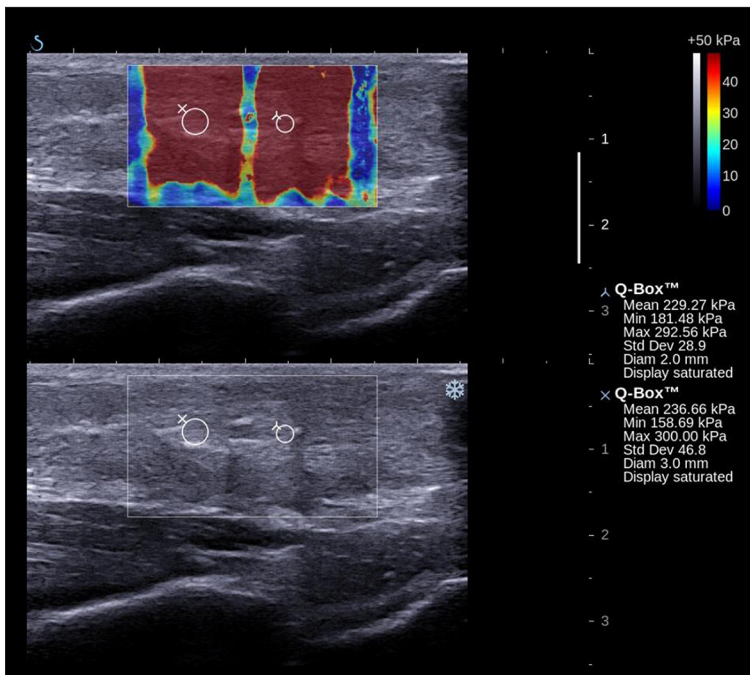
## Results

The average time from injury to surgery was 4.8 (range, 0.5–13) days. Postoperatively, none of the patients developed postoperative infections, deep venous thrombosis, recurrences, or pulmonary embolisms. The average follow-up time was 12.3 months, ranging from 10.2 to 15 months. The mean time to return to sports in the 26 patients who returned to sport was 15.3 weeks (range, 12 weeks to 18 weeks)

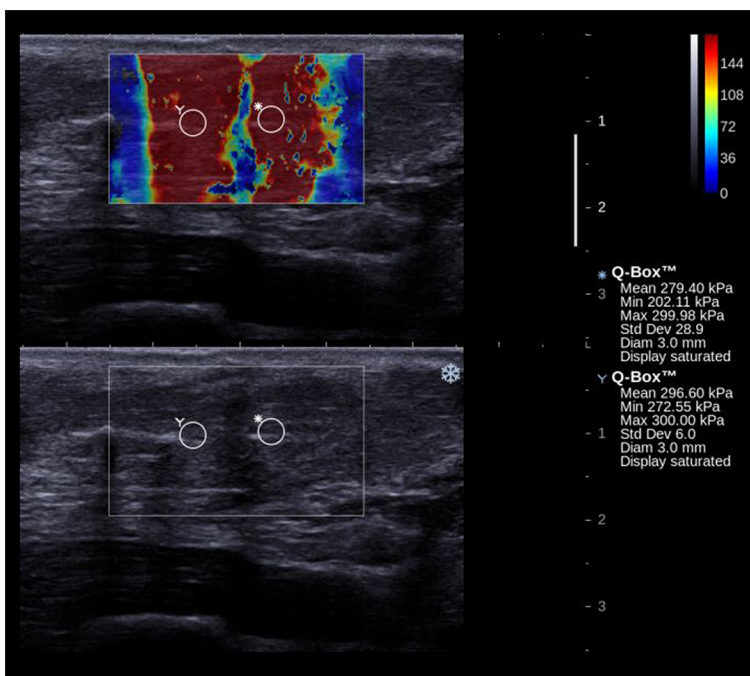
The mean values of elastic modulus of the repaired tendons were significantly different among the 3 time points postoperatively (12 weeks,  $187.7 \pm 23.8$  kPa, range, 163.8–201.7 kPa; 24 weeks,  $238.3 \pm 25.3$  kPa, range, 217.6–263.8 kPa; 48 weeks, and  $289.6 \pm 23.4$  kPa, range, 268.6–295.7 kPa) ( $P = 0.000$ ). SWE results showed that repaired tendons gradually became stiffer postoperatively (Figures 1–3). The mean AOFAS scores were significantly different among the 3 postoperative time points (12 weeks,  $84.5 \pm 5.1$  vs. 24 weeks,  $90.5 \pm 6.3$  vs. 48 weeks,  $98.2 \pm 3.1$ ) ( $P = 0.000$ ). The elasticity was significantly and positively correlated with the AOFAS scores ( $P = 0.0003$ ,  $OR = 0.9159$ ).

