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Ultrasound Shear Wave Elastography of the Elbow Ulnar Collateral Ligament: Reliability Test and a Preliminary Case Study in a Baseball Pitcher

Overhead throwing athletes are at high risk of the elbow ulnar collateral ligament (UCL) injury, and there is a need for clinical tools to objectively diagnose severity of injury and monitor recovery. Mechanical properties of ligaments can potentially be used as biomarkers of UCL health. The objectives of this study are to evaluate the reliability of shear wave ultrasound elastography (SWE) for quantifying UCL shear modulus in 16 healthy nonthrowing individuals and use this technique to evaluate the difference in UCL shear modulus between the injured and uninjured elbows in a baseball pitcher with UCL tear. In the reliability test, the UCL shear modulus of both elbows of each participant was evaluated by SWE for five trials. The same procedures were repeated on two different days. The intra-day and day-to-day reliabilities were determined by the five measurements on the first day and two averages on the two days, respectively. In the case study, each elbow of the baseball pitcher with UCL tear was tested for five trials, and the average was calculated. The intra-day (intraclass correlation coefficient (ICC) = 0.715, Cronbach's alpha = 0.926) and day-to-day (ICC = 0.948, Cronbach's alpha = 0.955) reliabilities were found to be good. There was no difference between both sides. In the case study, the UCL shear modulus of the injured elbow (186.45 kPa) was much lower than that of the uninjured elbow (879.59 kPa). This study shows that SWE could be a reliable tool for quantifying the mechanical properties and health status of the UCL. [DOI: 10.1115/1.4038259]

Keywords: shear wave elastography, elbow ulnar collateral ligament, shear modulus, ulnohumeral joint space, musculoskeletal ultrasonography, Tommy John surgery

Introduction

Overhead throwing athletes, such as baseball pitchers, exert tremendous repetitive stresses on the anterior band of the ulnar collateral ligament (UCL) of the medial elbow over time, and have a higher risk of an acute and/or chronic injury of the UCL [1,2]. Pitchers having UCL injuries demonstrate symptoms such as pain, decreased control, as well as declines in performance and career longevity [3,4]. If unfortunately, the UCL is partially or completely ruptured, the injured pitcher may have to undergo UCL reconstruction surgery. Surgical reconstruction requires an extensive period of 12–18 months for recovery and rehabilitation [5], placing a large burden on the pitcher and the team. Additionally, the player undergoing surgery may not be able to return to the same competitive level as that before the injury [6]. Quantification of UCL adaptation to throwing activity can enable early diagnosis and intervention for UCL injuries, and decrease the incidence of severe injuries. For this sake, a reliable, noninvasive tool for monitoring the health status of the UCL and the degree of injury would be a valuable tool. Currently, diagnosis of UCL injuries is based on physical examination and imaging techniques, such as plain radiography, conventional magnetic resonance imaging, and magnetic resonance arthrography [1,7]. These diagnostic techniques are useful for providing information related to UCL injuries but have some inherent limitations. For example, physical examination is subjective and not specific because other medial elbow lesions may present similar symptoms [8]. Plain radiography is capable of detecting bony changes but cannot provide direct information on the ligament [1]. Conventional magnetic resonance imaging is useful in identifying acute complete ruptures, but may not be accurate for partial or chronic injuries [1,9], and has limitations such as high cost for a single time point, and a long examination time. Magnetic resonance arthrography, a magnetic resonance imaging technique to diagnose joint conditions after the injection of contrast agent into the joint, is reported to be the most accurate technique having sensitivity of 92% and specificity of 100% at identifying UCL tears, but it may not play a major role in the clinical diagnosis mainly because of its invasiveness, and additional high expense in cost and time [7,9,10]. Ultrasonography is a noninvasive, cost-effective, portable imaging method to accurately evaluate anatomical changes of the UCL [9,11,12]. However, it has been reported that anatomical changes are not always related to symptoms and the degree of injury [13].

