Published in final edited form as:

Ultrasound Med Biol. 2015 October ; 41(10): 2722–2730. doi:10.1016/j.ultrasmedbio.2015.06.008.

IN VIVO MEASURES OF SHEAR WAVE SPEED AS A PREDICTOR OF TENDON ELASTICITY AND STRENGTH

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Abstract

The purpose of this study was to assess the potential for ultrasound shear wave elastography (SWE) to assess tissue elasticity and ultimate stress in both intact and healing tendons. The lateral gastrocnemius (Achilles) tendons of 41 New Zealand white rabbits were surgically severed and repaired with growth factor coated sutures. SWE imaging was used to measure shear wave speed (SWS) in both the medial and lateral tendons pre-surgery, and at 2 and 4 weeks post-surgery. Rabbits were euthanized at 4 weeks, and both medial and lateral tendons underwent mechanical testing to failure. SWS significantly ($p < 0.001$) decreased an average of 17% between the intact and post-surgical state across all tendons. SWS was significantly ($p < 0.001$) correlated with both the tendon elastic modulus ($r = 0.52$) and ultimate stress ($r = 0.58$). Thus, ultrasound SWE is a potentially promising noninvasive technology for quantitatively assessing the mechanical integrity of pre-operative and post-operative tendons.

Keywords

Ultrasound shear wave elastography (SWE); tendon stiffness; tendon repair; rabbit Achilles

Introduction

The clinical management of tendon tears remains challenging, with many individuals sustaining re-injury upon return to activity. Clinical return-to-activity criteria include assessments of pain, function and appearance on ultrasound or MR images, which may

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differentiate symptomatic vs. asymptomatic tendons, but are not necessarily indicative of the strength of the tissue (Devitt et al. 2009; van Schie et al. 2014). Thus, there is a strong need for *in vivo* quantitative indicators of tendon strength, which would provide more objective assessment of the recovery of tissue mechanical integrity. A recent meta-study demonstrated a strong correlation between the elastic modulus and ultimate stress of tendon (LaCroix et al. 2013), such that noninvasive measures of tissue elasticity may serve as an appropriate proxy for tendon strength. Both of these measures give important information about the ability of tendon to transmit and withstand forces encountered during activity. Elastic modulus is a metric which describes the percentage stretch tendon will undergo in response to a given applied axial stress and the ultimate stress is a measure of the maximum force per unit area that a tendon can endure before rupture.

Shear wave elastography (SWE) is a promising approach for assessing tissue elasticity by measuring the propagation speed of shear waves (Sarvazyan et al. 1998). The clinical viability of SWE has more recently been advanced by Bercoff et al. (2004), who introduced an ultrasound based method in which acoustic radiation force is used to induce shear waves and high frame rate imaging is used to track the propagation speed. Ultrasound SWE (specifically with the Supersonic Imagine Aixplorer system) has seen use in multiple clinical domains, including imaging for possible tumors (Wang et al. 2012) and lesions (Athanasίου et al. 2010) in breast tissue, in addition to the evaluation of liver fibrosis (Bavu et al. 2011). Numerous *in vivo* SWE analyses have been performed in tendon and muscle as well (Akagi & Takahashi 2013; Aubry et al. 2013; Aubry et al. 2015; Bouillard et al. 2012; Brum et al. 2014; Chen et al. 2013; Chernak et al. 2013; DeWall et al. 2014b; Eby et al. 2014; Gennisson et al. 2010; Hug et al. 2013; Kot et al. 2012; Nakamura et al. 2014; Yeh et al. 2014; Yoshitake et al. 2014), but these tissues present some unique challenges due to their inherent anisotropy. Recent studies have shown that shear wave speeds are dependent on both fiber-direction and load, with load effects arising from the strain stiffening behavior of tendinous tissues (Aubry et al. 2013; DeWall et al. 2014b; Yeh et al. 2014). It has been confirmed that ruptured tendons exhibit a reduction in shear wave speed (SWS) at and adjacent to the site of tissue damage (Chen et al. 2013; DeWall et al. 2014a). DeWall et al. (2014a) also found local disruptions of shear wave speed in partially torn tendons. Thus, it is possible that SWS measurements may serve as a proxy for localized tissue elasticity, and indirectly for ultimate stress of a healing tendon (LaCroix et al. 2013).

