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SCIENTIFIC ARTICLE

Shear-wave elastography of the ulnar collateral ligament of the elbow in healthy volunteers: a pilot study

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Abstract

Objective To estimate the intra-observer repeatability of shear wave elastography in the UCL of the elbow, and to compare shear wave velocities between dominant and non-dominant arms.

Materials and methods Twenty elbows in ten healthy volunteers were evaluated [five males, five females; mean age, 31.8 ± 10.3 years]. Shear wave velocity was measured on three separate days during the span of 1 week utilizing a linear 18-MHz transducer. Elastograms were obtained until ten ROIs were drawn, not drawing more than two ROIs on any elastogram. Elastograms were considered diagnostic if any portion of the UCL was colored in and free of boundary artifacts. Median velocity and interquartile range were recorded. A result was considered reliable if the IQR/median ratio of the ten measurements was < 0.3.

Results IQR/median was < 0.3 in 88% of sessions, although in 28% of sessions fewer than 60% of elastograms were diagnostic. The ICC was 0.05 (95% CI; −0.18–0.36; poor). Repeatability coefficient (95% limits of agreement) was 1.95 m/s (95% CI; 1.61–2.37 m/s). Mean velocity in dominant arms was 5.14 ± 0.53 m/s and 5.24 ± 0.39 m/s in non-dominant ($p = 0.558$).

Conclusions Mean shear wave velocity was similar between dominant and non-dominant arms. Although repeatability was poor as assessed by ICC, the repeatability coefficient may be a more useful indicator of clinical utility once shear wave velocities in diseased ligaments are explored. Future studies should therefore evaluate velocities in diseased ligaments and develop techniques to improve elastogram quality.

Keywords Ulnar collateral ligament · Shear wave · Elastography · Elbow

Introduction

The ulnar collateral ligament of the elbow (UCL), specifically its anterior bundle, is the primary stabilizer against valgus stress in overhand throwing athletes from 20 to 120 degrees of flexion [1, 2]. A valgus torque of approximately 120 N-m is imparted to the elbow during overhand pitching in baseball, and elbow injuries are a major cause of disability in pitchers [3]. Although UCL reconstruction has evolved significantly since its first description by Jobe in 1986, pitchers may still require 12–18 months of recovery [4]. Additionally, UCL injuries are on the rise, particularly amongst adolescent athletes [5]. Therefore, techniques to minimize or prevent UCL injury are of paramount interest.

Injuries to the UCL may occur either acutely or due to repetitive stress [4]. Clinical findings of elbow joint laxity under valgus stress were demonstrated in only 22% in one series of 1281 patients [6]. Radiographic signs such as olecranon osteophytes and UCL calcification may only be seen in 57% of patients [6]. MR arthrography is the gold standard for diagnosis of full-thickness UCL tears with a sensitivity of 84%, however this is an invasive and costly procedure, and the sensitivity for partial thickness tears is significantly less, at 74% in the same study [7].

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Sonoelastography is a novel non-invasive method of assessing the elasticity or 'stiffness' of tissues, specifically by measuring the tissue's elastic, or Young's modulus as first described [8]. Early studies have used sonoelastography to assess the Achilles' tendon, patellar tendon, and rotator cuff as well as other structures, and a recent publication demonstrated a significant difference in shear wave velocity between intact and torn Achilles' tendons [9–18]. The UCL is a much smaller structure than the Achilles tendon, however, with reported thickness ranging from approximately 2–7 mm [19–21]. Only one study to our knowledge has used sonoelastography to assess the UCL, although this utilized strain elastography not 2D-shear wave elastography (2D-SWE), which is a quantitative sonoelastography technique shown to have better repeatability than strain-based techniques [16, 22, 23].

The purpose of this study was to estimate the intra-observer repeatability of shear wave elastography in the UCL of the elbow, and to compare shear wave velocities between dominant and non-dominant arms. If validated, this technique could one day be used to non-invasively monitor the health and integrity of the UCL in overhand-throwing athletes.