Measurement of the mechanical properties of musculoskeletal soft tissues is a promising method for objectively evaluating the degree of injury and health status of tissues. It has been reported that injuries induce significant changes in the mechanical properties of tissues such as tendons and ligaments [14–16], and these changes may directly impact their functional performances [16–18]. Shear wave ultrasound elastography (SWE) is an imaging technique designed to noninvasively evaluate the mechanical properties of tissues [19–23]. Shear wave speed is directly related to the shear modulus (a measure of the stiffness) of the tissue. Measurements of shear modulus can indirectly provide information about changes in microstructure and composition of the tissue [21,24,25]. Like tendons and muscles, ligaments are hierarchical structures consisting of different levels of fibers [26–28]. SWE has been successfully applied to quantitatively evaluate the shear

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modulus of tendons and muscles, and characterize their changes following injuries and degeneration [21,29–31], but rarely applied to ligaments in previous research.

The primary objective of the present study was to investigate the reliability of SWE for evaluation of the UCL shear modulus in a group of healthy nonthrowing individuals, and to use this technique to evaluate the difference in UCL shear modulus, UCL thickness, and width of the ulnohumeral joint space between the injured and uninjured elbows in a collegiate baseball pitcher with partial UCL tear. The secondary objective was to investigate possible correlations of UCL shear modulus and thickness of the UCL or width of the ulnohumeral joint space. The results of this study can provide the foundation of future studies on healthy and injured overhead throwing athletes.

Materials and Methods

Subjects. This study was approved by the Institutional Review Board of The Pennsylvania State University, State College, PA. Each participant signed the informed consent before any data collection. Over 16 healthy nonthrowing participants (eight men and eight women; age = 27.1 ± 4.9 years; BMI = 22.1 ± 3.2 kg/m^2) were recruited. The self-reported dominant arms were right in all participants. The participants had never engaged in sports or physical activity that required an overhead throwing motion. The further exclusion criteria were elbow pain, systematic and neurological diseases at the time of evaluation, and a history of injury or surgery of the elbow.

In the case study, a right-handed 21-year-old collegiate baseball player (BMI = 24.3 kg/m^2) with partial UCL tear was recruited. He noted a sensation of pain and instability in the medial aspect of his pitching elbow while pitching in a game. He tried to pitch in another game but still felt pain, instability, and weakness in his pitching elbow. He then stopped pitching and was referred to an orthopedic specialist. Magnetic resonance imaging and ultrasound examinations revealed a suspected partial UCL tear in his pitching elbow. He received the SWE examination of the present study within one week after diagnosis.

Shear Wave Elastography System. The Verasonics ultrasound system (Verasonics Inc., Redmond, WA) with a linear array transducer L11-5 (128 elements, beamwidth = 5–11 MHz, center frequency = 7.813 MHz) was used to implement an SWE technique similar to that proposed by Bercoff and his colleagues, called supersonic shear imaging [19]. 64 elements of the transducer emitted focused ultrasound pushing beam (500 push cycles at 7.813 MHz frequency; push duration = 100 μs) successively at seven increasing, equally spaced focal depths to create quasi-plane shear waves propagating through the tissue. The propagation speed of the quasi-plane shear wave was calculated within the region of interest using high frame rate plane wave imaging (at 10,000 frames/s). The corresponding shear modulus map could then be constructed based on the equation $\mu = \rho c^2$, where μ is the shear modulus, ρ is the tissue density typically assumed as 1000 kg/m^3, and c is the shear wave speed. The technique was validated using calibrated homogeneous phantoms having different shear modulus values (Model 040GSE, CIRS, Norfolk, VA).

