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Short communication

Shear wave elastography of the supraspinatus muscle and tendon: Repeatability and preliminary findings

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ABSTRACT

Shear wave elastography (SWE) is a promising tool for estimating musculoskeletal tissue properties, but few studies have rigorously assessed its repeatability and sources of error. The objectives of this study were to assess: (1) the extent to which probe positioning error and human user error influence measurement accuracy, (2) intra-user, inter-user, and day-to-day repeatability, and (3) the extent to which active and passive conditions affect shear wave speed (SWS) repeatability. Probe positioning and human usage errors were assessed by acquiring SWE images from custom ultrasound phantoms. Intra- and inter-user repeatability were assessed by two users acquiring five trials of supraspinatus muscle and tendon SWE images from ten human subjects. To assess day-to-day repeatability, five of the subjects were tested a second time, approximately 24 h later. Imaging of the phantoms indicated high inter-user repeatability, with intraclass correlation coefficient (ICC) values of 0.68–0.85, and RMS errors of no more than 4.1%. SWE imaging of the supraspinatus muscle and tendon had high repeatability, with intra- and inter-user ICC values of greater than 0.87 and 0.73, respectively. Day-to-day repeatability demonstrated ICC values greater than 0.33 for passive muscle, 0.48 for passive tendon, 0.65 for active muscle, and 0.94 for active tendon. This study indicates the technique has good to very good intra- and inter-user repeatability, and day-to-day repeatability is appreciably higher when SWE images are acquired under a low level of muscle activation. The findings from this study establish the feasibility and repeatability of SWE for acquiring data longitudinally in human subjects.

1. Introduction

Chronic, pathologic tendon conditions (e.g., rotator cuff tears) are common, painful, and debilitating. Clinical interventions such as physical therapy or surgery are often indicated, but the extent to which these interventions affect the tendon's mechanical function or physical properties is difficult to assess, particularly under in-vivo conditions. Previous research has described implantable sensors and imaging-based approaches for measuring in-vivo tendon function (Bey and Derwin, 2012; Fleming and Beynnon, 2004), but these approaches are largely limited to research applications. Consequently, there remains a need for a clinical tool for assessing the physical properties of tendons in-vivo. Such a tool would aid clinicians in pre-surgical planning, counseling patients regarding expected outcomes, and monitoring the progression of repair tissue healing after surgery.

Shear wave elastography (SWE) is an ultrasound-based imaging modality that provides a non-invasive estimate of tissue properties by measuring the speed of shear wave propagation through soft tissues. SWE has been used extensively for breast and liver imaging (Franchi-Abella et al., 2015; Hagan et al., 2015; Kim et al., 2015; Lee et al., 2015; Park et al., 2015; Tang et al., 2015; Webb et al., 2015), and has been used increasingly in recent years to assess musculoskeletal soft tissues (e.g., (Andonian et al., 2016; Chino et al., 2015; Cortes et al., 2015; DeWall et al., 2014; Koo et al., 2013; Takenaga et al., 2015)). SWE may be a promising tool for assessing muscle and tendon properties, but the repeatability of this technique and potential sources of error have not been rigorously examined. Consequently, the objectives of this study were to assess: (1) the extent to which positioning error and human user error influence measurement accuracy, (2) intra-user, inter-user, and day-to-day repeatability, and (3) the extent to which

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active and passive conditions affect SWS repeatability for the rotator cuff's supraspinatus muscle and tendon.

2. Methods

To assess the feasibility of SWE, we conducted a series of in-vitro and in-vivo experiments. The in-vitro experiments used custom imaging phantoms to determine repeatability of the SWE system and to evaluate the role of positioning error and human user error on shear wave speed (SWS). The in-vivo experiments assessed the repeatability of muscle and tendon SWS under active and passive conditions.

To evaluate repeatability over a range of SWS values, three custom ultrasound phantoms were constructed using psyllium husk, gelatin, and water (Bude and Adler, 1995). Psyllium husk concentration was 3% by volume in each phantom, and SWS was manipulated by varying the concentration of gelatin (5%, 10%, and 15% by volume). SWE images of each phantom were acquired with a commercial ultrasound system (Siemens ACUSON S3000, 9L4 probe) under three testing conditions. The first (i.e., reference) testing condition was with the probe rigidly clamped. Five trials were acquired sequentially without altering the setup. To assess positioning error, five SWE images were acquired with the probe rigidly clamped during each trial, but with the probe removed and reattached to the clamp and repositioned between trials. To assess user error, five SWE images were acquired for each of two users (TB, JD) who manually operated the probe as would occur clinically.

Following IRB approval, SWE images of the supraspinatus tendon and muscle were acquired from the dominant shoulder of 10 subjects (age: 44.7 ± 18.8, range: 18–70). Long-axis tendon images were acquired by positioning the probe medial to the acromion and aligning it parallel to the intramuscular portion of the tendon. Supraspinatus muscle images were acquired anterior to the tendon with the image plane aligned parallel to the muscle fibers as described by Itoigawa and colleagues (Itoigawa et al., 2015). Probe positioning was facilitated by real-time brightness mode (B-mode) images.

