REVIEW ARTICLE

Ultrasound elastography and ultrasound tissue characterisation for tendon evaluation

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Received 10 February 2018; received in revised form 4 June 2018; accepted 7 June 2018
Available online 4 July 2018

KEYWORDS
Elastography; Strain elastography; Shear wave elastography; Ultrasound; Ultrasound tissue characterisation

Abstract Ultrasound elastography (UE) and ultrasound tissue characterisation (UTC) are two newer modes of ultrasound (US) which have begun to attract scientific interests as ways to improve tendon characterisation. These modes of US show early promise in improved diagnostic accuracy, prediction of at-risk tendons and prognostication capability beyond conventional grey-scale US. Here, we provide a review of the literature on UE and UTC for Achilles, patellar and rotator cuff tendons.

The translational potential of this article: The present literature indicates that UE and UTC could potentially increase the clinician’s ability to accurately diagnose the extent of tendon pathology, including preclinical injury.

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Introduction

Tendinopathy poses a large socioeconomic burden as one of the most common musculoskeletal injuries [1,2]. Tendonopathies comprise the majority of upper-limb musculoskeletal disorders in the work place, resulting in high economic costs [1]. For example, absenteeism from work in the United Kingdom in 2012 due to lateral
epicondylitis/tennis elbow alone was estimated to result in £27 million in lost productivity [2]. Today, grey-scale sonography is widely used for evaluation of suspected tendon injury [3]. In many tendons, such as the Achilles tendon, the diagnostic accuracy and sensitivity using grey-scale ultrasound (US) have been shown to be more than 90% for each [4]. Structural details gained through US (e.g., tendinopathy vs. a moderate-sized tear) have allowed the trained clinician to characterise and prognosticate injuries beyond the information gained from history and physical examinations alone. Recently, ultrasound elastography (UE) and ultrasound tissue characterisation (UTC) have been applied to tendons with the potential of increasing the diagnostic capability of US.

UE was first introduced in 1991 by Dr Jonathan Ophir with his work on foam blocks and bacon slabs [5]. Based largely on the work done by Hans Oestriecher, who had studied the physics of vibration in soft tissue, UE is able to measure the stiffness of biological tissues [5–7]. UE has been historically used in the assessment of internal organ pathology, and more recently, its clinical application to tendon tissue has been a growing area of interest.

Computerised UTC was first developed by van Schie et al for the assessment of equine tendon integrity and later applied to the Achilles tendon [8,9]. The technology evaluates tendon integrity based on a custom-designed algorithm that quantifies the three-dimensional stability of echo patterns [8,9].

In the present article, we aim to provide a comprehensive review of these newer diagnostic US methods in their clinical application to tendon tissue, including their technical strengths and limitations.

**UE technology and tendon-specific basic knowledge**

The two most common forms of UE are strain elastography (SE) and shear wave elastography (SWE). Both forms of UE assess the stiffness of the material, which is measured by Young’s modulus. The basic premise of UE is that an external force or stress is applied to a tissue, which induces certain strain on the deformed structure. Young’s modulus can be calculated by the following equation:

\[ E = \frac{\sigma}{\varepsilon} \]

where \( E \) is the Young’s modulus measured in pascals (Pa), \( \sigma \) is the force externally applied (“stress” measured in Pa), and \( \varepsilon \) is the strain, which is a unitless measure of relative tissue elongation [10,11].

**Physics of SE and SWE**

SE technology was the first form of UE developed by Ophir et al in the early 1990s [5]. The operator exerts an external force by means of repetitive compressions using the US probe. The inability to accurately measure the applied force limits the ability to calculate Young’s modulus [10,11]. Instead, analysis of the deformed tissue is displayed as a strain map, commonly referred to as an elastogram, which allows for a qualitative assessment of tissue stiffness (Figure 1) [10]. Most elastograms help to differentiate among three levels of stiffness—hard, medium and soft tissue—as compared to a nearby reference image point, typically subcutaneous fat, by means of a colour scale [12]. In contrast to SE, SWE involves a force created by a US pulse to form shear waves with measurable velocity, which allows for the calculation of Young’s modulus [10,11,13]. In SWE, Young’s modulus can be estimated based on the adjusted formula:

\[ E \equiv 3\rho v_s^2 \]

where \( E \) represents Young’s modulus (kPa), \( \rho \) is the density of the tissue (believed to be constant at 1000 kg/m³ with the assumption that tissue is purely elastic and isotropic), and \( v_s \) is the shear wave velocity (SWV) (m/s) [10,11,13].

**Comparing SE and SWE: advantages and limitations**

The advantage of SE is that it tends to be more readily available in mobile cart-based systems as the hardware can be compact. The largest limitation to SE is that the technology generates a qualitative outcome without generating an actual stiffness value.

The most significant advantage of SWE is that it can quantify the stiffness of the tissue. The “stress” is generated by a US pulse as opposed to human pressure, which allows for quantification of tissue stiffness with Young’s modulus [10]. Limitations of SWE include the following: (1) the necessity of a depth of about 0.4 cm for shear waves to be generated [13]; (2) structures deeper than 9 cm from the surface of the skin are not assessed properly due to US pulse attenuation [14]; and (3) inaccurate assessment of fluid filled structures as shear waves are not generated within fluids [15]. A potential limitation shared by both

![Figure 1](image_url)
forms of UE is the inability to evaluate soft tissue embedded within harder, incompressible tissue [16].