The purpose of this study was to investigate the relationship between measured SWS and tendon elasticity and strength in a healing rabbit tendon model. We tested the hypothesis that unloaded tendon SWS measured *in vivo* would provide a reliable representation of tendon elastic modulus and ultimate stress determined via mechanical testing. The investigation was conducted in conjunction with a project aimed at determining the effects of different growth factor treatments on the healing of surgically repaired tendons.

Materials and Methods

Experimental Design

This study was approved by the UW-Madison Institutional Animal Care and Use Committee. The study was conducted on the lateral and medial Achilles tendons of 48 6-

month-old New Zealand White rabbits (41 male, 7 female). The proximal rabbit Achilles consists of distinct medial and lateral tendons arising from the medial and lateral gastrocnemius (Doherty et al. 2006), respectively. The two tendons merge just proximal to the calcaneus forming the true Achilles tendon, allowing them to be treated separately over the majority of their length. The lateral tendons of 41 rabbits (5F) were surgically severed and then repaired using sutures coated with varying levels (zero, low, or high concentration) of vascular endothelial growth factor (VEGF) and/or fibroblast growth factor 2 (FGF-2). Rabbits in the surgery group were randomly allocated to 9 growth factor groups (all combinations of VEGF and FGF-2 concentration levels) using block randomization and a random number generator, with a block size of 6 rabbits for each group. An additional group of 7 non-surgical rabbits (2F) from a separate study served as a control for intact lateral gastrocnemius tendons. Medial gastrocnemius tendons were left intact in all rabbits. This report does not consider the effects of growth factor treatments, but uses the inherent variability caused by differing treatments to aid in assessment of the relationship between shear wave speed and mechanical properties.

Surgical Protocol

Rabbits in the surgery group were subjected to bilateral surgical transection and repair of the lateral gastrocnemius tendon. Rabbits were given buprenorphine (0.01–0.05 mg/kg IM), carprofen (4 mg/kg SQ) and midazolam (1 mg/kg IM) pre-surgery. Rabbits were then placed in a gas chamber and anesthetized using isoflurane gas flow. Once anesthetized, rabbits were intubated and maintained on an oxygen/isoflurane gas mixture. An intravenous catheter was placed in the marginal ear vein to supply maintenance rate fluid therapy (Lactated Ringers Solution) during surgery. The rabbits were placed on a heat blanket (Hot-Dog system, Augustine Biomedical and Supply, Eden Prairie, MN, USA) in ventral recumbency in a frog-legged position. Legs were clipped and aseptically prepared and were draped from the mid metatarsus to the proximal tibia.

A 1.5 cm skin incision was made centered 1.5 cm proximal to the calcaneus on the lateral aspect of the metatarsus, and over the region of the medial and lateral gastrocnemius tendons. The skin and subcutaneous tissue were sharply transected using a #15 scalpel blade. The subcutaneous fascia was then separated in proximal and distal directions using Metzenbaum scissors down to the level of the paratenon. Any hemorrhage was stemmed using hand held monopolar cautery (Cardinal Health Surgical Cautery 65410-183, Cardinal Health, Dublin, OH, USA). The paratenon between the medial and lateral gastrocnemius branches was incised and split slightly proximally and distally using Castroviejo Scissors. Jewelers micro forceps were used to carefully separate the medial and lateral gastrocnemius tendon bundles. Bishop Harman forceps were then used to separate the gastrocnemius tendon bundles along their length, from just proximal to the point of merger near the calcaneus to just distal to the musculotendinous junction.

The leg was then held in slight tarsal flexion, placing the lateral gastrocnemius tendon under tension while Bishop Harman forceps were used to isolate the tendon from the surrounding tissue. The tendon was sharply transected 1.5 cm proximal to the calcaneus with a #15 scalpel blade. The paratenon was then bluntly dissected off the proximal and distal stumps

for approximately 10 mm. The body of the tendon was repaired in apposition using a single locking loop of 4-0 braided nylon coated with a hydroxyapatite layer containing growth factors. Once the body of the tendon was repaired, a circumferential repair of the paratenon using 4-0 braided polyglactin 910 (also coated with a hydroxyapatite layer containing growth factors) was applied in a Silfverskiöld epitendinous repair. The subcutaneous fascia was sutured using 6-0 polyglactin 910 in a simple continuous pattern and the skin was sutured using 3-0 nylon in a cruciate pattern.