## Discussion

To the best of our knowledge, no study in the literature has investigated the changes of the mechanical properties of healing Achilles tendon after surgical repair of a tendon rupture using SWE. The present study quantitatively measured the elastic modulus values of the surgically repaired Achilles tendon. The shear modulus and its functional changes were detected and



**Figure 2.** Conventional ultrasound and SWE images of surgically repaired Achilles tendon at 24 weeks postoperatively. The boxes are the regions of interest for quantitative measurement.



**Figure 3.** Conventional ultrasound and SWE images of surgically repaired Achilles tendon at 48 weeks postoperatively. The boxes are the regions of interest for quantitative measurement.

reported with a complete set of quantitative data. These data may help elucidate the healing process of the Achilles tendon and provide a method to quantitatively assess the mechanical properties of repaired Achilles tendons.

The Achilles tendon is the strongest and thickest tendon in the human body; it plays a role in transferring forces from bone to muscle, and is therefore prone to injury and rupture. Injury of the Achilles tendon can change its mechanical properties and

the function of the lower limb. Surgical repair and rehabilitation are considered the standard treatment for restoring the original mechanical properties of the tendon. Therefore, it is very important to detect the changes of mechanical properties in the healing tendon *in vivo* and investigate the correlation between clinical functional outcomes and the mechanical properties of the Achilles tendon. This knowledge will allow for improved evaluation of tendons during injury healing and maturation. The current criterion standard imaging techniques

for tendon injury assessment are ultrasound and magnetic resonance imaging (MRI). They allow precise morphological analysis of normal and damaged Achilles tendons, but do not quantitatively evaluate biomechanical properties such as viscoelasticity. Thus, a new imaging method capable of quantifying tendon mechanical properties is needed for clinical use. Recently, SWE has become of interest as an ultrasound-based technique to assess structural and biomechanical features of biological tissues, such as “elasticity” [19]. They consist basically of 3 main steps: the tissue is mechanically stressed, resulting in a shear wave generation, after which the induced displacements are imaged, and finally the shear wave speed is locally retrieved by estimating the shear wave time of flight. SEW techniques have been successfully applied to determine *in vivo* and non-invasively the mechanical properties of soft tissue, such as liver [20], muscle [21], or breast [22]. The use of SSI in tendons, however, has been investigated less extensively. In recent years, ultrasound elastography has been used to characterize the mechanical properties of the healthy and pathologic Achilles tendon [23,24]. These studies report only qualitative information in tracking tissue movement during compression, and have poor reproducibility due to operator-dependent factors [25]. To date, only limited studies have focused on the elastographic appearance of the repaired Achilles tendon [26,27] and qualitatively described the results of sonoelastography (such as grades I, II, and III). However, the subjectivity of different examiners may impact the reproducibility of research results. Therefore, the present study was conducted to investigate whether SWE can serve as a new tool for monitoring tendon healing and/or if there was a demonstrable relationship between functional outcomes and elastic modulus values.

In our study, we used SWE to evaluate the changes of the elastic modulus of healing Achilles tendons *in vivo* at different time points postoperatively, and found significant increase during the process of healing. Our results suggest that the stiffness of the surgically repaired Achilles tendon gradually increases as the wound-healing process continues. We also found significant differences with respect to the AOFAS scores at different time points postoperatively (12, 24, and 48 weeks). In addition, a significant positive correlation between AOFAS scores and the elasticity of healing tendons was noted. This finding suggests that lower elastic modulus values might predict poor mechanical properties, functional outcomes, and healing of repaired tendons.

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The mechanical properties of the Achilles tendon (e.g., stiffness and dissipative properties) underlie the tension transmission and the storage-recoil process of potential elastic energy [28]. Poor mechanical properties may play a role in debilitating injuries, including Achilles tendon rupture. Therefore, poor mechanical properties may also predict a higher risk of re-rupture of surgically repaired Achilles tendons.

The present study has several limitations. First, the study was a prospective cohort study, which included a small number of patients from a single center. Large-scale, multicenter, prospective, randomized controlled studies are necessary to further validate our findings. Second, the elastic modulus values determined by SWE may only reflect the relative stiffness of the healing Achilles tendon and thus not be equivalent to the true modulus of elasticity obtained through biomechanical testing *in vitro*. More experiments are needed to confirm the correlation between the elastic modulus values obtained by SWE and the true modulus of elasticity. Third, measurement bias may exist related to positioning or direction of the transducer or positioning of the ROI. As the tendon is highly anisotropic, a difference of a few degrees in the positioning of the transducer can be responsible for significant differences in measurements. To overcome this bias, we selected longitudinal sections of the tendons to measure the elasticity modulus.

## Conclusions

Our results suggest that SWE can detect postoperative changes in the stiffness of a repaired Achilles tendon, and that elasticity values determined by SWE are positively correlated with functional outcomes. Future studies with larger series of patients and long-term follow-up are necessary to validate the benefit of this technique in healing Achilles tendons after surgery.

## Conflict of interest

The authors declare that they have no competing interest.

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