There are a number of complicating, procedural factors with both forms of UE which can potentially influence the assessment of tendon stiffness. These factors include: (1) anisotropic changes due to the angulation of the probe; (2) the amount of physical pressure exerted through the US probe on the area of interest; (3) joint positioning, and/or muscle activation, which influences the tension of the tendon; (4) orientation of the probe in relation to the tendon (i.e., long vs. short axis); and (5) the specific location of the tendon being analysed (enthesis vs. midportion vs. myotenous junction) [14,17–24]. These factors are more influential on SWE in contrast to SE because of the quantitative nature of SWE. As such, subtle changes in the probe and tendon placement alter the values obtained for SWV and Young’s modulus and therefore the measured tendon stiffness. For example, values for SWV and Young’s modulus have been shown to significantly increase (i.e., stiffer tendon) as the ankle progresses from a more relaxed, plantarflexed position to a dorsiflexed position [19,25–27].

**UE for tendon: fundamental knowledge**

It is generally agreed that injured Achilles and rotator cuff (RTC) tendons are softer than healthy, asymptomatic tendon tissue (Tables 1 and 3) [4,18,21,22,24,28–39]. Of the four studies that had compared tendinopathic Achilles tendons with normal tendon using SE, pathological tendons were found to be softer than healthy tendon tissue in three studies (n = 545 tendon thirds), whereas one study by Sconfienza et al (n = 48) showed opposite results [4,29,31,40]. The discrepancy in these findings may be due in part to the low-frequency-range transducer (10–6 MHz) that Sconfienza et al used as compared to the high-frequency-range transducers (14- or 13–6 MHz) used in other studies [4,29,31,40]. The low-frequency-range transducer could potentially degrade the resolution of the elastogram and affect the observed tendon stiffness [4].

Healthy, asymptomatic patellar tendon tissue, however, has been shown to be more consistent with softer, more elastic tissue than tendinopathic patellar tendons (Table 2) [24,41,42]. These findings may be explained by the fact that the patellar tendon spans two bony end points, thus increasing the inherent elasticity of the tendon (i.e., the ability to return to original length after deformation) [41]. In contrast, the Achilles and RTC tendons are directly attached to compliant structures (muscle), which may result in a decreased inherent elasticity of the muscle—tendon system and its ability to return to its original shape (i.e., stiffer tendon) [41]. However, a couple of studies have demonstrated the opposite, finding tendinopathic changes in the patellar tendon more consistent with softer tissue [22,43]. The discrepancy among these studies may be explained by spatial differences in stiffness within the patellar tendon as the proximal portion has been shown to be significantly stiffer than the distal portion [41,44]. For reasons previously mentioned, the distal portion of the tendon has a less compliant end point (tibial tuberosity) than the proximal attachment (patella and quadriceps tendon), which may result in increased distal elasticity (i.e., softer tendon).

Several factors are known to influence the findings of UE for the patellar tendon, such as sex, body mass index (BMI) and quadriceps strength [45]. In a study of 67 healthy, sedentary individuals, Tas et al found patellar tendon stiffness to be significantly lower in females and obese (BMI > 25 kg/m²) individuals [45]. The authors suggested that these findings may be due to hormonal and metabolic differences [45]. Furthermore, the study found increased quadriceps strength to be significantly correlated with stiffer tissue on SWE [45].

Normative SWE values for healthy Achilles, patellar, and RTC tendons have been studied (Tables 1–3). The measured elasticity modulus and SWV for the Achilles tendon have ranged from 74.4 to 779.5 kPa and 5.1–12.0 m/s, respectively [17,19,22,25–27]. SWV for the RTC has been shown to range from 2.9 to 9.0 m/s, with one study measuring the elasticity modulus at 31.2 kPa [17,36–38]. SWE studies for the patellar tendon have found the elasticity modulus to range from 25.8 to 157.20 kPa and the SWV to range from 6.9 to 7.24 m/s [22,24,42]. The wide variability in these quantitative measurements can be attributed to procedural factors previously described, such as joint positioning and probe placement.

**Age-related tendinopathic changes on UE**

Age-related degeneration of tendon seems to result in a stiffer Achilles tendon with SE [31,46]. In a study of 45 elderly individuals, Turan et al found significantly stiffer Achilles tendons (p < 0.001) as compared to 42 younger individuals at all three thirds of the tendon [46]. However, age-related thickening of the Achilles tendon does not appear to affect SWE measurements [47]. In a large prospective study of 652 healthy tendons, Fu et al found a gradual increase in the thickness of the Achilles tendon with age, but no significant correlation between age and tendon stiffness with SWE [47]. These findings were consistent with those of other studies that found no correlation between SWE and age-related changes in tendon stiffness [17,25,48]. Slane et al demonstrated age-related spatial variation in elasticity of the Achilles tendon as measured by SWV, which may explain the lack of consensus for UE findings in the ageing Achilles tendon [27].

Age-related tendinopathic changes with UE for the RTC have also demonstrated mixed results in the literature [17,37]. In Arda et al’s study of 127 participants, ranging in age from 17 to 63 years, there was no significant correlation between tendon stiffness and age [17]. However, in a smaller study, Baumer et al found a significant increase in tendon stiffness with increasing age [37]. The lack of standard shoulder positioning and probe orientation may explain the differences in these studies. For example, a short axis view and an abducted shoulder will both result in decreased tendon stiffness for reasons previously discussed [17,37].

