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Feasibility Assessment of Shear Wave Elastography to Rotator Cuff Muscle

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Abstract

Introduction—Pre -surgical measurement of supraspinatus muscle extensibility would be important for rotator cuff repair. The purpose of the present study was to explore the potential feasibility of a shear wave ultrasound electrograph (SWE) based method, combined with B-mode ultrasound, to non-invasively measure *in vivo* stiffness of supraspinatus muscle, and thus obtaining the key information on supraspinatus muscle extensibility.

Materials and Methods—Our investigation consisted of 2 steps. First, we evaluated orientation of the supraspinatus muscle fiber on cadaveric shoulders without rotator cuff tear in order to optimize the ultrasound probe positions for SWE imaging. Second, we investigated the feasibility of quantifying the normal supraspinatus muscle stiffness by SWE *in vivo*.

Results—The supraspinatus muscle was divided into four anatomical regions, namely anterior superficial (AS), posterior superficial (PS), anterior deep (AD) and posterior deep (PD) regions. SWE was evaluated at each of these regions. SWE stiffness on AD, AS, PD, and PS were measured as 40.0±12.4, 34.0±9.9, 32.7±12.7, 39.1±15.7 kPa, respectively.

Conclusions—SWE combined with B-Mode ultrasound image may be a feasible method to quantify local tissue stiffness of the rotator cuff muscles.

Keywords

rotator cuff; muscle; tendon; ultrasound; shear wave elastography; imaging; supraspinatus

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CONFLICT OF INTEREST
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INTRODUCTION

Rotator cuff tear is one of the most common causes of shoulder pain and dysfunction, especially in the middle-aged or elder population (Minagawa et al., 2013; Yamamoto et al., 2010). Acute tears can usually be readily mobilized and repaired; however, management becomes more challenging in the chronic setting. In the chronic condition, Safran et al. demonstrated that the detached rotator cuff becomes stiffer and requires a large passive load to bring torn tendons together to repair it (Safran et al., 2005). Because of these large tensile forces, the repaired tendon may re-tear, which is estimated to occur in 40% to 70% of cases (Bartl et al., 2012; Khazzam et al., 2012; Kim et al., 2012; Miller et al., 2011; Zumstein et al., 2008). In part, large or massive tears may be difficult to repair not only because of their size, but also because of the histological and ultrastructural changes which occur in the tendon and muscles (Matthews et al., 2006). These changes include development of fatty degeneration (Goutallier et al., 1994; Goutallier et al., 2003; Goutallier et al., 2005; Itoigawa et al., 2011), alteration of the pennation angle (Meyer et al., 2006; Zuo et al., 2012), a decreased number of sarcomeres (Firat and Turker, 2012; Tomioka et al., 2009), and fibrosis; often these changes lead to changes in stiffness of the muscle (Liu et al., 2011; Steinbacher et al., 2010). Therefore, detecting the passive stiffness of the rotator cuff muscles in patients with cuff tears is clinically important because the knowledge about the rotator cuff muscle passive stiffness can help determining the optimal surgical procedure such as anatomical repair, versus tendon grafting options, as well as predicting the prognosis such as the chance of retear and functional recovery.

Therefore, it is clinically significant to develop a non-invasive tool for acquiring the information on passive stiffness of rotator cuff muscles for the sake of better pre-surgical planning. We aim to achieve this goal by adopting a novel ultrasound based technology termed Shear Wave Elastography (SWE, which provides quantitative in vivo measurements of tissue stiffness by evaluating shear wave propagation speed, and is inherently related to tissue mechanical properties (Bercoff et al., 2004; Chen et al., 2009a; Chen et al., 2009b; Mariappan et al., 2010; Sarvazyan et al., 1998). We propose this approach, when combined with B-Mode ultrasound imaging, to quantify structural properties which will then be used to measure the passive stiffness, and consequently, the extensibility of supraspinatus muscles.