Materials and methods

Population

This was a pilot study to estimate the intra-observer repeatability of shear wave velocity (SWV) measurements in the UCL, and to compare the mean SWV in the UCL of the dominant and non-dominant elbow in healthy volunteers as obtained with a high-resolution linear probe. This study was performed in accordance with the Declaration of Helsinki and was approved by the Houston Methodist Institutional Review Board. All participants provided written informed consent to participate in this study. Inclusion criteria were adults over the age of 18 and ability to provide consent. Exclusion criteria were history of prior elbow trauma or surgery as well as those with current elbow pain or elbow-related complaints. Ten volunteers were consecutively recruited between April 3, 2017 and April 10, 2017. Subjects ranged in age from 23 to 55 years, with a mean of 31.8 ± 10.3 years. Two subjects had a history of prior participation in overhead-throwing sports. There were five female and five male subjects, and all were right-hand dominant.

Imaging protocol

Subjects underwent 2D-SWE of the UCL in both their dominant and non-dominant arms on three separate days during the span of 1 week. Imaging was performed with a Toshiba Aplio™ i800 ultrasound system utilizing an 18-MHz linear high-resolution transducer with 2D-SWE capability (Toshiba i18LX5). Subjects were seated upright for the examination. All examinations and measurements were performed by the same fellowship-trained radiologist (NG) with 2 years' experience in sonoelastography. The anterior bundle of the UCL was located as an oblique iso- to hypoechoic band deep to the common flexor tendon extending from the medial epicondyle of the humerus to the sublime tubercle of the ulna, and an optimized longitudinal B-mode image demonstrating the length of the anterior bundle was obtained (Fig. 1). During the first scan session, the UCL thickness was recorded, as was the ulnohumeral distance at rest and with 5 daN of stress applied with a Telos™ SD 900 stress device (similar to the technique described by Ciccotti et al.) [20]. Two female subjects could not achieve 5 daN of stress due to joint laxity, and were instead imaged at 1 and 2 daN of stress, respectively. UCL thickness was measured orthogonally at the midsubstance of the ligament during the initial scanning session (Fig. 1). UCL thickness and ulnohumeral distance were not measured on subsequent scan sessions. During each of the three sessions, 2D color elastograms were obtained from each arm with the elbow in approximately 15–30 degrees flexion and with valgus stress applied by the Telos™ device, encompassing the region of the UCL as shown in Fig. 2. Care was taken to minimize transducer pressure while maintaining adequate skin contact with an appropriate amount of ultrasound coupling gel. Elastograms were considered diagnostic if any portion of the UCL was colored in and free of boundary artifacts. Elastograms were serially obtained until ten circular ROIs were drawn, not drawing more than two ROIs on any one elastogram. ROIs were preferentially placed in the middle 1/3 of the ligament (Fig. 2), although this was not always possible due to elastogram quality. Therefore, ROIs were allowed to be placed in any portion of the UCL that was colored in on the elastogram and free of boundary artifacts, resulting in variable placement of ROIs along the ligament substance within and across scanning sessions. ROI sizes were manually adjustable, and boundaries were confined to within the substance of the UCL to minimize volume averaging at the edges of the ligament. SWV from each ROI was then recorded. If the elastogram was unsatisfactory (no portion of the UCL was colored in or free of artifact), no ROIs were obtained from it (Fig. 3).

Statistical analysis

A threshold of $\alpha = 0.05$ was used to determine statistical significance. Statistical analysis was performed using Stata Statistical Software: Release 15 (StataCorp LLC; College Station, TX, USA).

Fig. 1 Grayscale image demonstrating the length of the UCL. *Green* UCL mid-substance thickness. *Blue* ulnohumeral distance

Grayscale features

Descriptive statistics including mean, median, maximum, minimum, and standard deviation were reported for UCL thickness (Table 1). Multi-level mixed effects linear regression models were used to determine whether sex, arm dominance or history of prior overhead throwing were significantly correlated with UCL thickness or with change in ulnohumeral distance between rest and stress. Elbow nested within subject were included as random effects in the models while sex, arm dominance, and history of prior overhead throwing were included as fixed effects.