At the patellar tendon, UE has shown increased softening with increasing age [49]. In a study of individuals older than 60 years, Hsiao et al found increased softness at the patellar tendon when compared with younger individuals [49].
| Primary author | Year | Form of US | Sample size | Study type | Tendon location | Joint position | Key findings |
|----------------|------|------------|-------------|------------|----------------|---------------|--------------|
| De Zordo       | 2009 | SE         | 225 tendons | Validity   | All 3 tendon thirds | Neutral       | 93.7% sensitivity and 99.23% specificity using clinical examination as the gold standard |
| Drakonaki      | 2009 | SE         | 50 tendons  | Reliability| Middle third      | Neutral       | Reliability of SE is good to excellent, highest in the long axis view versus short axis |
| Sconfienza     | 2010 | SE         | 48 tendons  | Descriptive| All 3 tendon thirds | Neutral       | Symptomatic tendons are stiffer than healthy controls |
| Klauser        | 2013 | SE         | 13 tendons  | Validity   | Middle & Distal thirds | Neutral       | 100% accuracy for detecting histological degeneration in a cadaveric study |
| Ooi            | 2015 | SE         | 240 tendons | Validity & Reliability | All 3 tendon thirds | Neutral       | 97.5% sensitivity and 94.5% specificity using clinical examination as the gold standard, with good interoperator agreement (0.70) |
| Ooi            | 2015 | SE         | 83 tendons  | Descriptive| Greatest AP distance | Neutral       | Decreased tendon stiffness occurs after marathon; decreased baseline tendon stiffness correlated with postrace Achilles tendon pain |
| Turan          | 2015 | SE         | 174 tendons | Descriptive| All 3 tendon thirds | Neutral       | Achilles tendon was stiffer in elderly individuals than in young individuals in all parts of the tendon |
| Balaban        | 2016 | SE         | 84 tendons  | Descriptive| All 3 tendon thirds | Neutral       | Softening in the midportion of Achilles tendon of volleyball players compared with healthy, matched controls |
| Busilacchi     | 2016 | SE         | 25 tendons  | Descriptive| All 3 tendon thirds | Neutral       | Increased stiffness at the site of the sutured tendon (myotendinous junction) correlated with improved symptom scores |
| Ooi            | 2016 | SE         | 42 athletes | Descriptive| Middle third      | Neutral       | Intratendinous softening at baseline associated with pain onset during the season |
| Arda           | 2011 | SWE        | 127 individuals | Descriptive | Unclear | Neutral | Normative values for Young’s modulus in longitudinal (74.4 ± 45.7 kPa) and transverse (51.5 ± 25.1 kPa) planes |
| Aubry          | 2011 | SWE        | 60 tendons  | Descriptive & reliability | Unclear | Dorsiflexed, neutral and plantarflexed Max plantarflexed, 45° plantarflexed, neutral and 45° dorsiflexed | Mean elasticity: 104 ± 46 kPa with extension, 464 ± 144 kPa in neutral, 410 ± 196 kPa with maximum dorsiflexion; Good reliability with ankle extension (Intraclass CC: 0.8) |
| Aubry          | 2013 | SWE        | 160 tendons | Descriptive & reliability | Middle third | Increase in Young’s modulus (i.e., stiffer tendon) as the angle of the ankle moves from maximum plantarflexion to dorsiflexion |
| Chen           | 2013 | SWE        | 50 tendons  | Descriptive | Middle & distal thirds | Neutral       | Healthy Achilles tendons are stiffer than ruptured tendons |
| DeWall         | 2014 | SWE        | 10 individuals | Descriptive | Entire tendon length | 15° plantarflexion, neutral and 15° dorsiflexion Max plantarflexion and 0° flexion | Tendon stiffness increases in dorsiflexed position compared with neutral and plantarflexed positions; Distal tendon is stiffer than proximal tendon |
| Aubry          | 2015 | SWE        | 210 tendons | Validity & descriptive | Middle third | Max plantarflexion and 0° flexion | Specificity ranges 91.5—75.6%; Sensitivity ranges 66.7—41.7%; Softer tissue in tendinopathic tendons than in healthy tendons in both positions |
| Dirrichs       | 2016 | SWE        | 82 tendons  | Descriptive | Variable | Neutral       | Symptomatic tendons are softer than asymptomatic tendons |
| Name      | Year | Location | Tendon Number | Methodology | Location | Stiffness | Findings                                                                                                                                 |
|-----------|------|----------|---------------|-------------|----------|-----------|------------------------------------------------------------------------------------------------------------------------------------------|
| Fu        | 2016 | SWE      | 652 tendons   | Descriptive & reliability | Middle third | Neutral | No correlation between tendon stiffness and age; No difference in tendon stiffness between men and women; Excellent reliability (intraclass CC: 0.923–0.870) |
| Petrescu  | 2016 | SWE      | 80 tendons    | Descriptive | Middle third | 0° plantarflexion | No correlation between tendon stiffness and age, sport and body mass index. Increased tendon stiffness in individuals who perform frequent weight-bearing exercise (≥6 h per week) |
| Siu       | 2016 | SWE      | 72 tendons    | Descriptive | Greatest AP distance | 0° plantarflexion | Increased tendon stiffness in individuals who perform frequent weight-bearing exercise (≥6 h per week). Longitudinal increase in tendon stiffness in repaired tendons at 12, 24 and 48 weeks postoperatively. Achilles tendon is softer than healthy tendon; Distal tendon is stiffer than the middle third. |
| Zhang     | 2016 | SWE      | 26 tendons    | Descriptive | Middle third | Neutral | Excellent reliability (intraclass CC: 0.870)                                                                                                 |
| Coombes   | 2017 | SWE      | 50 tendons    | Descriptive & reliability | Middle & distal thirds | Neutral | Achilles tendon is softer than healthy tendon; Distal tendon is stiffer than the middle third. Increased stiffness at the slack tendon compared with both aponeuroses. Decreased stiffness at the stretched aponeuroses in older individuals. |