Measurement Procedures. Sonographic measurement was performed by an experienced sonographer in musculoskeletal ultrasound using the system described above. Three parameters were obtained from measurement, including the UCL shear modulus, UCL thickness, and width of the ulnohumeral joint space. During measurement, the participant was lying supine on the examination table with the elbow at 30 deg of flexion [1,7,32–34], and the shoulder at 30 deg of abduction and 90 deg of external rotation (Fig. 1). The forearm was in the neutral position and stabilized on the table by a 4.5 kg sandbag (Fig. 1). One edge of the transducer was placed and fixed at the medial epicondyle of the humerus. The other edge of the transducer was pointed to the coronoid process of the ulna and rotated slightly toward the lateral side of the arm. The acceptable image included the medial epicondyle and trochlea of the humerus, coronoid process of the ulna, common flexor tendon, and superficial part of the UCL (Fig. 2). The superficial part of the UCL was identified as a hyperechoic band-like structure that was attached to the medical epicondyle of the humerus and the coronoid process of the ulna [12,33]. In this scanning plane, the deeper part of the UCL within the medial joint capsule was hypoechoic. Once all of the anatomical landmarks were clearly identified in the image, the SWE mode was then activated. Typically, the size of the rectangular field of view (FOV) for acquiring shear wave speed data was around 11 mm in width and 7 mm in height. The measurement depth (from the transducer

Fig. 1 The participant laying supine on the examination table with the elbow at 30 deg of flexion, and the shoulder at 30 deg of abduction and 90 deg of external rotation during measurement

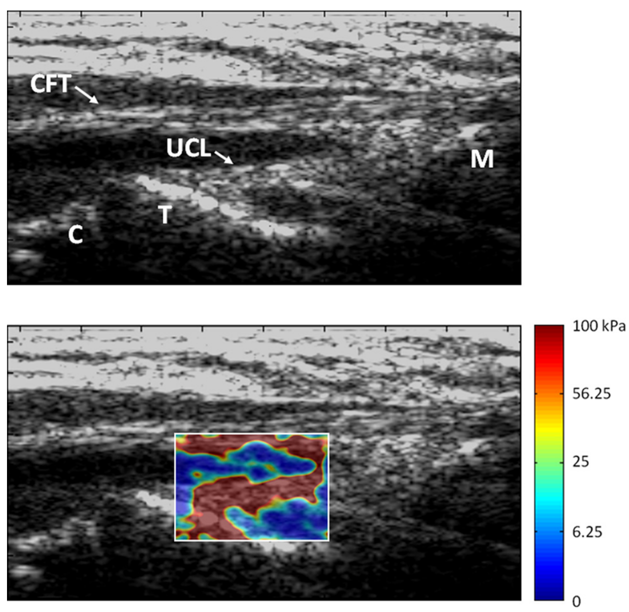

Fig. 2 Shear wave elastography evaluation of the UCL. An acceptable B-mode image for evaluating the UCL includes the medical epicondyle (M) and trochlea of the humerus (T), coronoid process of the ulna (C), common flexor tendon (CFT) and superficial part of the UCL. The two-dimensional shear modulus map corresponding to the rectangular FOV shows the shear modulus levels of the tissues represented by colors ranging from red (stiff) to blue (soft). The band-like shear modulus distribution of the UCL could be observed in the central horizontal region of the image. The high shear modulus distributions observed in the upper and lower left regions of the FOV correspond to the common flexor tendon and the periosteum of the trochlea of the humerus, respectively.

surface to the bottom of the FOV) differed between individuals because of individual differences in anatomy. In this study, the average measurement depths for eight male and eight female participants were 16.98 mm (standard deviation = 3.16 mm, range = 13.15–20.57 mm) and 15.12 mm (standard deviation = 1.92 mm, range = 12.68–19.01 mm), respectively. After keeping the transducer stationary for a few seconds, the shear wave speed data were captured and the two-dimensional shear modulus map corresponding to the FOV was calculated (Fig. 2). The shear modulus of the UCL, defined as the median shear modulus of the superficial part of the UCL region on the two-dimensional shear modulus map, was determined by selecting a region of interest by manually tracing the contour of the superficial part of the UCL in the B-mode image using a custom-designed MATLAB program (Fig. 3). The B-mode image was saved as an image file and imported into MATLAB for analysis of the UCL thickness and width of the ulnohumeral joint space using a custom-designed MATLAB program. The UCL thickness was measured at the midportion of the superficial part of the UCL, and the width of the ulnohumeral joint space, defined as the distance between the edge of the trochlea of the humerus and the edge of the coronoid process of the ulna [9], was measured as shown in Fig. 3.