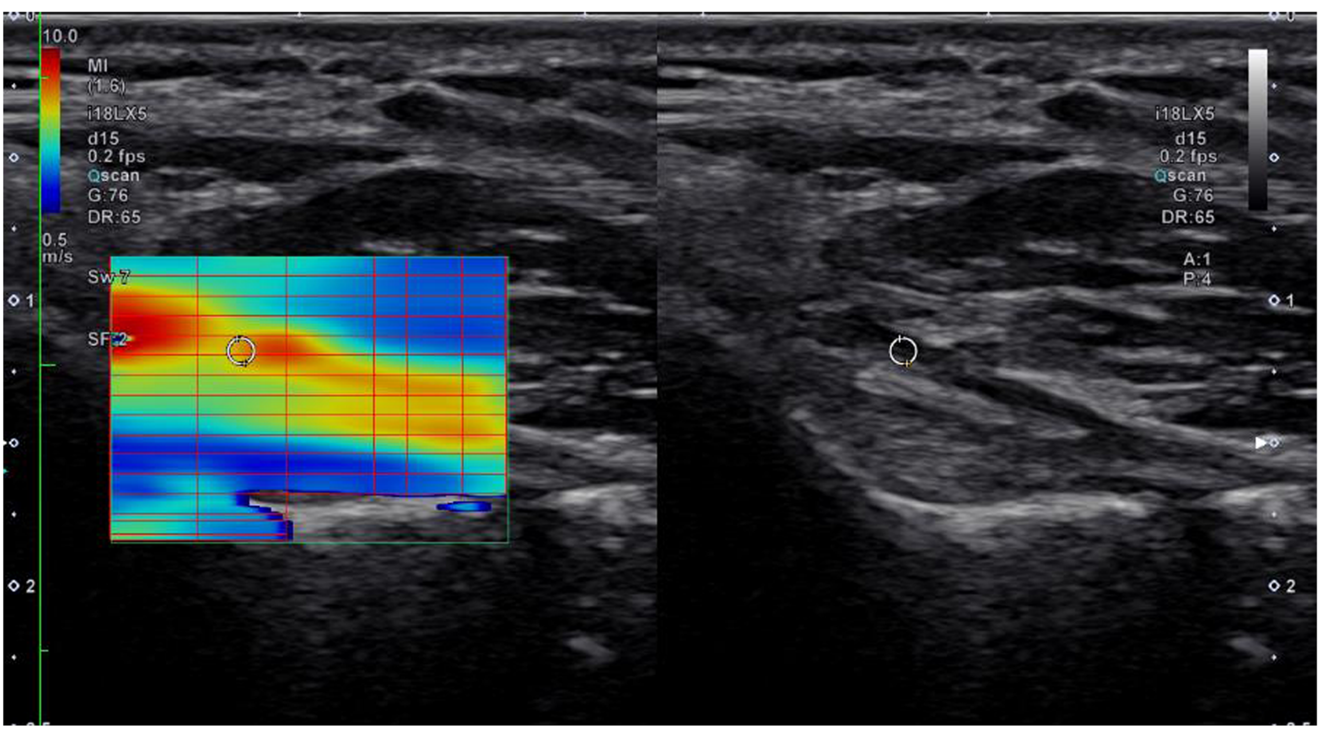

Fig. 2 2D elastogram demonstrating circular ROI placement within the UCL substance