| Leung     | 2017 | SWE      | 45 tendons    | Descriptive & reliability | Middle third | 30° plantarflexion | Increased stiffness at the slack tendon compared with both aponeuroses; Decreased stiffness at the stretched aponeuroses in older individuals. 88% sensitivity, 77% specificity and interobserver CC of 0.95 using clinical examination as the gold standard. Increase in echo types I & II with PRP and exercise therapy at 1-year follow-up, but no difference from sham treatment. Increase in echo types I & II with PRP and exercise therapy at 24-week follow-up, but no difference from sham treatment. Increased echo type III & IV in symptomatic tendons. Increase in echo types III + IV in DM-II individuals compared with matched controls. Reduction in echo type I in Australian football players after a single match. 5 months of intense, preseason training induces changes in all four echo types in Australian football players. Echo type I + II consistent with healthy tendon; Excellent reliability. |
| Slane     | 2017 | SWE      | 35 tendons    | Descriptive | Slack tendon and Gastroc & Soleus aponeuroses | 15° plantarflexed and dorsiflexed from resting | Increased stiffness at the slack tendon compared with both aponeuroses. Decreased stiffness at the stretched aponeuroses in older individuals. 88% sensitivity, 77% specificity and interobserver CC of 0.95 using clinical examination as the gold standard. Increase in echo types I & II with PRP and exercise therapy at 1-year follow-up, but no difference from sham treatment. Increase in echo types I & II with PRP and exercise therapy at 24-week follow-up, but no difference from sham treatment. Increased echo type III & IV in symptomatic tendons. Increase in echo types III + IV in DM-II individuals compared with matched controls. Reduction in echo type I in Australian football players after a single match. 5 months of intense, preseason training induces changes in all four echo types in Australian football players. Echo type I + II consistent with healthy tendon; Excellent reliability. |
| van Schie | 2009 | UTC      | 52 tendons    | Validity & reliability | Greatest AP distance | Max dorsiflexion | Increased stiffness at the slack tendon compared with both aponeuroses. Decreased stiffness at the stretched aponeuroses in older individuals. 88% sensitivity, 77% specificity and interobserver CC of 0.95 using clinical examination as the gold standard. Increase in echo types I & II with PRP and exercise therapy at 1-year follow-up, but no difference from sham treatment. Increase in echo types I & II with PRP and exercise therapy at 24-week follow-up, but no difference from sham treatment. Increased echo type III & IV in symptomatic tendons. Increase in echo types III + IV in DM-II individuals compared with matched controls. Reduction in echo type I in Australian football players after a single match. 5 months of intense, preseason training induces changes in all four echo types in Australian football players. Echo type I + II consistent with healthy tendon; Excellent reliability. |
| de Jonge  | 2011 | UTC      | 54 tendons    | Descriptive | Greatest AP distance | 15° dorsiflexion | Increased stiffness at the slack tendon compared with both aponeuroses. Decreased stiffness at the stretched aponeuroses in older individuals. 88% sensitivity, 77% specificity and interobserver CC of 0.95 using clinical examination as the gold standard. Increase in echo types I & II with PRP and exercise therapy at 1-year follow-up, but no difference from sham treatment. Increase in echo types I & II with PRP and exercise therapy at 24-week follow-up, but no difference from sham treatment. Increased echo type III & IV in symptomatic tendons. Increase in echo types III + IV in DM-II individuals compared with matched controls. Reduction in echo type I in Australian football players after a single match. 5 months of intense, preseason training induces changes in all four echo types in Australian football players. Echo type I + II consistent with healthy tendon; Excellent reliability. |
| de Vos     | 2011 | UTC      | 54 tendons    | Descriptive | Greatest AP distance | 15° dorsiflexion | Increased stiffness at the slack tendon compared with both aponeuroses. Decreased stiffness at the stretched aponeuroses in older individuals. 88% sensitivity, 77% specificity and interobserver CC of 0.95 using clinical examination as the gold standard. Increase in echo types I & II with PRP and exercise therapy at 1-year follow-up, but no difference from sham treatment. Increase in echo types I & II with PRP and exercise therapy at 24-week follow-up, but no difference from sham treatment. Increased echo type III & IV in symptomatic tendons. Increase in echo types III + IV in DM-II individuals compared with matched controls. Reduction in echo type I in Australian football players after a single match. 5 months of intense, preseason training induces changes in all four echo types in Australian football players. Echo type I + II consistent with healthy tendon; Excellent reliability. |
| de Jonge  | 2015 | UTC      | 27 tendons    | Descriptive | Entire length of tendon | Unclear | Increased stiffness at the slack tendon compared with both aponeuroses. Decreased stiffness at the stretched aponeuroses in older individuals. 88% sensitivity, 77% specificity and interobserver CC of 0.95 using clinical examination as the gold standard. Increase in echo types I & II with PRP and exercise therapy at 1-year follow-up, but no difference from sham treatment. Increase in echo types I & II with PRP and exercise therapy at 24-week follow-up, but no difference from sham treatment. Increased echo type III & IV in symptomatic tendons. Increase in echo types III + IV in DM-II individuals compared with matched controls. Reduction in echo type I in Australian football players after a single match. 5 months of intense, preseason training induces changes in all four echo types in Australian football players. Echo type I + II consistent with healthy tendon; Excellent reliability. |
| Wezenbeek | 2017 | UTC      | 140 tendons   | Descriptive & reliability | Entire length of tendon | 5–10° dorsiflexion | Increased stiffness at the slack tendon compared with both aponeuroses. Decreased stiffness at the stretched aponeuroses in older individuals. 88% sensitivity, 77% specificity and interobserver CC of 0.95 using clinical examination as the gold standard. Increase in echo types I & II with PRP and exercise therapy at 1-year follow-up, but no difference from sham treatment. Increase in echo types I & II with PRP and exercise therapy at 24-week follow-up, but no difference from sham treatment. Increased echo type III & IV in symptomatic tendons. Increase in echo types III + IV in DM-II individuals compared with matched controls. Reduction in echo type I in Australian football players after a single match. 5 months of intense, preseason training induces changes in all four echo types in Australian football players. Echo type I + II consistent with healthy tendon; Excellent reliability. |