In the reliability test, both elbows of each participant were tested. Each elbow was tested for five successive trials for evaluating intra-day test-retest reliability, and the three parameters were collected in each trial. To evaluate day-to-day reliability, the same procedures were repeated on two different days with an interval of at least one day. In the case study, injured and uninjured elbows of the baseball pitcher were tested at one time point. Each elbow was tested for five successive trials, and the three parameters were collected in each trial. For each parameter, the average of the five trials was calculated for reporting the result.

Statistical Analysis. Intraclass correlation coefficient (ICC) and Cronbach's alpha reliability coefficient were used to calculate the measurement reliability of the three parameters. The five measurements on the first day were used to determine the intra-day reliability using the ICC(2,1) and Cronbach's alpha. The average of the five measurements on the first day and that on the second day were used to determine the day-to-day reliability using the ICC(2,k) and Cronbach's alpha. The side-to-side difference of each parameter was determined by the paired t-test. The spearman's rank correlation coefficient was applied to analyze the correlation between the UCL shear modulus and UCL thickness, between the UCL shear modulus and width of the ulnohumeral joint space, or between the UCL thickness and width of the ulnohumeral joint space. In the side-to-side difference and correlation tests, the average of the five measurements on the first day of each parameter was used. The level of statistical significance was set as $p < 0.05$. All data and statistical analyses were performed using MATLAB software (The Mathworks, Inc., Natick, MA) and IBM SPSS statistics software (IBM, SPSS Inc., Chicago, IL).

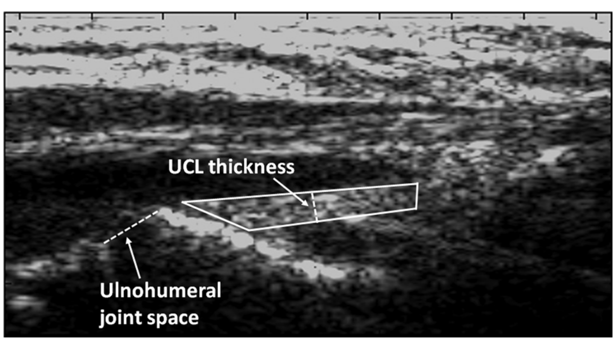

Fig. 3 The shear modulus of the UCL was determined by selecting a region of interest (the solid-line region) by manually tracing the contour of the superficial part of the UCL in the corresponding B-mode image using a custom-designed MATLAB program. The UCL shear modulus was defined as the median shear modulus in that region. Measurements of the UCL thickness (the length of the right dashed line) and the width of the ulnohumeral joint space (the length of the left dashed line) were illustrated.

Results

The measurement results of the UCL shear modulus, UCL thickness, and width of the ulnohumeral joint space in 16 healthy nonthrowing participants were summarized in Table 1. For the UCL shear modulus, the ICC and Cronbach's alpha for the intra-day reliability were 0.715 (95% CI = 0.587–0.828) and 0.926, respectively, indicating that the reliability was good. The day-to-day reliability was excellent based on the associated ICC (0.948 with 95% CI = 0.884–0.976) and Cronbach's alpha (0.955). The scatterplot of the averages on two different days was shown in Fig. 4. For the UCL thickness, the ICC and Cronbach's alpha for the intra-day reliability were 0.883 (95% CI = 0.816–0.934) and 0.974, respectively, and those for the day-to-day reliability were 0.972 (95% CI = 0.943–0.986) and 0.972, respectively, indicating that the reliability was excellent. For the width of the ulnohumeral joint space, the ICC and Cronbach's alpha showed excellent reliability for both the intra-day reliability (ICC = 0.951 with 95% CI = 0.921–0.973; Cronbach's alpha = 0.990) and the day-to-day reliability (ICC = 0.976 with 95% CI = 0.951–0.988; Cronbach's alpha = 0.976).

Table 1 UCL shear modulus, UCL thickness, and width of the ulnohumeral joint space measured in 16 healthy nonthrowing participants. (Data presented as average ± standard deviation.)