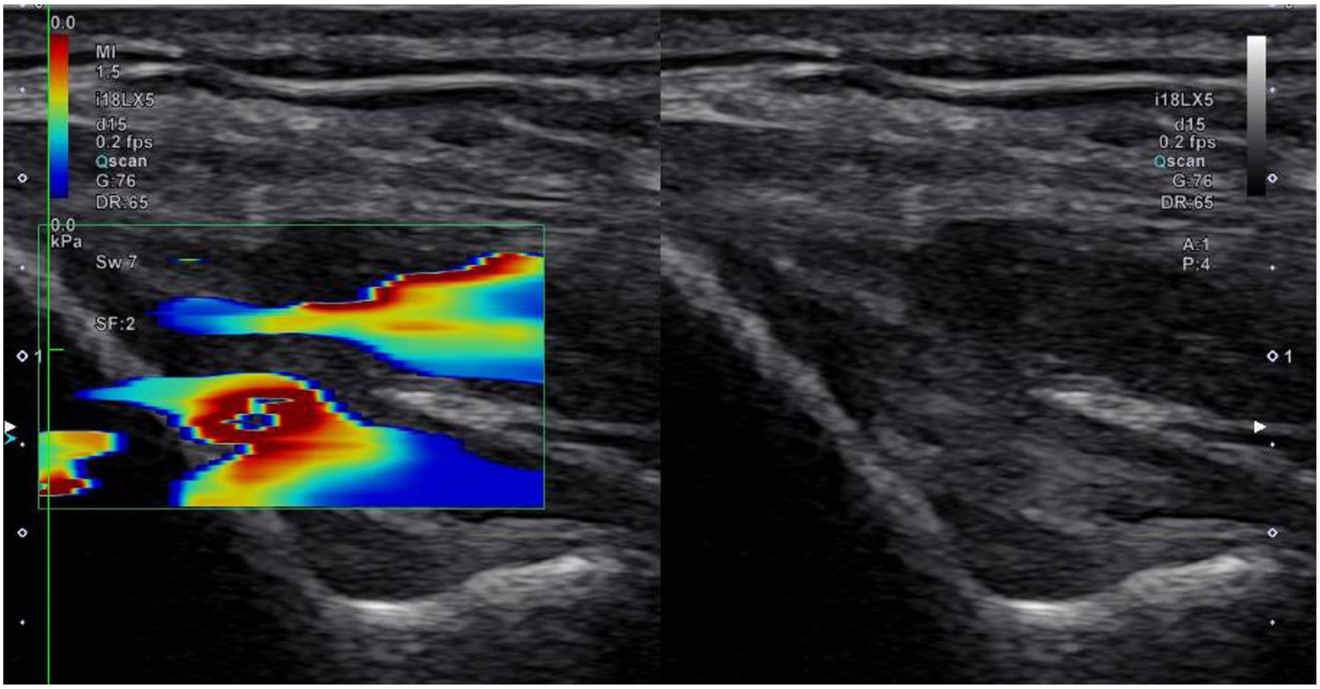

Fig. 3 Unsatisfactory elastogram - ligament is not 'colored' and there are extensive artifacts

Shear wave velocities

We calculated that a sample size of ten would give 80% power to detect a difference of 15% in SWV between dominant and non-dominant arms, assuming a correlation factor of 0.7, and a SD of 20% at a 95% significance level. For each set of ten SWV measurements, the median and interquartile range (IQR) were calculated and reported. A set of measurements was deemed reliable if the IQR/median ratio was < 0.3, as is standard in evaluation of liver fibrosis [24]. The median values reported for each extremity for each of the three scan sessions were then averaged to determine the mean SWV for that extremity. Summary statistics were then calculated from these average values for dominant and non-dominant arms (Table 2). Standard errors were calculated using cluster robust methods to account for clustering of elbows within subjects.

Intraclass correlation (ICC) with 95% confidence interval for the median SWV obtained from each elbow across the three trials was estimated utilizing a single measurement, absolute-agreement, two-way mixed effects model. ICC results were classified on the following scale: < 0.40 = poor; 0.40–0.59 = fair; 0.60–0.74 = good; > 0.75 = excellent [25]. Repeated measures ANOVA was utilized to compare the raw values obtained for each elbow between the three scan sessions. A multi-level mixed effects linear regression model was used to estimate the repeatability coefficient, which is defined as $2.77\sqrt{\sigma^2}$ (where σ^2 is the residual error variance of the model) and which represents the maximum difference that is likely to occur between two repeated test results with a probability of 95% [26]. Median shear-wave velocity was the response variable with sex, arm dominance, history of prior overhead throwing, and trial as fixed effects. To account for the clustered and hierarchical nature of the data, individual elbows were nested as level 1 unit within patients as level 2 units in the random effects portion of the model.

Table 1 Grayscale parameters (all measurements in mm)

		Right	Left	Males	Females	All
Mean UCL thickness (mm)		1.2 (1.1–1.4)	1.4 (1.1–1.6)	1.3 (1.1–1.6)	1.3 (1.1–1.5)	1.3 (1.1–1.4)
Ulnohumeral distance (mm)	Stress	2.5 (1.9–3.1)	2.9 (2.4–3.3)	2.6 (2.1–3.0)	2.7 (2.1–3.4)	2.7 (2.3–3.0)
	Rest	2.1 (1.7–2.5)	2.3 (1.9–2.7)	2.3 (1.9–2.7)	2.1 (1.7–2.5)	2.2 (1.9–2.5)
	Delta			0.2 (−0.2–0.7)	0.7 (0.2–1.1)	

95% CIs in parentheses

Table 2 Shear wave velocity data aggregated across all three scan sessions and all subjects