Post-surgery, no external coaptation was provided. Rabbits were individually housed in cage confinement for the duration of the study. A dose of carprofen was provided 6-8 hours postsurgery. Rabbits were carefully monitored to assess difficulties in ambulation or evidence of pain post-surgery.

Imaging Protocol

Rabbits were given buprenorphine (0.01–0.05 mg/kg IM) and midazolam (1 mg/kg IM) prior to induction for imaging. Rabbits were then placed in a gas chamber and anesthetized using isoflurane gas flow. Once anesthetized, a facial mask was placed on rabbits and they were maintained on an oxygen/isoflurane gas mixture.

Shear Wave Elastography

For the surgery group, quantitative SWE imaging was performed bilaterally on the medial and lateral gastrocnemius tendons at 0 weeks (pre-surgery), and at 2 and 4 weeks post-surgery. For the control group, SWE imaging was performed bilaterally on the lateral tendons once, just prior to euthanasia. All rabbits were placed under general anesthesia to prevent any movement during scanning. The rabbits' legs were clipped from the calcaneus to the stifle joint to provide a clean imaging surface. Legs were placed in a custom designed mold to maintain the tarsus at 90 degrees flexion during each scan.

Shear wave images were collected with the Supersonic Imagine Aixplorer system (Aixen-Provence, France; software version: 5; preset: superficial MSK; opt: penetrate; persist: high; smoothing: 7). A 50 mm linear transducer (Supersonic Imagine L15-4) was manually positioned over a 2 cm ultrasound standoff pad (Aquaflex, Parker Laboratories, Fairfield, NJ, USA) placed over the lateral side of the leg, with ultrasound gel added to enhance contact with the pad and leg. A single operator performed all ultrasound scans to eliminate inter-observer variability (Peltz et al. 2013; Zhang and Fu 2013). The transducer was positioned to visualize the entire length of the Achilles tendon unit along the longitudinal axis, extending from the gastrocnemius muscle-tendon junction to the calcaneal insertion, and was shifted appropriately to obtain views of the lateral or medial tendon (Fig 1). Minimal transducer pressure was applied to avoid strainstiffening effects (Kot et al. 2012). Shear wave speeds were measured within a 15 mm square region of interest (ROI) at 3 locations along the tendon: centered over the tendon repair (distal), 10 mm proximal to the repair (mid) and 20 mm proximal to the repair (proximal). Three repeated images were obtained at each location without repositioning the transducer, but after sufficient image refresh time.

Shear wave speed measures were obtained post hoc from exported DICOM images. A custom MATLAB (Mathworks, Inc., Natick, MA, USA) graphical user interface (GUI) was used to manually select sub-regions within the ROIs which only included the tendon tissue of interest. These sub-regions extended along the length of tendon present in the ROI, and spanned the thickness of the tendon from the superficial border to the deep border. Images yielding ROI subregions with an average quality factor of less than 0.6 were rejected. The mean shear wave speeds across repeated images were then computed.

Mechanical Testing

Surgically treated rabbits were sacrificed at 4 weeks post-surgery, immediately after completion of the final imaging session. The Achilles tendon unit was dissected out from the talocalcaneal junction with a portion of the gastrocnemius muscles retained, so as not to damage the tendon. For each rabbit, mechanical testing was performed on the lateral tendon from one leg (randomly selected) and the medial tendon from the contralateral leg. The lateral tendon of the contralateral leg was retained for histological analysis in a separate study.

Tendons were tested in uniaxial tension using a MTS 858 Bionix Test System (Eden Prairie, MN, USA) with a 500 lb load cell. The proximal portion of the tendon was placed in a cryoclamp, and the calcaneus was rigidly clamped at the distal end. Tendons were kept moistened with saline solution at 37 degrees Celsius. Preconditioning began when the proximal muscle reached 0 degrees Celsius in the clamped section, indicating freeze-binding to the clamp. Tendons were preconditioned with 10 cycles to 3% strain at a rate of 2.5mm/s. Initial grip-to-grip tendon length was then recorded. Additionally, tendon thickness was measured at 4 positions along the tendon using a hand-held digital micrometer (General Tools, New York City, NY, USA). Thickness measures were used to estimate the tendon cross-sectional area, which was assumed to be elliptical.

