Journal of Biomechanics 53 (2017) 201–204

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

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

Timothy G. Baumer [a,*], Leah Davis [b], Jack Dischler [a], Daniel S. Siegal [b], Marnix van Holsbeeck [b], Vasilios Moutzouros [c], Michael J. Bey [a]

[a] *Department of Orthopaedic Surgery, Bone and Joint Center, Henry Ford Health System, USA*
[b] *Department of Radiology, Henry Ford Health System, USA*
[c] *Department of Orthopaedic Surgery, Sports Medicine Division, Henry Ford Health System, USA*

ARTICLE INFO

*Article history:*
Accepted 5 January 2017

*Keywords:*
Muscle
Tendon
Rotator cuff
Shear wave elastography

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

---

[*] Correspondence to: Bone and Joint Center, 6135 Woodward Ave, Detroit, MI 48202, USA. Fax: +1 313 871 2607.
*E-mail address:* tbaumer1@hfhs.org (T.G. Baumer).

http://dx.doi.org/10.1016/j.jbiomech.2017.01.008
0021-9290/© 2017 Elsevier Ltd. All rights reserved.

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: $44.7 \pm 18.8$, 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 user**s** (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 $3\,\text{cm} \times 2.5\,\text{cm}$. 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 $4223 \pm 3104$ 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 ($3.74 \pm 0.64$ m/s) was greater than passive muscle ($2.23 \pm 0.29$ m/s; $p < 0.001$), and mean SWS of active tendon ($5.97 \pm 1.72$ m/s) was greater than passive tendon ($2.80 \pm 0.59$ 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 ($5.97 \pm 1.72$ 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<br>(0.004) | 3.18<br>(0.01) | 3.97<br>(0.02) | – | – | – | – | – | – |
| Positioning error | 1.58<br>(0.03) | 3.19<br>(0.04) | 3.98<br>(0.09) | 0.03<br>(0.03) | 0.01<br>(0.04) | 0.01<br>(0.09) | 0.04 | 0.04 | 0.08 |
| User1 error | 1.61<br>(0.04) | 3.24<br>(0.05) | 4.01<br>(0.12) | 0.05<br>(0.04) | 0.06<br>(0.05) | 0.04<br>(0.12) | 0.06 | 0.07 | 0.11 |
| User2 error | 1.58<br>(0.01) | 3.14<br>(0.01) | 3.88<br>(0.04) | 0.02<br>(0.01) | $-0.04$<br>(0.01) | $-0.09$<br>(0.04) | 0.03 | 0.04 | 0.10 |

reported good to very good ICC values for inter-user repeatability in imaging phantoms (Dillman et al., 2015) or human subjects (Dubois et al., 2015; Rosskopf et al., 2016; Siu et al., 2016; Yoshitake et al., 2014). However, in contrast to the work by Yoshitake and colleagues, the muscle and tendon images acquired under passive conditions in the current study showed only fair to moderate inter-day repeatability.

The day-to-day repeatability under active conditions was appreciably higher than passive conditions for both the supraspinatus muscle and tendon. Although the explanation for this finding is not clear, it is possible that passive tissue properties may be sensitive to fluctuations in mechanical loading associated with activities of daily living. It is important to note that the study participants' activity levels between testing sessions was neither controlled nor documented. Consequently, variability in the subjects' daily activities may have negatively affected day-to-day repeatability when acquiring images under passive conditions. Interestingly, a small level of muscle activation largely reduces this day-to-day variability. This finding suggests that acquiring SWE images during a low level of muscle activation maximizes repeatability, which is especially important when conducting a longitudinal study with multiple imaging sessions. This finding is consistent with the work of Moreau and colleagues who reported that images of the multifidus muscle acquired during passive stretching had slightly better repeatability than images acquired with the subject at rest (Moreau et al., 2016).

The findings reported here lend further support to previous reports regarding the utility of SWE for assessing musculoskeletal tissues (e.g., (Hatta et al., 2015; Martin et al., 2015; Slane et al., 2016; Yavuz et al., 2015)), but the clinical significance of these preliminary data is not yet fully understood. For example, there was high inter-subject variability in the in-vivo data, with active supraspinatus tendon SWS values ranging from 3.1 to 8.0 m/s and active supraspinatus muscle SWS values ranging from 2.6 to 4.6 m/s. A secondary regression analysis indicated that there was a significant association between age and SWS, but only for the active tendon condition ($r^2=0.40$, $p=0.05$). This finding is generally consistent with the work by Eby and colleagues who reported an association between age and SWS in the biceps muscle in subjects over age 60 (Eby et al., 2015). The presence/absence of asymptomatic rotator cuff pathology may have also influenced SWS values, but the underlying condition of the subjects' rotator cuff was not assessed in this study. Regardless of the explanation for the wide range of SWS values, the primary objective for this study was to assess repeatability and the findings show that the approach has high intra- and inter-user repeatability. SWS values may be useful for predicting a patient's outcome after clinical intervention and/or for monitoring the progression of healing after surgical intervention, but further research is needed to characterize the relationship between mean SWS and tissue properties.