	Dominant	Non-dominant	Males	Females	All
Mean (m/s)	5.14 (4.76–5.52)	5.24 (4.96–5.52)	5.35 (4.93–5.77)	5.03 (4.73–5.34)	5.19 (4.91–5.48)
SD (m/s)	0.53 (0.36–0.97)	0.39 (0.27–0.71)	0.42 (0.29–0.77)	0.46 (0.32–0.84)	0.46 (0.35–0.67)
SE (m/s)	0.17	0.12	0.19	0.14	0.12
Median (m/s)	5.03	5.14	5.44	5.01	5.07
Q1 (m/s)	4.89	4.87	4.93	4.87	4.88
Q3 (m/s)	5.56	5.64	5.73	5.30	5.57
IQR (m/s)	0.67	0.77	0.80	0.43	0.69
IQR/median	0.13	0.15	0.15	0.09	0.14
Max (m/s)	5.95	5.79	5.95	5.79	5.95
Min (m/s)	4.06	4.78	4.78	4.06	4.06

Values from the three scan sessions were averaged for each extremity and summary statistics were calculated from these average values. *Numbers in parentheses* represent 95% CI's

SD standard deviation, *SE* standard error, *Q1* first quartile, *Q3* third quartile, *IQR* interquartile range

Results

This was a pilot study to estimate the intra-observer repeatability of shear wave elastography (repeatability coefficient) in the UCL of the elbow, and to compare shear wave velocities between the dominant and non-dominant arms of ten healthy volunteers. Grayscale parameters are summarized in Table 1. The average UCL thickness was 1.3 mm in our study. Sex and arm dominance were not significant predictors of UCL thickness ($p = 0.223$ and 0.348, respectively). Participation in prior overhead throwing sports demonstrated a trend towards decreased UCL thickness, with a coefficient of − 0.37 (95% CI – 0.75–0.02) although this did not reach statistical significance ($p = 0.062$). Notably, only two subjects reported prior participation in overhead-throwing sports. As expected, the average ulnohumeral distance at rest was less than after application of valgus stress, with an average decrease of 0.46 mm ($p = 0.001$). The average delta between stress and rest measurements of ulnotrochlear distance was higher for females (0.7 mm) than for males (0.2 mm), although not reaching statistical significance ($p = 0.097$). Sex, arm dominance, and participation in overhead-throwing sports were not significant predictors of change in ulnohumeral distance ($p = 0.097$, 0.741, and 0.340, respectively).

SWV data is shown in Fig. 4 and summarized in Table 2. Mean velocity in dominant arms was 5.14 ± 0.53 m/s and 5.24 ± 0.39 m/s in non-dominant arms. These were not significantly different ($p = 0.558$). Sex, arm dominance, scan session, and participation in prior overhead-throwing sports were not significant predictors of SWV ($p = 0.237$, 0.558, 0.816, and 0.885, respectively). Reliable results (defined as IQR/median ratio < 0.3) were ultimately obtained in 53/60 (88%) scan sessions. However, in 17/60 (28.3%) sessions, fewer than 60% of elastograms were of diagnostic value. ICC value was 0.05 (95% confidence interval − 0.18–0.36; poor). Data were tested for normality and sphericity. One-way repeated measures ANOVA demonstrated no statistically significant difference between the three scan sessions ($F(2,38) = 0.82$, $p = 0.45$). The multi-level mixed linear regression model demonstrated a residual variance of 0.497 (95% CI 0.336–0.735). The repeatability coefficient (RC) was therefore 1.95 m/s (95% CI 1.61–2.37 m/s).

Discussion

The UCL is a small structure, with a thickness near the lower limits of the minimum circular ROI size allowed by our system (1 mm). Estimates of sonographic UCL thickness in the literature range from < 2 to 7 mm [19–21, 27]. In our study, the average UCL thickness was 1.3 mm. The variation in the literature is likely due to differences in measurement technique, with two different techniques being described. The method described by Nazarian et al. results in higher measurements than that described by Jacobson and Ward. Our measurement mirrors a modified Jacobson/Ward technique, which recently demonstrated a mean UCL thickness of 1.38 mm in volunteers, similar to ours [27]. Earlier studies with less advanced technology may have reported higher thickness because it was more difficult to separate the ligament substance from the underlying tissue/fat. Using a high-resolution 18-MHz linear probe, the ligament substance was clearly differentiable from the underlying fat in most patients (Fig. 1). Additionally, our measurements are comparable to an MRI study in healthy volunteers, which demonstrated a median thickness of 2.5 mm [28]. The difference between MRI and US measurements may be related to differences in measurement plane, location (i.e., midsubstance vs. ulnar footprint where the ligament may 'fan out'), and the higher spatial resolution of US, particularly with high-frequency probes. As