	Side	Day 1	Day 2
UCL shear modulus (kPa)	Right	109.82 ± 43.45	113.50 ± 37.52
	Left	103.90 ± 35.61	113.58 ± 36.55
UCL thickness (mm)	Right	1.79 ± 0.32	1.80 ± 0.30
	Left	1.78 ± 0.33	1.79 ± 0.27
Ulnohumeral joint space width (mm)	Right	4.05 ± 0.68	4.02 ± 0.59
	Left	4.12 ± 0.69	4.12 ± 0.66

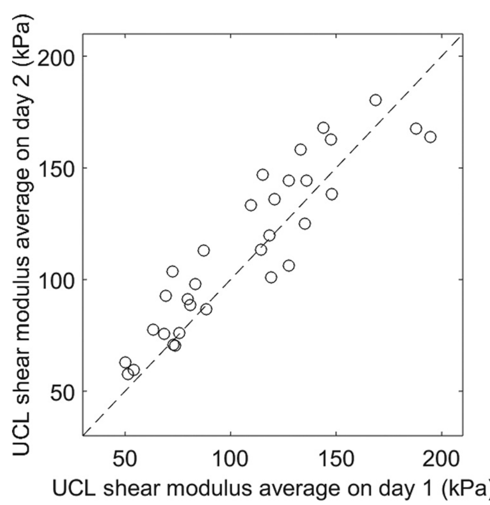

Fig. 4 The scatterplot of the averages on two different days for the UCL shear modulus in 16 healthy nonthrowing participants. The dashed line indicates the 1:1 perfect agreement.

There was no significant difference between the right and left sides in the UCL shear modulus, UCL thickness, or width of the ulnohumeral joint space. It meant that there was no significant difference between the dominant and nondominant arms in the three parameters since all of the participants were right-handed. There was no significant correlation between the UCL shear modulus and UCL thickness (rho = 0.0242, $p = 0.8953$), between the UCL shear modulus and width of the ulnohumeral joint space (rho = −0.2336, $p = 0.1982$) or between the UCL thickness and width of the ulnohumeral joint space (rho = 0.0838, $p = 0.6485$).

In the case study, the UCL shear modulus of the injured elbow (186.45 kPa; shear wave speed = 13.65 m/s) was much lower than that of the uninjured elbow (879.59 kPa; shear wave speed = 29.66 m/s). The UCL thickness and width of the ulnohumeral joint space of the injured elbow were 2.30 and 4.03 mm, respectively, and those of the uninjured elbow were 2.35 and 4.68 mm, respectively.

Discussion

The present study applied SWE to the UCL and investigated the reliability of the technique. The intra-day and day-to-day reliabilities were found to be good and excellent, respectively, demonstrating that SWE could be a useful tool in the assessment of the shear modulus and mechanical integrity of the UCL. It should be noted that the reason why the day-to-day reliability was higher than the intra-day reliability is because of the protocol used in the present study, that is, the day-to-day reliability was determined by the two averages on the two days while the intra-day reliability was determined by the five separate measurements on the same day. The observed variations in the data among separate measurements in using ultrasound elastography indicate that, in clinical application, the average over several measurements should be used for analysis, rather than a single measurement result. In the case study, it was found that the shear modulus of the injured UCL of the baseball pitcher was around 79% lower than that of the healthy one. Although only one baseball pitcher was evaluated at only one time point in this case study, this exciting finding revealed that the shear modulus could be a promising biomarker to quantitatively evaluate the health status of the UCL for diagnosis and is worthy to be further studied in the future. It is interesting to note that the UCL shear moduli in the baseball pitcher were much higher than those observed in the healthy nonthrowing participants. This may be due to adaptation and remodeling responses of the ligament to long-term repetitive mechanical loading. A longer follow-up on this baseball pitcher and other patients will be reported in future studies.