AP = anteroposterior; CC = correlation coefficient; DM = diabetes mellitus; kPa = kilopascals; PRP = platelet-rich plasma; SE = strain elastography; SWE = shear wave elastography; US = ultrasound; UTC = ultrasound tissue characterisation.
Table 2  Summary table for patellar tendon.

| Primary author | Year | Form of US | Sample size | Study type | Tendon location | Joint position | Key findings |
|----------------|------|------------|-------------|------------|----------------|----------------|--------------|
| Porta          | 2014 | SE         | 22 tendons  | Reliability & descriptive | All 3 thirds | Flexed to 30° | Excellent reliability; Asymptomatic tendon consistent with soft tissue increased tendon stiffness with passive extension and isometric extension |
| Berko          | 2015 | SE         | 56 tendons  | Descriptive | Proximal tendon | Flexed to 30°, full extension, resisted extension at 90° | |
| Ooi            | 2016 | SE         | 70 tendons  | Validity    | Variable       | Full extension | Sensitivity 70% and specificity 53.5% using clinical examination as the gold standard |
| Ozcan          | 2016 | SE         | 148 tendons | Descriptive | Distal & proximal | Flexed to 20–30° | No difference in tendon stiffness between athletes and healthy volunteers; Soft patellar tendon compared with quadriceps tendon Painful tendons are stiffer and larger than the nonpainful side |
| Zhang          | 2014 | SWE        | 66 tendons  | Descriptive | Proximal       | Flexed to 30° | Excellent correlation with VISA-A score; Asymptomatic tendon is stiffer than healthy tendon |
| Hsiao          | 2015 | SWE        | 122 tendons | Reliability | All 3 thirds   | Flexed to 90° | Reliability ranged from good to excellent, with highest reliability occurring in the middle third |
| Dirrichs       | 2016 | SWE        | 51 tendons  | Validity & descriptive | All 3 thirds | Fully extended | |
| Coombes        | 2017 | SWE        | 45 tendons  | Validity & descriptive | Proximal & middle thirds | Flexed to 30° | Excellent correlation with VISA-A score; Asymptomatic tendon is stiffer than healthy tendon |
| Tas            | 2017 | SWE        | 24 tendons  | Reliability | Middle third   | Flexed to 30° | Good to excellent reliability |
| Tas            | 2017 | SWE        | 67 tendons  | Descriptive | Middle third   | Flexed to 30° | |
| Docking        | 2016 | UTC        | 50 tendons  | Descriptive | Entire length of tendon | "Lunge" position | Pathological tendon contains greater amounts of disorganised structure |
| van Ark        | 2016 | UTC        | 41 tendons  | Reliability & descriptive | Entire length of tendon | Flexed to 100° | Good reliability for echo types I and II; No change in echo types I and II in volleyball players during tournament competition |
| Esmaeili       | 2017 | UTC        | 52 tendons  | Descriptive | Entire length of tendon | "Lunge" position | Patellar tendons show small improvements (increase in echo type I) over an 18-week training period in Australian football players |

SE = strain elastography; SWE = shear wave elastography; US = ultrasound; UTC = ultrasound tissue characterisation; VISA-A = Victorian Institute of Sports Assessment—Achilles score.

UE for prediction of at-risk tendon

UE has been used to predict at-risk Achilles tendons in athletes such as volleyball players, soccer players and marathon runners [50–52]. In a study of 21 asymptomatic professional volleyball players, Balaban et al found the majority of athletes (26 of 42) to have intermediate and soft tissue on SE at the middle third of the tendon, which was different from a matched cohort of healthy volunteers who predominantly (40 of 42) had hard tissue [52]. The authors of this study concluded that SE could be useful in identifying early tendon degeneration [52]. In a study of asymptomatic football players at baseline, preseason softening of the Achilles tendon on SE was found to be a significant predictor for the development of symptoms post-season [51]. Ooi et al replicated similar findings in marathon runners who demonstrated softening within the Achilles tendon after a marathon run, suggesting that softening is a subclinical finding that might predict at-risk tendon [50].

SWE has been used to assess the physical properties of the RTC in athletes as they correlate to functional scores [53]. In a study of 18 collegiate swimmers, Dischler et al found a decrease in stiffness at the supraspinatus tendon with increased years of participation, which corresponded to increased tendon thickness on grey-scale US and a self-
reported decline in function with the Western Ontario Rotator Cuff score [53]. These findings indicate progressive softening of the supraspinatus tendon with years of participation and further elucidate the potential mechanical changes at the RTC tendon in overuse sports.

At the patellar tendon, Ozcan et al found no difference in tissue stiffness with SE between professional athletes and age-matched healthy individuals [44]. However, this study did not control for sport participation, and the size of the subgroups resulted in weak statistical power [44].