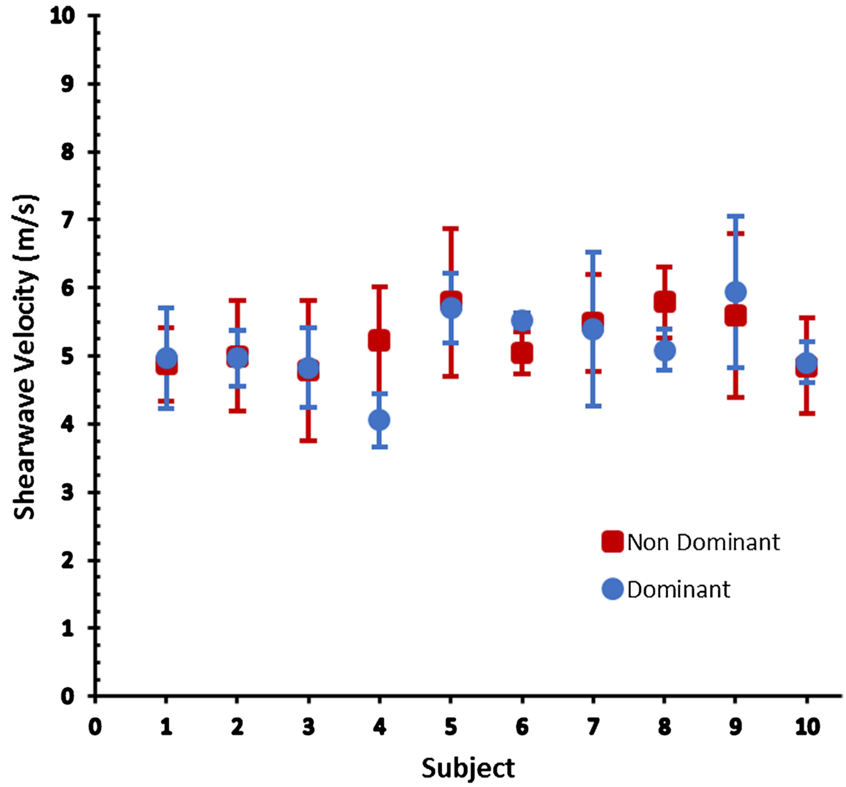

Fig. 4 Shear-wave velocities. Mean shear-wave velocity ± SD across the three trials for dominant and non-dominant arms in each subject

expected, ulnotrochlear distance increased with valgus stress, with a mean difference of 0.46 mm, comparable to the 0.5 mm reported by Nazarian et al. in non-throwing arms of baseball pitchers [29]. Females have been shown to demonstrate higher joint laxity than males, and we demonstrated a strong trend towards increased mobility at the ulnotrochlear joint in females as well [30, 31]. The average delta between stress and rest measurements of ulnotrochlear distance was 0.2 mm for males and 0.7 mm for females, although not reaching statistical significance with $p = 0.097$.

We have reported for the first time to our knowledge the average SWV in the UCL of the elbow in healthy volunteers. This data may be useful as a baseline value for comparison in future studies assessing diseased ligaments. However, these values may be specific to the particular scanner model utilized in this study, and it may not be valid to compare SWV obtained from different platforms and vendors until comparative studies have been performed. While normal ranges for liver elastography have largely been established, musculoskeletal elastography remains in its infancy and there is limited and sometimes conflicting data regarding normative values for SWV in ligaments and tendons [32]. For example, a recent study by Payne et al. demonstrated an average SWV in the Achilles tendon of approximately 9–9.5 m/s with the ankle fixed at 90°, although the true value may in fact be higher, as their system saturates at a velocity of 10 m/s [16]. They reported good reproducibility based on ICC, although this could be influenced by system saturation causing clustering of values near this maximum. Indeed, Aubry et al. previously reported a velocity of approximately 15–16 m/s with the ankle in a similar position, using a different system [18]. Their system had a saturation limit of 16 m/s, so they too were potentially under-reporting the true velocity. Both studies demonstrated positional changes in velocity, with higher velocities when the tendon was more ‘stretched’. Our system had a saturation limit of 10 m/s, although none of our measurements approached this.