The purpose of this preliminary study was, as a very first step towards the above goal, to explore the method to measure stiffness of normal rotator cuff muscle, in particular, supraspinatus, using SWE and B-mode ultrasound. Our hypothesis was that SWE image is able to quantify stiffness of rotator cuff muscles. Our investigation consisted of 2 steps. First, we evaluated orientation of the supraspinatus muscle fiber on cadaveric shoulders without rotator cuff tear in order to optimize the ultrasound probe positions for SWE imaging. Second, we investigated the feasibility of quantifying the normal supraspinatus muscle stiffness by SWE *in vivo*.

MATERIALS AND METHODS

In vitro Experiments

Specimen Preparation—Three fresh-frozen shoulders with no rotator cuff tear (age 63, 78, and 59 years) were used. The frozen shoulders were thawed overnight at room temperature for experimentation. For first specimen (right shoulder), the subcutaneous soft tissues were removed except for the rotator cuff muscles, and the supraspinatus muscle was observed grossly. The other specimens (right and left shoulders) were dissected after measurement of SWE and B-mode ultrasound.

Gross anatomy—Superficial muscle fiber and intramuscular tendon on supraspinatus muscle of one specimen were observed from superior view. The scapular spine and acromion were preserved in order to properly identify the location of the area in the supraspinatus muscle to be evaluated by ultrasound. After observation of the superficial muscle, the superficial portion of the muscle was removed until the intramuscular tendon was exposed. On the other specimen s, the supraspinatus muscle was cut between anterior and posterior muscles to observe the muscle fiber on coronal section, and compared to the ultrasound images.

Orienting the Ultrasound images—The first step was to determine the proper orientation of the ultrasound probe in relation to the muscle fiber architecture. According to previous studies, the supraspinatus muscle consists of anterior and posterior regions with distinct muscle fiber architectures (Kim et al., 2010; Kim et al., 2007). Therefore, we hypothesized that the intramuscular tendon could be used as a landmark for dividing the supraspinatus muscle into two primary regions: the anterior region and the posterior region. To identify the proper orientation of the intramuscular tendon, the ultrasound probe was placed perpendicularly to skin surface of the middle of the spine of scapula, in the mediolateral direction, and between clavicle and scapula spine in the anteroposterior direction. This position was defined as Position A (Fig 1C black box). The ultrasound probe was then shifted parallel 1 cm anteriorly (Fig 1C red box) and 1 cm posteriorly (Fig 1C gray box) to investigate if intramuscular tendon was observed on those images on the anterior or posterior muscle regions or not. On the other hand, the probe was then rotated from Position A either clockwise (Fig 2A, white box) or counter -clockwise (Fig 2A, yellow box) until the muscle fiber displayed in the B-mode ultrasound screen reached its maximal length. At such position, the ultrasound probe was considered aligned with the intramuscular tendon orientation. The anterior region and the posterior region were further divided into the superficial region and the deep region bounded by intramuscular tendon, with superficial region being the one superior to the intramuscular tendon in the B-mode ultrasound image and the deep region being the one inferior to the intramuscular tendon in the B-mode ultrasound image. SWE images were then collected for each “quadrant”: that is, anterior superficial, anterior deep, posterior superficial, and posterior deep. When collecting SWE images in each quadrant, orientation of the ultrasound probe was fine tuned by inclining sagittally within ±20° until the muscle fiber length in the B-mode image of that quadrant reached maximal length. At such orientation, the ultrasound transducer was considered represent the optimal projection of the muscle fibers in that quadrant. SWE images were then collected at such final orientation.

In vivo Experiments

Participant—Three subjects (age 37, 38, and 37 years) participated in this study. They had no history or findings of shoulder pain, and did not have rotator cuff tear on ultrasound images. The B-mode ultrasound and SWE were performed together on the subjects (two right and one left shoulders). The right supraspinatus was scanned with the arm resting on side and supported by the chair armrest. This study was approved by our institutional review board and informed consent was obtained.

Muscle Material Properties by Shear Wave Elastography—In both the *in vivo* and *in vitro* experiment, to assess the material properties of the muscle (along muscle fiber direction), shear wave speed maps were acquired with SWE on an Aixplorer® ultrasound scanner using an SL 10-2 linear array transducer (Supersonic Imagine, Aix-en-Provence, France). Alignment of the ultrasound probe with the muscle fiber orientation was achieved using the method described in the above sections. For each ultrasound measure, shear waves were generated in the supraspinatus via an unfocused ultrasound “push” beam transmitted by 16 elements of the transducer. The same transducer then detected propagation of the shear waves for 20 ms at a frame rate of 7.4 kHz within a small 2-D region of interest (ROI) to one side of the push beam. The ROI was selected mid-depth. The shear wave propagation velocity within the ROI was monitored and recorded for later analysis to calculate the shear modulus.