**Table 3** Summary table for rotator cuff tendon.

| Primary author | Year | Form of US | Sample size | Study type | Tendon location | Joint position | Key findings |
|---------------|------|------------|-------------|------------|----------------|----------------|-------------|
| Lalitha 2011  | SE   | 3 tendons  | Descriptive | Varied     | Hand on back   | Asymptomatic tendon is associated with increased stiffness on SE |
| Liu 2015      | SE   | 60 tendons | Validity    | Varied     | Prone          | Tendon softening on SE correlates with symptoms of RTC |
| Muraki 2015   | SE   | 23 tendons | Reliability | Superior facet of greater tuberosity | Abducted arm to 10° | Excellent reliability (intraclass CC: 0.931–0.998) |
| Tudisco 2015  | SE   | 100 tendons| Validity & descriptive | Varied | Forearm behind back, palm facing posterior | Positive correlation between tendon stiffness and Constant—Murley and ASES scores |
| Kocyigit 2016 | SE   | 50 tendons | Reliability | Supraspinatus fossa | Hand on back | Excellent reliability (interclass CC: 0.92) |
| Lee 2016      | SE   | 39 tendons | Validity    | Anterior to AC joint | Internally rotated, hyperextended arm | Increase in tendon softness correlates with increased grade of tendinosis on MRI |
| Arda 2011     | SWE  | 127 individuals | Descriptive | Unclear | Hand on back | No significant correlation between age and tendon stiffness |
| Rosskopf 2016 | SWE  | 8 tendons  | Reliability & descriptive | Supraspinous fossa | Forearm resting on thigh | Excellent reliability (intraclass CC: 0.89; intraclass CC: 0.7–0.8); Stiffer tendon in controls than in patients |
| Baumer 2017   | SWE  | 30 tendons | Descriptive | Anterior to the tendon, medial to acromion | Passive at 30° & active scapular plane abduction | Tendon stiffness positively associated with age under passive and active conditions; Softer tendon resulted from muscle activation |
| Dischler 2017 | SWE  | 18 swimmers (no specified form) | Descriptive | Midway between the acromion and medial border of the scapula | Forearm resting on thigh | Years of participation is negatively associated with tendon stiffness and WORC score and positively associated with tendon thickness |
| Hou 2017      | SWE  | 53 tendons | Descriptive | Greater tuberosity | Mild shoulder extension and internal rotation | Decrease in tendon stiffness in the proximal tendon in symptomatic patients; No difference seen in the distal tendon |
| Krepkin 2017  | SWE  | 9 tendons  | Validity    | Superior facet of greater tuberosity | Crass or modified Crass | Negative correlation between T2 MRI and tendon stiffness |

**UE for postintervention prognostication**

UE may have utility in assessing the healing tendon after surgical repair. A study of 25 individuals who had undergone Achilles tendon repair for tendon rupture showed increased tendon stiffness at the site of the sutured tendon at the 1-year follow-up on SE [54]. The increased stiffness was found to be inversely correlated with improved Achilles tendon total rupture scores. Similarly, a progressive increase in Achilles tendon stiffness has been demonstrated with SWE.
on postoperative patients completing a rehabilitation pro-
gram for a torn tendon, which correlated with improved
functional scores [55].

For nonruptured Achilles tendinopathy, UE has revealed
increased tendon stiffness in response to long-term therapy
[23]. These changes can be observed immediately after a
therapy session [56]. Specifically, eccentric loading of the
Achilles tendon has been shown to immediately induce
increased tendon stiffness with SWE [56].

**Ultrasound tissue characterisation**

UTC was first developed for tendons in equine medicine
with the goal of quantifying tendon integrity [57]. The
procedure entails translation of the US probe over the
length of the tendon, which is held in a fixed position, while
transverse images are taken at even distances of 0.2 mm
[9]. Although the US probe was initially moved manually,
recent developments have made it possible to move the
probe automatically by means of a motor-driven device
[9,58]. This advancement controls for variation in trans-
ducer angle and minimises the operator-dependent nature
of transducer movements [9,58]. Factors such as transducer
tilt, gain, focus and depth are therefore standardised
throughout the procedure [58].

**Physics of UTC**

UTC images are compiled into a three-dimensional data
volume block. The echo patterns that result from the US
waves within the sample block are categorised into echo
types by unique algorithms depending on the stability of
the image pixels [9]. There are four echo types established,
which are based on the stability of the echo pattern in
contiguous transverse images [9]. These echo types are
dependent on the integrity of the tendon and are classified
as (I) highly stable, (II) medium stable, (III) highly variable
and (IV) constantly low intensity echo types with variable
distribution [8,9,57]. Echo type I indicates intact and
continuous fibres, whereas echo type IV indicates disinte-
gration of the tendon and an amorphous matrix (i.e.,
“diseased” tissue) [8,9,57]. Echo type II has been differen-
tiated from type I by less waving tendon bundles, and
echo type III has been defined as having decreased fibrillar
integrity [8,9,57,59].

**Tendon-specific findings with UTC**

In general, both echo type I and echo type II are thought to
be the characteristics of normal healthy tendon when eval-
uated with UTC [9,58–62]. More unstable echo types, III and
IV, have also been shown to exist in healthy Achilles and
patellar tendons, however comprising a very low percentage
[9,58–60,63]. In a study of 50 pathologic patellar tendons,
the investigators found an increase in the cross-sectional
area of echo type I/II, which altogether correlated with a
greater anteroposterior patellar tendon thickness [63]. The
authors suggested that such an increase in stable echo types
may be adaptive and that thickening may not simply be a
pathological response of a tendon irritation [63].