There was no break between pre-conditioning and testing. Tendons were stretched at a rate of 2.5 mm/s to failure. Force and elongation data were continuously sampled at a rate of 50 Hz. Elongation was used to compute the average strain along the tendon. Average tendon stress was determined by dividing axial force by the average cross-sectional areas of the 4 axial locations. Ultimate stress was taken as the peak stress reached during loading. Tendon elastic modulus was calculated from the linear portion of the stress-strain curve.

Statistical Analyses

We first assessed temporal and spatial variations in shear wave speed in medial and lateral tendons. In these analyses, temporal SWS changes in medial tendons were only considered in the proximal region due to the difficulty in isolating the medial tendon in images collected at the mid and distal locations following surgical repair of the lateral tendon. The missing data groups necessitated separate analyses of variance (ANOVAs) on the lateral and medial tendons. For lateral tendons, a two-way repeated measures ANOVA was performed to assess the effects of scanning location (proximal/mid/distal) and time point (0, 2, 4 weeks) on SWS. For medial tendons, a one-way repeated measures ANOVA was performed to assess the effects of time point on SWS at the proximal scanning location. All main effects

were followed up with post-hoc pairwise comparisons. Bonferroni correction factors were used to account for multiple between time point ($n = 3$) and between scanning location ($n = 3$) comparisons (Brown and Russell 1997).

Linear Deming regression (Linnet 1993) was performed to assess the relationship between tendon elastic modulus and SWS, and between ultimate stress and SWS. Deming regression was used due to the potential for error in both the predictor (SWS) and the predicted variables. Error in each variable (normalized to standard deviation) was weighted equally. Regressions were repeated for intact tendons and repaired tendons individually to assess the consistency with a combined fit (Table 1). For repaired lateral tendons, SWS data measured at 2 and 4 weeks post-surgery at the distal location were analyzed. Because there was no significant difference in SWS at these time points, these data were averaged for comparison to mechanical measures. The distal location almost exclusively represented the failure region. For medial tendons and intact lateral tendons, SWS values measured pre-surgery at the distal location were used for comparison to mechanical measures.

We also assessed the sensitivity and specificity of SWS, elastic modulus and ultimate strength for distinguishing surgically repaired tendons from intact control tendons (medial and non-surgical lateral). This was done by comparing individual SWS measures to means from each group (control or treated) and assigning them to the group for which they have a lower z-score.

Results

Spatial and Temporal Variation of Shear Wave Speeds

The average tendon shear wave speed at baseline was $10.5 (\pm 2.2)$ m/s over the entire length of the tendon, with significantly higher measures obtained at the distal (10.9 ± 2.1 m/s) and mid (11.0 ± 2.1 m/s) locations, relative to the proximal (9.5 ± 2.1 m/s) location ($p < 0.001$). SWS significantly decreased in the repaired lateral tendons two weeks after surgical repair, with the greatest decrease seen in the distal ROI (21% decrease, $p < 0.001$). SWS decreased to a lesser extent at mid and proximal locations (18% and 11% decrease respectively, $p < 0.001$). There was a tendency for a slight recovery of SWS between two and four weeks at the distal location, though this change was not significant ($p = 0.09$).

Relationship between Shear Wave Speed, Elasticity and Strength

When all tendons were considered, both the ultimate stress ($r = 0.58$, $p < 0.001$) and elastic modulus ($r = 0.52$, $p < 0.001$) were significantly correlated with post-surgical shear wave speeds. When intact and severed/repaired tendons were considered separately, ultimate strength remained significantly positively correlated with SWS (Table 1). However, elastic modulus was not significantly correlated with SWS in this case.

Sensitivity and Specificity

Of the metrics considered, ultimate stress exhibited the greatest combination of sensitivity and specificity in distinguishing between damaged and intact tendons. Elastic modulus exhibited similar sensitivity to, but lower specificity than ultimate stress. SWS was both less

sensitive and less specific than the other tests in distinguishing the surgically repaired tendons (Table 2).