We have demonstrated that SWE of the UCL may be feasible, as the vast majority (53/60; 88%) of scan sessions generated reliable results (IQR/M < 0.3). We selected this IQR/M cutoff as it was initially validated for transient elastography (TE) of the liver, although an even lower cutoff of 0.1 is suggested to describe ‘very reliable’ TE data [33, 34]. Only 8% (5/60) of our sessions were ‘very reliable’ by this measure. Although use of an IQR/M cutoff of 0.3 has been extended by many authors to 2D-SWE, there are important differences [35, 36]. TE reports the Young’s modulus (E) in kPa, while 2D-SWE measures the SWV and indirectly calculates the shear modulus (G) as $G = \rho c^2$ (where ρ = density and c = SWV). Although Young’s modulus can be derived as $E = 3G$ (assuming tissue is incompressible), this is based on the assumption that the tissue being imaged is isotropic. While this may be true for the liver, ligaments and tendons are anisotropic structures. Therefore, we advocate reporting of SWV for musculoskeletal applications rather than Young’s or shear modulus. Additionally, the relationship between G and c is a square

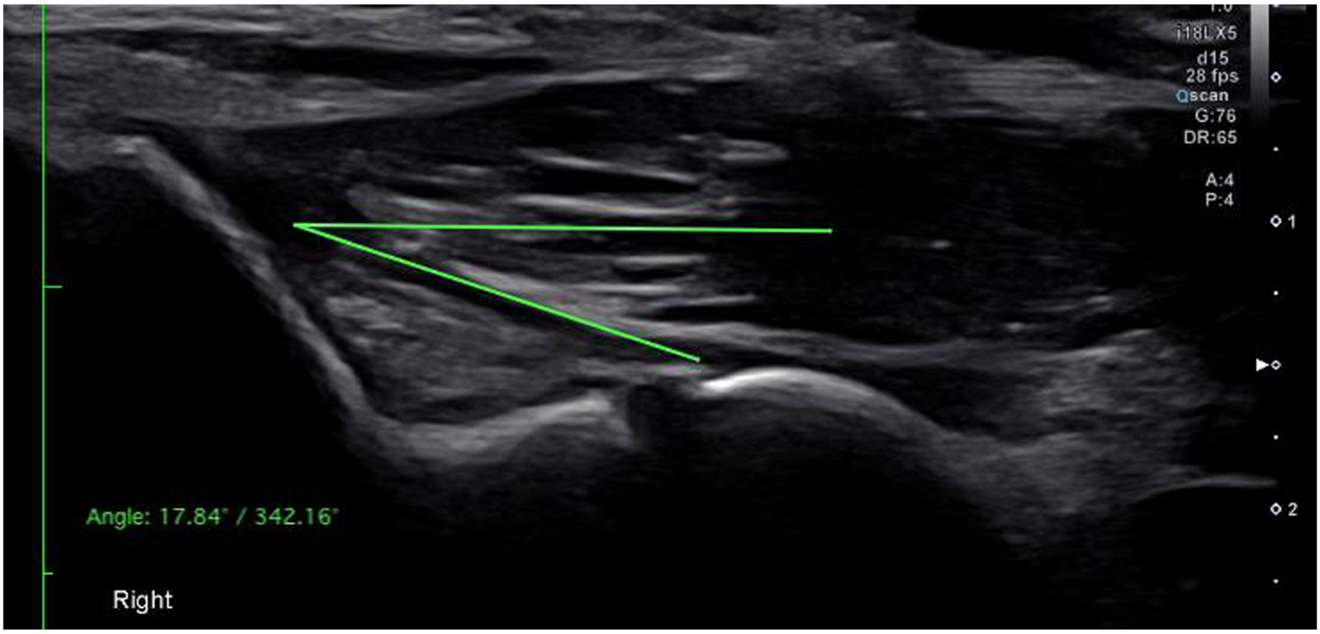

Fig. 5 Angle of insonation. In this case, the angle of insonation was less than 20° (17.8°)

relationship. Therefore, an IQR/M of 0.3 amongst values of *G* likely corresponds to a lower IQR/M among the corresponding SWV's. Further studies are needed to establish the optimal criteria for reliability of SWV in musculoskeletal applications.