**UTC evaluation of tendon response to loading**

The proposed advantage of UTC over grey-scale US is its
ability to detect subtle tissue changes and adaptations by
evaluating echo stability. Alterations in the echo pattern
within the Achilles tendon have been studied after physical
stimuli [60,64]. Baseline UTC examinations were performed
on 18 professional Australian football players with no
known history of tendinopathy before a match. After a
single match, the same tendon was examined using UTC,
which demonstrated a decrease in echo type I and a
reciprocal increase in echo type II, suggesting negative
changes in tendon integrity. However, such alteration was
temporary and was normalised by day 4. The authors spec-
ulated the transient changes to be secondary to a cellular
response to tendon loading [60]. Furthermore, a general
trend towards an increase in echo type I has been demon-
strated in Australian football players after 5 months of
intensive preseason training [64]. UTC may therefore allow
observation of adaptations within the Achilles tendon in
response to loading and training [60,64].

UTC has also been used to evaluate adaptations within
the patellar tendon in response to loading [61,62]. In a
study of 26 elite Australian football players, there was ev-
idence of increased echo type I after an 18-week preseason
training period [62]. Improvement in the structural integ-
rety of the patellar tendon may be sport and/or time
dependent as there was no significant change in echo type
in the patellar tendons of 41 volleyball players after a 5-day
tournament [61].

**Metabolic effect on UTC findings**

The integrity of the Achilles tendon has been studied in the
diabetic population using UTC [65]. Individuals with type 2
diabetes mellitus have been found to have a significantly
higher percentage of unstable echo patterns (echo type III
and IV) than healthy controls [65]. Furthermore, there ap-
pears to be a strong association between unstable echo
patterns and a larger BMI [65]. The authors hypothesised
that the accumulation of advanced glycation end products
in the tendon of diabetics may contribute to these changes
[65].

**Effect of orthobiologics on UTC findings**

UTC has been used to study the architectural response of
the Achilles tendon to orthobiologics in the treatment of
tendinopathy [66,67]. In a double-blind, randomised con-
trol study of individuals with midportion Achilles tendin-
opathy, individuals who received a platelet-rich plasma
(PRP) injection in addition to exercise therapy demon-
strated an increase in echo types I and II at the 6-month and
1-year marks [66,67]. However, this improvement was not
significantly different from the group that received a sham
treatment and exercise therapy [66,67]. The UTC findings
in these studies correlated to the clinical improvement noted
in both groups, as well as the degree of neovascularization
on Doppler US imaging [66,67].
Diagnostic accuracy of tendons using SE

Achilles tendon

SE for the Achilles tendon has been validated in four studies, which examined a total of 945 Achilles tendon thirds (Table 1) [4,28,29,31]. The diagnostic accuracy of SE ranges from 97 to 100% with sensitivity ranging from 94% to 97.5% and specificity ranging from 94.5% to 99% when using clinical examination as the gold standard [4,29]. The highest sensitivity has been reported at the distal tendon third, whereas the specificity tends to be the lowest at the middle tendon third [4,29]. Histological findings were used as the gold standard in a cadaveric study of 13 Achilles tendons, which found 100% sensitivity, specificity, positive predictive value and negative predictive value with SE [31]. It should be noted that the sensitivity and specificity of SE are influenced by the degree of softening/stiffness that is deemed pathological [29].

SE has been shown to have good/excellent correlation with grey-scale US findings [4,29,31]. De Zordo et al demonstrated the highest correlation (κ = 0.95) between grey-scale US and SE at the distal third of the Achilles tendon [29]. When compared to the overall diagnostic accuracy of grey-scale US (94.7%) or colour Doppler US (82.5%) alone, SE (97.8%) has been shown to be superior [4]. The diagnostic specificity and accuracy of SE are increased when combined with grey-scale US [4]. Furthermore, the mean diagnostic sensitivity, specificity and accuracy of SE combined with grey-scale US (95.9%, 95.8% and 98.3% respectively) have been shown to be significantly higher (p < 0.001) for the Achilles tendon than those of the more conventional combination of grey-scale and Doppler US (67.2%, 94.6% and 83.9% respectively) [4].

Patellar tendon

SE has been validated for the patellar tendon in an assessment of 70 patellar tendons (Table 2) [43]. Using the clinical presentation as the gold standard, the diagnostic accuracy of SE for the patellar tendon has been reported at 62.9%, with a sensitivity and specificity of 70% and 53.3%, respectively [43]. In comparing SE with conventional US methods, the diagnostic accuracy and negative predictive value of SE (62.9% and 57.1%, respectively) were shown to be superior over grey-scale US (60.0% and 54.2%, respectively) and power Doppler US (50.0% and 46.2%, respectively) [43]. However, SE was found to be less sensitive than grey-scale US (70.0% vs. 72.5%) and less specific than power Doppler US (53.3% vs. 100%) [43]. The sensitivity of SE or grey-scale US alone increased from 70.0% and 72.5%, respectively, to 82.5% when combined [43]. The authors hypothesised that the lower diagnostic percentages for SE in the patellar tendon as compared to the Achilles tendon may be due to a higher percentage of subclinical patellar tendinopathic cases, resulting in higher false positive results [43].

RTC tendon

Softening of the RTC tendon with SE has been shown to agree with findings of the shoulder on magnetic resonance imaging [35]. Findings on SE have also been shown to correlate with the visual analogue scale for pain, in addition to other various functional scores for the shoulder, including the Constant–Murley score, the American Shoulder and Elbow Surgeons Shoulder Score, the Simple Shoulder Test and the University of California at Los Angeles (UCLA) shoulder score [34].