Discussion

Due to its ease of use, ultrasound shear wave elastography could easily be adapted to clinical use for noninvasively and quantitatively tracking changes in shear wave speed following a tendon tear and subsequent treatment. This study was undertaken to assess the potential of using the shear wave speed metric as a biomarker of tendon elasticity and ultimate strength following repair and healing. The results are encouraging, with a significant decrease in SWS observed after severing and surgically repairing a tendon, which may reflect a decrease in mechanical integrity of the damaged tissue (DeWall et al. 2014a; Yeh et al. 2013). Additionally, with all data considered, we found a highly significant correlation between shear wave speed and both the ultimate stress and elasticity of tendons, supporting the potential of SWS as a proxy measure for tendon mechanical properties. However, it is recognized that the linear regressions could explain only 33% of the variance in ultimate stress and 27% of the variance in elastic modulus. Hence, currently, SWE would seem to be most useful for assessing substantial changes in tendon mechanical integrity. Further, the use of SWS measures to track short-term temporal changes during healing was not supported since we found no significant increase in SWS between 2 and 4 weeks post-surgery (Fig 2). This latter result could mean a majority of healing had already taken place before the 2 week scan, or alternatively, those two weeks were an insufficient amount of time for SWS to significantly change with healing.

The positive relationship between SWS and mechanical measures is particularly encouraging given the small size of the rabbit tendon structures being imaged. Shear wavelengths are generally larger than tendon thickness, causing guided wave propagation along the tendon as the shear wave reflects off its boundaries (Brum et al. 2014; Yeh et al. 2014). Such effects may be more pronounced in smaller tendons, such as the rabbit Achilles. Further, there is also potential for interference from adjacent tissues since SWS transitions smoothly between relatively stiffer and more compliant tissues, causing a spatial averaging effect. Here we chose to include all visible tendon tissue in our ROI sub-regions, extending to borders with adjacent tissues. This may introduce error because tendon wave speeds are considerably higher than wave speeds in adjacent tissues such as muscle (Arda et al. 2011; Chernak et al. 2013). Both the wave guiding and spatial averaging effects on SWS error would be lessened in larger tendons, such that there is potential for obtaining more reliable SWS measures in a larger animal model.

The treatment group included rabbits undergoing repair using sutures coated with varying level of VEGF and FGF-2 growth factors, which contributed to the variability in the elastic modulus and strength measured for repaired lateral tendons. Moreover, we tested both repaired tendons and intact tendons so as to include distinct “injury states” in our analysis. While the reason for a lack of difference in fit between injury states is unclear, it is encouraging that the SWS relationship to tendon mechanics was evident when examining individual groups or the combined dataset (Table 1). This suggests that SWS may serve as a proxy for mechanical properties irrespective of the state of the tendon or the specific

treatment approach used on a torn tendon, which would clearly represent the case in clinical settings.

Shear wave speed is a function of shear modulus in both isotropic and transversely isotropic materials. In an isotropic, purely elastic material, there is an easily defined relationship between the shear and elastic moduli, such that the elastic modulus can be estimated based on the shear wave speed. However, the relationship between the shear and elastic moduli in transversely isotropic tissues like tendon is more complex (Royer et al. 2011), raising interesting questions about how the more functionally relevant axial elastic modulus may be related to the shear modulus, and thus the shear wave speed. While not well understood for tendon, a strong linear correlation between shear modulus and axial elastic modulus has been observed in muscle (Eby et al. 2013) which is often also considered transversely isotropic (Gennisson et al. 2003; Gennisson et al. 2010). Such a relationship would support the idea that shear wave speed in transversely isotropic materials, being an indicator of shear modulus, may be at least a good correlate of elastic modulus as well. However, more experimental and modeling work is needed to understand this relationship in greater detail.