Although our measurements were reliable in terms of IQR/M, there were limitations in elastogram quality. In addition to IQR/M, reliability criteria for TE include a stipulation that success rate must be > 60%. Fewer than 60% of elastograms were satisfactory in 17/60 of our scan sessions. Using both criteria, 35% (21/60) of sessions were inadequate. While the ICC was only 0.05 in our study, we do not believe the ICC is the best measure of repeatability in this setting. Although ICC is frequently reported in repeatability studies, a poor ICC can be due to limited between-subjects variation, rather than within-subject error [15, 16, 37]. Also, ICC does not reflect whether differences between measurements are clinically meaningful or not. We believe the repeatability of 2D-SWE is best described in terms of the repeatability coefficient (RC), which was 1.95 m/s. This is an objective numerical measure of the limits of the expected difference between repeat measurements on the same subject. While 1.95 m/s may seem high, the significance of this value is unknown; it will depend on future studies of SWV in diseased ligaments. If injury results in a large change in SWV relative to the RC, then this may prove to be sufficient. On the other hand, if changes in SWV are very small relative to the RC, then this may prove insufficient.

There are several limitations to our study. Although subjective attempts were made to ensure similar positioning among subjects and between trials, we did not measure the angle of flexion of the elbow. Others have utilized a goniometer for this purpose, and one such trial used an angle of 30° [29]. We qualitatively aimed for 15–30° of flexion. Although we acknowledge the limitations of this approach (namely intra- and inter-operator variation), it may be cumbersome to use a goniometer consistently in practice, and our approach would be more easily adopted. Secondly, our study did not include any left-handed subjects. However, we feel this would be unlikely to alter the results, as we did not find arm dominance to be a significant predictor of UCL thickness or SWV. Third, the location of ROI measurement was not standardized within the ligament. This was primarily because the same portion of the ligament did not consistently yield a reliable shear wave reading (i.e., was not consistently 'colored' on the elastogram). This may explain some of the variation in SWV measurements, as it is conceivable that certain portions of the tendon may be stiffer or softer than others. Although this is theoretically less likely in a healthy ligament, it certainly could be the case in a partial or full-thickness tear. Future studies should aim to replicate measurements within the same portion of the tendon.

Another limitation is that the angle of insonation was not standardized. While the probe was placed parallel to the skin surface in all subjects, the angle of the UCL relative to the skin surface likely varied. Although we did not measure the transducer angle relative to the UCL in every scan, it was subjectively less than 30° (Fig. 5). Shear-wave propagation can be affected by the angle of incidence in isotropic tissues such as tendons and ligaments. While the angle of insonation should ideally be close to 90°, at least one recent study demonstrated little effect of transducer angle on the measured shear modulus in pennate muscle up to an angle of 20°, as long as the transducer remained aligned with the plane of the muscle fascicles [37]. Nevertheless, one solution would be to implement an angled gel standoff to achieve 90° insonation. 2D-SWE relies upon an acoustic radiation force impulse (ARFI) 'push pulse' to generate shear waves in the tissue of interest. This push pulse is focused at a specific depth, and it is possible that in some subjects the UCL was more superficial than the optimal focal depth of the push pulse, which may result in suboptimal shear-wave propagation, and could explain some of the variation and unreliable readings. A gel standoff could also be used to optimize the focal depth of the ARFI push pulse and address this limitation.

Finally, it has been recognized that propagating shear waves at high frequencies is technically more demanding than at lower frequencies [38]. This is due largely to the decreasing shear-wave amplitude at higher frequencies. While high-frequency probes are preferred for B-mode MSK imaging, it may ultimately be the case that lower-frequency probes are beneficial for shear-wave applications. While we used an 18-MHz probe, future studies may evaluate lower-frequency probes for 2D-SWE.

In conclusion, we have estimated the repeatability coefficient of 2D-SWE in the UCL of healthy volunteers with a linear high-resolution 18-MHz probe to be 1.95 m/s with this particular system. We found no significant difference in SWV between dominant and non-dominant arms, and have estimated the average SWV in the UCL of healthy volunteers to be 5.19 m/s. Future studies in diseased ligaments will be needed to determine if this degree of repeatability is sufficient clinically, as well as to develop techniques to improve the proportion of diagnostic elastograms.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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