Diagnostic accuracy of tendons using SWE

Achilles tendon

SWE has been validated for the assessment of Achilles tendon pathology when using the clinical presentation as the gold standard [18,21,22,24]. The specificity of SWE ranges from 68.2% to 91.5%, with the sensitivity ranging from 35.3% to 66.7% [21,24]. The lower sensitivity and specificity of SWE have been attributed to the methodological factors previously discussed. Given the relatively low sensitivity scores for SWE alone, SWE may not be as good as conventional grey-scale US in early detection of Achilles tendinopathy [21]. SWE has been shown to have good agreement with grey-scale US for the assessment of symptomatic Achilles tendon [18,21,22]. When combined with SWE, the combined diagnostic sensitivity of grey-scale US and Doppler imaging has been shown to increase from 73% to 96% [22]. Furthermore, lower symptom scores have been shown to correlate with decreased stiffness with SWE [22].

Patellar tendon

The diagnostic sensitivity and specificity of SWE for patellar tendinopathy range from 35.3% to 76.5% and 82.1%—92.9%, respectively [24]. Similar to the findings in the Achilles tendon, these diagnostic values are dependent on both the cutoff SWV value used for the diagnosis of tendinopathy as well as the specific location of the tendon being analysed [24]. When added to the conventional combination of grey-scale and power Doppler US, SWE for the patellar tendon has been shown to significantly increase the diagnostic sensitivity, but not the specificity [22]. In a study of 51 symptomatic patellar tendons, Dirrichs et al demonstrated an increase in sensitivity from 71% to 100% when SWE was added to the combination of grey-scale and power Doppler US [22]. The same authors found pathologic changes in 13 symptomatic patellar tendons with SWE that had failed to demonstrate any notable abnormality with combined grey-scale and power Doppler US [22]. SWE has also been shown to have a good correlation [correlation coefficient (CC): 0.81] with the Victorian Institute of Sports Assessment—Achilles score [22].

RTC tendon

SWE has become increasingly more popular in the assessment of RTC pathology due to its validity in assessing the tendon [36,39]. Abnormal findings on SWE for the RTC have been validated and correlated to findings on magnetic resonance imaging and grey-scale US [36,38,39].
Specifically, Rosskopf et al demonstrated decreasing stiffness for the supraspinatus with increasing fat content at the supraspinatus [36]. In a study of 21 symptomatic shoulders due to RTC pathology, Hou et al demonstrated a strong correlation between findings on SWE and grey-scale US imaging [38].

Diagnostic accuracy of tendons using UTC

Achilles tendon

In the Achilles tendon, UTC has been shown to have a diagnostic accuracy of 83% when clinical symptoms are used as the gold standard, and a threshold of 75% in echo types I + II is selected [9,58]. Using the same standards and thresholds, UTC has a diagnostic sensitivity of 88% and a specificity of 77% for the Achilles tendon [9].

Patellar tendon

Studies using UTC for the patellar tendon are much more limited than those for the Achilles tendon. Nevertheless, there has been some literature that indicates good agreement between findings on UTC and grey-scale US for the patellar tendon [61].

Reliability of UE and UTC for tendons

UE and UTC have been shown to have fair to excellent reliability for tendon assessment (Tables 1–3) [4,9,28,33,36,41,49,58,61,68,69]. SE has been shown to have fair to excellent interobserver and intraobserver agreement (CC: 0.41–0.95) for the Achilles tendon, with the highest agreement in the long axis view [4,28]. SE has also been shown to have excellent intraobserver (CC range: 0.850–0.919) and good interobserver (CC range: 0.527–0.644) agreement for all three portions of the patellar tendon (proximal, middle and distal), with the highest CC values recorded for the proximal portion [41]. SE has also been shown to be a reliable diagnostic tool for the RTC tendon, with the intraobserver reliability reported at 0.953 [33,68].

SWE for the Achilles tendon has fair to excellent interobserver agreement (CC: 0.43–0.987) and excellent intraobserver agreement (CC: 0.870–0.978) [25,26,47,56]. At the patellar tendon, SWE has been shown to have excellent intraobserver (CC: 0.831–0.966) and interobserver (CC: 0.71–0.821) agreement [49,69]. These results, however, may be influenced by the location of the tendon being tested, with the middle portion of the patellar tendon resulting in the highest intrarater and interrater reliability [49]. SWE has also demonstrated excellent test–retest reliability at the supraspinatus (CC: 0.7–0.8) with excellent interexaminer CC reported at 0.89 [36].

UTC has demonstrated excellent reliability, with both interobserver and intraobserver CC reported at >0.92 for the Achilles tendon [9,58]. Similarly, at the patellar tendon, UTC has been shown to have excellent reliability with the intraobserver reliability CC reported at 0.82 and interobserver reliability CC of 0.73 for echo types I and II [61].

Conclusions

UE and UTC are two forms of advanced US imaging that are becoming more widely used in the assessment of tendon injury. In review of the present literature, these newer forms of US can offer improved characterisation of tendons beyond grey-scale and power Doppler US, which are heavily dependent on the user’s experience and level of training. UE and UTC offer various advantages, including the prediction of tendon injury risk, assessment of tendon healing and provision of further insight into tendon physiology. The clinical application of UE and UTC for tendon injury needs to incorporate the tendon-specific nature of these newer US methods. The noninvasive and resource-sensitive nature of UE and UTC make these technologies viable evaluation tools for tendon-related research. Future research with UE and UTC may focus on explaining why some forms of tendinopathies are more prevalent in certain patient populations or recalcitrant to existing treatments.

Conflict of interest

The authors have no conflicts of interest to disclose in relation to this article.

Acknowledgement/Funding

The authors have no acknowledgements to disclose and they received no funding for the work described in this article.

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Ultrasound elastography and tissue characterization

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