SWE images of the supraspinatus tendon and muscle were acquired under passive and active conditions. For the passive condition, subjects were seated with their elbow resting against a 30° abduction pillow (Bledsoe Arc 2.0, Carlsbad, CA) and their forearm pronated and resting on their thigh. The active condition involved the subjects lifting their forearm off their thigh and abducting their shoulder only enough to remove contact with the abduction pillow. For each subject, a convenience sample of five trials of SWE images were acquired by two users (TB, JD) for each of the four combinations of tissue (muscle, tendon) and testing condition (active, passive). SWE image acquisition for a convenience sample of five of these subjects was then performed by both users approximately 24 hours later. No activity restrictions were placed on these subjects between testing sessions.

The ultrasound system's proprietary software calculated SWS at each pixel within a rectangular region of approximately $3\,cm \times 2.5\,cm$. For the phantom images, this entire region was selected as the region of interest (ROI) for further analysis. For images acquired from human subjects, a semi-automated thresholding algorithm was applied to the B-mode image (acquired simultaneously with the SWE image) to segment the image into soft tissue regions based on an echogenic threshold value. The region corresponding to the tissue of interest (muscle or tendon) was manually selected as the ROI for each trial. The ROI boundaries identified in the B-mode image were then applied to the SWE image, and all SWS values within the ROI were used for further analysis. For each trial, a single SWS value was calculated as the average of the central 90th percentile of individual SWS values within the ROI. The ROI consisted of an average of 4223 ± 3104 individual SWS values for tendon trials, and an average of $15{,}825 \pm 5719$ individual SWS values for muscle trials. For each testing condition, mean SWS was calculated as the average of the five trials.

Positioning error and user error were assessed from the phantom images by calculating accuracy with respect to the mean SWS from the reference condition. Accuracy was quantified in terms of bias and precision, which were defined as the average and standard deviation, respectively, of the difference between the positioning/user error trials and the mean SWS of the reference condition (ASTM, 1996). RMS error was calculated as a composite measure of accuracy. Inter-user repeatability was assessed by calculating the intra-class correlation coefficient (ICC) for the phantom images collected by the two users. Similarly, inter-user, intra-user, and inter-day repeatability were assessed using the ICC from the human subject images. ICC values of 0–0.2 were considered poor, 0.21–0.4 fair, 0.41–0.6 moderate, 0.61–0.8 good and 0.81–1.0 very good (Altman, 1991). A paired *t*-test assessed differences in mean SWS between passive and active conditions. Statistical significance was set as $p \leq 0.05$.

3. Results

For the phantom studies, positioning error resulted in a bias of 0.01–0.03 m/s, precision of 0.03–0.09 m/s, and RMS error of 0.04–0.08 m/s (Table 1). User error resulted in a bias of −0.09 to 0.06 m/s, precision of 0.01–0.12 m/s, and RMS error of 0.03–0.11 m/s (Table 1). Phantom SWE imaging had high repeatability, with intra- and inter-user ICC values of greater than 0.99 and 0.68, respectively.

SWE imaging of the supraspinatus muscle and tendon had high repeatability, with intra-and inter-user ICC values of greater than 0.87 and 0.73, respectively. Day-to-day repeatability was tissue/condition dependent, with ICC values greater than 0.33 for passive muscle, 0.48 for passive tendon, 0.65 for active muscle, and 0.94 for active tendon. Mean SWS of active muscle (3.74 ± 0.64 m/s) was greater than passive muscle (2.23 ± 0.29 m/s; $p < 0.001$), and mean SWS of active tendon (5.97 ± 1.72 m/s) was greater than passive tendon (2.80 ± 0.59 m/s; $p < 0.001$).

4. Discussion

The approach described here has high intra-user and inter-user repeatability, and high day-to-day repeatability for measuring supraspinatus mean SWS under a low level of muscle activation. Errors due to repositioning and user operation are small, with normalized RMS values (i.e., RMS/mean) of 2.6% for positioning error and 4.1% for user error when compared to the reference condition. The 4.1% error is a cumulative effect of positioning error and user operation error, and can be interpreted as the upper bounds of error. Compared to the mean SWS for active tendon (5.97 ± 1.72 m/s), this error is less than 2%.

The results are generally in good agreement with previous research. For example, the findings of inter-user ICC values greater than 0.68 for the phantom images and greater than 0.73 for the human images are consistent with previous studies that have

Table 1
Shear wave speed values reported as mean (standard deviation). P5 = 5% phantom, P10 = 10% phantom, P15 = 15% phantom.

Testing condition	Mean (st dev)			Bias (precision)			RMS		
	P5	P10	P15	P5	P10	P15	P5	P10	P15
Reference	1.55 (0.004)	3.18 (0.01)	3.97 (0.02)	–	–	–	–	–	–
Positioning error	1.58 (0.03)	3.19 (0.04)	3.98 (0.09)	0.03 (0.03)	0.01 (0.04)	0.01 (0.09)	0.04	0.04	0.08
User1 error	1.61 (0.04)	3.24 (0.05)	4.01 (0.12)	0.05 (0.04)	0.06 (0.05)	0.04 (0.12)	0.06	0.07	0.11
User2 error	1.58 (0.01)	3.14 (0.01)	3.88 (0.04)	0.02 (0.01)	−0.04 (0.01)	−0.09 (0.04)	0.03	0.04	0.10

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