This study is premised on the idea that tendon elasticity is related to tendon strength, as described in a meta-study by LaCroix et al. (2013). One potential explanation for this empirical observation is that failure is ultimately dependent on strain the tissue can withstand, which can be estimated from the tissue elasticity. We indeed found a high correlation between tendon elastic modulus and ultimate stress ($r = 0.85$, $p < 0.001$), lending credibility to this idea. This relationship can also be seen in a previous rabbit Achilles regeneration study (Nagasawa et al. 2008), which showed similar percent increases in ultimate stress and elastic modulus during healing. Importantly, our mechanical measures are similar to those reported in the literature. We found a mean elastic modulus of 250 MPa and mean ultimate stress of 34 MPa, which are within the 20-350 MPa (Leek et al. 2012, Kahn et al. 2013; Nagasawa et al. 2008; Ni et al. 2012; Reddy et al. 1999; Reddy 2004; Revel et al. 2003) and 8-40 MPa (Leek et al. 2002; Nagasawa et al. 2008; Ni et al. 2012; Reddy et al. 1999; Reddy 2004) ranges reported for the elastic modulus and ultimate stress, respectively, of healthy rabbit Achilles tendons.

The observed difference in strength and stiffness of healthy versus healing tendons is mediated by two interrelated factors. In the initial stages of healing, fibrous scar tissue is formed. This tissue is mainly comprised of type III collagen, which is characterized by smaller fibril diameter and a higher degree of vascularization compared with type I collagen. As the tendon heals, collagen content trends back towards its initial state (Kumagi et al. 1992). Additionally, scar tissue is characterized by its irregular orientation of collagen fibrils. As healing progresses, collagen alignment returns to its initial, highly parallel state (Bruns et al. 2000). Each of these injury effects leads to a decrease in tendon strength. Theoretically, they should lead to a decreased in tendon shear wave speed as well, given that a high degree of collagen alignment in the axial direction in tendon leads to higher observed SWS in the axial versus the transverse direction (Aubry et al. 2013).

We did observe some differences in SWS between tendons that are not well understood. In particular, there was a significant difference ($p < 0.001$) between SWS of intact lateral and

medial tendons, with mean distal location SWS values of 9.7 m/s and 11.5 m/s respectively (Fig. 3). However, in treated rabbits, the lateral and medial tendons exhibited similar ($p = 0.56$) presurgery SWS measures at the distal location, with means of 10.9 m/s and 11.0 m/s respectively (Fig. 2). While the exact cause of this difference is unknown, it is noted that the intact lateral tendons came from a subset of rabbits involved in a separate study, and thus may have been subject to protocols which altered tendon mechanics.

There remain challenges in using SWS measures to assess tendon mechanics. First is the recognition that tendon exhibits strain-stiffening behavior at low loads (Fung 1993), such that one observes an increase in shear wave speed with tendon stretch. A monotonic increase in SWS with stretch has previously been observed in both *in vivo* (Aubry et al. 2013; DeWall et al. 2014b; Yeh et al. 2014) and *ex vivo* (DeWall et al. 2014a) studies. This stretch dependence can affect repeatability of SWS measures if posture and muscle loading are not well controlled. Indeed, it is possible that stretch dependence may underlie the broad range of repeatability measures that have been reported for tendon SWS. Using the Aixplorer system, researchers have reported single observer intraclass correlation coefficient (ICC) values of 0.98 (Zhang and Fu 2013) and 0.57 (Peltz et al. 2013) for the human patellar tendon, and 0.42 for the human Achilles tendon (Peltz et al. 2013). In this study, we attempted to control for the strain-stiffening effect by collecting all images at a set ankle position. While this resulted in good inter-observation repeatability in our study ($ICC = 0.87 - 0.98$), there remains the possibility that the slack length of the tendon is altered with severing and surgical repair. Hence, it is not certain that the same posture results in the same loading and strain at the tissue level after surgical repair, and this could account for some of the SWS variability we observed.