Currently, the health status and degree of injury of the UCL are evaluated by physical examination, as well as imaging techniques based on the detection of anatomical changes. However, anatomical changes do not always correlate to symptoms and the degree of injury. Several previous studies have reported that many baseball pitchers of different levels and ages, although asymptomatic, showed significant thickening of the UCL in the pitching arms compared to the nonpitching arms [1,3,9,13,32]. Hypoechoic foci and calcifications, two signs of abnormalities evaluated by ultrasonography, could be detected in both the pitching and nonpitching arms [1,3,32]. It has been suggested that these anatomic changes may be adaptations and responses to the stress sustained by the elbow during the throwing motion, and may not necessarily mean that the ligament is injured [13]. Hence, the use of the morphological properties and their changes alone could not accurately reflect the presence and degree of injury of the UCL. In recent years, there has been a growing interest in using the information of the mechanical properties as a biomarker to evaluate the health status of tissues due to their drastic change after injury [35]. Stress radiography [36–38] and stress ultrasonography [1,3,7,9,12,32,34,39] can provide information about the stiffness of the UCL based on evaluating the laxity of the medial elbow joint, and their methodology and clinical application have been investigated in several previous studies. However, these methods could not provide a direct and quantitative evaluation of the stiffness of the individual UCL, and the properties of other tissues within the joint complex may affect the measurement result. The SWE technique used in the present study could offer a more direct evaluation of the UCL mechanical properties than stress imaging because it is capable of specifically targeting the tissue of interest.

In the technique of using SWE to evaluate the UCL shear modulus presented in this study, the sonographer should precisely and consistently capture the superficial part of the UCL for obtaining an accurate and repeatable measurement result. Hence, it may be a technically demanding technique that may require a skilled sonographer. Accordingly, there may be some inherent limitations of the present study associated with this technique. First, it has been reported in several previous studies that hypoechoic lesions and calcifications are more common in the ultrasound B-mode image of the UCL in pitching arms of baseball pitchers [1,3,9,11,13,39]. In this kind of image, the thin, band-like superficial part of the UCL may not be clearly identified, likely increasing the difficulty in using this technique. For overcoming this limitation, other associated anatomical bony landmarks should be carefully identified. Second, all examinations were performed by a single experienced sonographer in the present study. As mentioned previously, the skill and experience of the sonographer may play important roles in using this technique. In the future, the interrater reliability of this technique should be investigated.

The reliabilities of evaluating the UCL thickness and width of the ulnohumeral joint space were found to be excellent. In previous studies, these two properties were used as the biomarkers to evaluate the functional status of the UCL and medial elbow [1,3,9,13,32,33]. The reliability of the evaluation of these morphological properties reported in the present study could be served as a reference for future studies. No significant correlation was found among the UCL shear modulus, UCL thickness, and width of the ulnohumeral joint space, probably because the properties being investigated were the individual baseline properties in a group of healthy, nonthrowing individuals. In the future, the correlation among the mechanical and morphological properties should be studied in both symptomatic and asymptomatic overhead throwing athletes.

The technique of evaluating the UCL shear modulus by SWE reported in the present study holds promise as a potential tool for evaluation of the health status of the UCL and early detection of injury for future sports medicine applications. For example, it could be used to routinely monitor the UCL of athletes during a season in order to understand if a UCL is injured or if it has a higher risk of injury, and coaches and trainers can make use of this information to optimize the training and intervention protocols. It could also be applied to evaluate the degree of injury for providing a more accurate diagnosis, and helping medical doctors identify the optimal intervention strategy, monitor the recovery process and the effect of the treatment. In comparison to other imaging techniques such as magnetic resonance imaging, ultrasound elastography is relatively cheaper, faster, and capable of assessing the morphological and mechanical properties of the UCL at the same time. It is our hope that ultrasound elastography technique could serve as a useful tool bringing benefits to athletes and communities, and helping reduce the incidence of UCL injuries and reconstruction surgeries.

In conclusion, we demonstrated that SWE could be a reliable tool in the quantitative assessment of the shear modulus of the UCL, and could be a useful clinical tool for objectively evaluating the health status of the UCL for sports medicine applications. Future studies will focus on applying this technique to healthy and injured throwing athletes. The skill and experience of the sonographer may play important roles in using this technique adequately and reliably. No significant correlation was found among the UCL shear modulus, UCL thickness, and width of the ulnohumeral joint space, perhaps because the properties being investigated were the individual baseline properties in the healthy nonthrowing individuals.

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