One potential limitation of this study is that it reported only a single measure of SWS for the entire supraspinatus muscle and tendon. This approach is in contrast to previous studies which have reported shear wave values for multiple regions of the supraspinatus muscle (Hatta et al., 2015; Rosskopf et al., 2016) or Achilles tendon (Slane et al., 2016). While there is certainly a biomechanical rationale for reporting region-specific measures of shear wave speed within an individual muscle or tendon, the approach reported here was chosen in the interest of clinical utility and simplicity.

In summary, the technique reported here for measuring mean SWS has good to very good repeatability within a user, between users, and between successive testing days. In-vitro experiments performed on imaging phantoms demonstrated that there is relatively little uncertainty introduced as a result of repositioning and user operation errors. The preliminary data indicate that measuring SWS in the supraspinatus muscle and tendon have highest repeatability when acquiring images under a low level of muscle activation. Further research is needed to characterize the relationship between mean SWS and mechanical properties and to evaluate the clinical utility of SWE imaging.

## Conflict of interest statement

None of the authors have any conflict of interest to disclose.

## References

Altman, D.G., 1991. Practical Statistics for Medical Research. Chapman and Hall, London.

Andonian, P., Viallon, M., Le Goff, C., de Bourguignon, C., Tourel, C., Morel, J., Giardini, G., Gergele, L., Millet, G.P., Croisille, P., 2016. Shear-wave elastography assessments of quadriceps stiffness changes prior to, during and after prolonged exercise: a longitudinal study during an extreme mountain ultramarathon. PloS one 11, e0161855.

ASTM, 1996. Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods, West Conshohocken, PA.

Bey, M.J., Derwin, K.A., 2012. Measurement of in vivo tendon function. J. Shoulder Elb. Surg. 21, 149–157.

Bude, R.O., Adler, R.S., 1995. An easily made, low-cost, tissue-like ultrasound phantom material. J. Clin. ultrasound: JCU 23, 271–273.

Chino, K., Kawakami, Y., Takahashi, H., 2015. Tissue elasticity of in vivo skeletal muscles measured in the transverse and longitudinal planes using shear wave elastography. Clin. Physiol. Funct. Imaging.

Cortes, D.H., Suydam, S.M., Silbernagel, K.G., Buchanan, T.S., Elliott, D.M., 2015. Continuous shear wave elastography: a new method to measure viscoelastic properties of tendons in vivo. Ultrasound Med Biol. 41, 1518–1529.

DeWall, R.J., Slane, L.C., Lee, K.S., Thelen, D.G., 2014. Spatial variations in Achilles tendon shear wave speed. J. Biomech. 47, 2685–2692.

Dillman, J.R., Chen, S., Davenport, M.S., Zhao, H., Urban, M.W., Song, P., Watcharotone, K., Carson, P.L., 2015. Superficial ultrasound shear wave speed measurements in soft and hard elasticity phantoms: repeatability and reproducibility using two ultrasound systems. Pediatr. Radiol. 45, 376–385.

Dubois, G., Kheireddine, W., Vergari, C., Bonneau, D., Thoreux, P., Rouch, P., Tanter, M., Gennisson, J.L., Skalli, W., 2015. Reliable protocol for shear wave elastography of lower limb muscles at rest and during passive stretching. Ultrasound Med. Biol. 41, 2284–2291.

Eby, S.F., Cloud, B.A., Brandenburg, J.E., Giambini, H., Song, P., Chen, S., LeBrasseur, N.K., An, K.N., 2015. Shear wave elastography of passive skeletal muscle stiffness: influences of sex and age throughout adulthood. Clin. Biomech. (Bristol, Avon) 30, 22–27.

Fleming, B.C., Beynnon, B.D., 2004. In vivo measurement of ligament/tendon strains and forces: a review. Ann. Biomed. Eng. 32, 318–328.

Franchi-Abella, S., Corno, L., Gonzales, E., Antoni, G., Fabre, M., Ducot, B., Pariente, D., Gennisson, J.L., Tanter, M., Correas, J.M., 2015. Feasibility and diagnostic accuracy of supersonic shear-wave elastography for the assessment of liver stiffness and liver fibrosis in children: a pilot study of 96 patients. Radiology, 142815.

Hagan, M., Asrani, S.K., Talwalkar, J., 2015. Non-invasive assessment of liver fibrosis and prognosis. Expert Rev. Gastroenterol. Hepatol. 9, 1251–1260.