A second challenge arises from a stretched tendon having the capacity to propagate shear waves at speeds higher than the current ultrasound systems can track. The Aixplorer system has a maximum tracking speed of 16.3 m/s, which did result in SWS saturation in a subset of images collected for intact tendons. Further analysis revealed that partial SWS saturation arises at measured shear wave speeds of about 12 m/s, with the percent then increasing rapidly at speeds above 14 m/s (Fig. 4). SWS values within the range of 14-16.3 m/s (or corresponding modulus values) have previously been reported for tendon using the Aixplorer system (e.g., Aubry et al. 2013; Aubry et al. 2015; DeWall et al. 2014a; DeWall et al. 2014b; Yeh et al. 2014), such that the effects of partial SWS saturation on study findings should be considered. In the present study, we repeated our correlation analysis using only those images that did not exhibit any SWS saturation and obtained similar results ($r = 0.52$, $p < 0.001$ for elastic modulus, and $r = 0.60$, $p < 0.001$ for ultimate stress) to those reported with the full data set (Table 1). Hence, the monotonic relationship between tendon SWS and mechanical measures persists even when images with partial saturation are excluded (as labeled in Fig. 3).

When examining the effectiveness of ultrasound SWE as a diagnostic tool for tendon health, we found that it did not match the effectiveness of mechanical testing for elasticity or strength in differentiating between fully intact and severed/repaired tendons (Table 2). However, the benefit of SWE is that it is a noninvasive measurement technique, and thus can be used clinically. SWE showed reasonable sensitivity as an *in vivo* test (0.81), but poor

specificity (0.64) when using z-score as differentiator. It should be noted that in this case, sensitivity is the more important of the two metrics, being that a false negative result would be more detrimental than a false positive result.

Conclusions

We observed significant correlations between shear wave speed and tendon elasticity and strength measures in surgically repaired tendons. Thus, ultrasound shear wave elastography is a potentially promising noninvasive technology for quantitatively tracking the mechanical integrity of tendon following damage and clinical treatment.

Acknowledgements

This study was supported by the AO Research Foundation, Grant Number S-11-79B, the American College of Veterinary Surgeons Zoetis Dual Training Grant 2014, the Radiological Society of North America Scholar Grant Award #RSCH1317, the Raymond G. and Anne W. Herb Wisconsin Distinguished Graduate Fellowship, and the UW-Madison Radiology Department Research and Development Fund #1204-001. The project described was additionally supported by the Clinical and Translational Science Award program (CTSA #10012012), through the NIH National Center for Advancing Translational Sciences (NCATS), grant #UL1TR000427. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH. The authors would like to acknowledge the help and expertise for conducting this study provided by Brett Nemke, Yan Lu, Carissa Sawyer, Alyssa White, Kelley Encinas and Sarah Rossmiller, as well as Sarah Kohn and the Wisconsin Institutes for Medical Research Ultrasound Research Lab.

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Figure 1.

Representative anatomical and ultrasound images showing relative location of the calcaneus, and lateral and medial gastrocnemius tendons. A: Transducer position for imaging lateral and medial tendons. B: View of Achilles tendon unit (fascia intact). C: View of Achilles tendon unit (exterior fascia removed). Tendon unit rotated to obtain better view of lateral tendon. D: Ultrasound image of lateral tendon. E: Ultrasound image of medial tendon. Note that lateral tendon is also visible.

Figure 2.
Spatial and temporal variation in shear wave speed. Significant differences ($p < 0.0167$) shown for time point (*) and scanning location (**).

Figure 3. Elastic modulus and ultimate stress versus shear wave speed for repaired lateral, intact lateral, and intact medial tendons. Best fit line obtained via Deming regression with normalized error in each variable weighted equally.

Figure 4. Percentage of pixels exhibiting saturated shear wave speed as a function of measured shear wave speed – evaluated for a subset of images.

Table 1

Best fit slope (Deming regression), correlation and significance for relationship between shear wave speed and elastic modulus and ultimate stress for the cases of: intact tendons only, severed/repaired tendons only, and all tendons combined together.

		Intact	Surgically Repaired	Combined
Elastic Modulus	Slope [MPa×m ⁻¹ s]	51.6	43.3	54.8
	r	0.19	0.22	0.52
	p	0.09	0.08	0.00
Ultimate Stress	Slope [MPa×m ⁻¹ s]	6.17	4.64	7.09
	r	0.24	0.30	0.58
	p	0.04	0.03	0.00

Table 2

Sensitivity and specificity for shear wave speed, elastic modulus, and ultimate stress as diagnostic tests for tendon state (fully intact vs. severed/repaired).

	Elastic Modulus	Ultimate Stress	Shear Wave Speed
Sensitivity	0.93	0.93	0.81
Specificity	0.79	0.88	0.64