Hatta, T., Giambini, H., Uehara, K., Okamoto, S., Chen, S., Sperling, J.W., Itoi, E., An, K.N., 2015. Quantitative assessment of rotator cuff muscle elasticity: reliability and feasibility of shear wave elastography. J. Biomech. 48, 3853–3858.

Itoigawa, Y., Sperling, J.W., Steinmann, S.P., Chen, Q., Song, P., Chen, S., Itoi, E., Hatta, T., An, K.N., 2015. Feasibility assessment of shear wave elastography to rotator cuff muscle. Clin. Anat. 28, 213–218 (New York, N.Y.).

Kim, H.J., Lee, H.K., Cho, J.H., Yang, H.J., 2015. Quantitative comparison of transient elastography (TE), shear wave elastography (SWE) and liver biopsy results of patients with chronic liver disease. J. Phys. Ther. Sci. 27, 2465–2468.

Koo, T.K., Guo, J.Y., Cohen, J.H., Parker, K.J., 2013. Relationship between shear elastic modulus and passive muscle force: an ex-vivo study. J. Biomech. 46, 2053–2059.

Lee, S.H., Chang, J.M., Han, W., Moon, H.G., Koo, H.R., Gweon, H.M., Kim, W.H., Noh, D.Y., Moon, A.W., 2015. Shear-wave elastography for the detection of residual breast cancer after neoadjuvant chemotherapy. Ann. Surg. Oncol.

Martin, J.A., Biedrzycki, A.H., Lee, K.S., DeWall, R.J., Brounts, S.H., Murphy, W.L., Markel, M.D., Thelen, D.G., 2015. In vivo measures of shear wave speed as a predictor of tendon elasticity and strength. Ultrasound Med Biol. 41, 2722–2730.

Moreau, B., Vergari, C., Gad, H., Sandoz, B., Skalli, W., Laporte, S., 2016. Non-invasive assessment of human multifidus muscle stiffness using ultrasound shear wave elastography: a feasibility study. Proc. Inst. Mech. Eng. H 230, 809–814.

Park, H.S., Kim, Y.J., Yu, M.H., Jung, S.I., Jeon, H.J., 2015. Shear wave elastography of focal liver lesion: intraobserver reproducibility and elasticity characterization. Ultrasound Q. 31, 262–271.

Rosskopf, A.B., Ehrmann, C., Buck, F.M., Gerber, C., Fluck, M., Pfirrmann, C.W., 2016. Quantitative shear-wave US elastography of the supraspinatus muscle: reliability of the method and relation to tendon integrity and muscle quality. Radiology 278, 465–474.

Siu, W.L., Chan, C.H., Lam, C.H., Lee, C.M., Ying, M., 2016. Sonographic evaluation of the effect of long-term exercise on Achilles tendon stiffness using shear wave elastography. J. Sci. Med. sport / Sport. Med. Aust.

Slane, L.C., Martin, J., DeWall, R., Thelen, D., Lee, K., 2016. Quantitative ultrasound mapping of regional variations in shear wave speeds of the aging Achilles tendon. Eur. Radiol.

Takenaga, T., Sugimoto, K., Goto, H., Nozaki, M., Fukuyoshi, M., Tsuchiya, A., Murase, A., Ono, T., Otsuka, T., 2015. Posterior shoulder capsules are thicker and stiffer in the throwing shoulders of healthy college baseball players: a quantitative assessment using shear-wave ultrasound elastography. Am. J Sport. Med 43, 2935–2942.

Tang, L., Xu, H.X., Bo, X.W., Liu, B.J., Li, X.L., Wu, R., Li, D.D., Fang, L., Xu, X.H., 2015. A novel two-dimensional quantitative shear wave elastography for differentiating malignant from benign breast lesions. Int. J. Clin. Exp. Med. 8, 10920–10928.

Webb, M., Shibolet, O., Halpern, Z., Nagar, M., Amariglio, N., Levit, S., Steinberg, D. M., Santo, E., Salomon, O., 2015. Assessment of liver and spleen stiffness in patients with myelofibrosis using fibroscan and shear wave elastography. Ultrasound Q. 31, 166–169.

Yavuz, A., Bora, A., Bulut, M.D., Batur, A., Milanlioglu, A., Goya, C., Andic, C., 2015. Acoustic Radiation Force Impulse (ARFI) elastography quantification of muscle stiffness over a course of gradual isometric contractions: a preliminary study. Med. Ultrason. 17, 49–57.

Yoshitake, Y., Takai, Y., Kanehisa, H., Shinohara, M., 2014. Muscle shear modulus measured with ultrasound shear-wave elastography across a wide range of contraction intensity. Muscle Nerve 50, 103–113.