RESULTS

In vitro Experiments

Gross anatomy—The superficial muscle fiber consisted of anterior (AS) and posterior (PS) muscles, and pennately ran from lateral to medial in the center of intramuscular tendon (Fig 3A). The deep muscle fiber consisted of anterior (AD) and posterior (PD) muscles, and pennately ran the same as the superficial fiber (Fig 3B). However, the pennation angles of muscle fiber to intramuscular tendon were different on both anterior and posterior muscles between the superficial and deep muscles (Fig 3A, B). The intramuscular tendon was also observed on coronal section from posterior view (Fig 1A).

Ultrasound images—The intramuscular tendon was identified on ultrasound image on Position A (Fig 1B). Area in this ultrasound image was grossly the same as the area inspected in coronal sectioned gross anatomy (Fig 1A, B, yellow box). When the probe positioning was deviated 1 cm anterior or posterior from Position A, the intramuscular tendon was not seen on the both images (Fig 1D, E), as expected. Furthermore, when the probe was inclined by more than approximately 20° to anterior direction, or approximately 20° to posterior direction from Position A, the intramuscular tendon also vanished in all ultrasound images (Fig 1F), suggesting that it was off the view from such scan angle.

The muscle fiber orientation within each quadrant (AS, PS, AD, and PD) was determined by inclining the ultrasound probe orientation until the muscle fiber displayed in the B-mode ultrasound screen reached its maximal length. The muscle fibers mostly ran parallel and observed from origin of muscle to intramuscular tendon on all quadrants (Fig 2C, D, E, F). On the gross anatomy, probe positioning of AS or PS meant runs of anterior or posterior muscle fibers, respectively (Fig 2A, B). The SWE stiffness of each muscle quadrant could be then measured by the Aixplorer® machine. The mean SWE stiffness on AD, AS, PD, and PS were 59.8±3.5, 56.2±5.0, 57.1±12.0, 57.0±7.4 kPa, respectively.

In vivo Experiments

Muscle Material Properties by Shear Wave Elastography—Similar to the in vitro experiment, the muscle fibers and intramuscular tendon on all quadrants (AS, PS, AD, and PD) were indentified on the B-mode ultrasound images (Fig 4b, d, f, g) on all subjects. The muscle fibers mostly ran parallel and observed from origin of muscle to intramuscular tendon on each image. The probe positioning drawn on all subject's skins to indicate the angle of each muscle fiber was different among 4 quadrants (Fig 4A). The mean SWE stiffness of each muscle quadrant under such orientation on all subjects could be then measured by the Aixplorer® machine and reported (Fig 4B). The mean SWE stiffness on AD, AS, PD, and PS were 40.0±12.4, 34.0±9.9, 32.7±12.7, 39.1±15.7 kPa, respectively. The side-to-side comparison was not part of the purpose of this study, thus will be considered in the future.

DISCUSSION

The goal of this study was to investigate the potential of SWE imaging in the quantification of rotator cuff muscle passive stiffness. Previous studies suggested that the supraspinatus muscle consists of several regions with distinct muscle fiber architectures (Kim et al., 2010; Kim et al., 2007). Congruent with those, our gross anatomy and ultrasound images indicated that the muscle stiffness can be measured by scanning four regions, namely, of AS, AD, PS, and PD, as bounded by intramuscular tendon. In order to have adequate shear wave propagation, the ultrasound transducer needs to be parallel to the muscle fiber to be able to quantify muscle stiffness by SWE (Eby et al., 2013). Previous studies have evaluated the supraspinatus tendon and muscle stiffness using SWE (Arda et al., 2011; Plagou et al., 2011). However, a detailed probe orientation on the muscle has not been described. In the present study, within each region (quadrant), the muscle fibers ran approximately parallel to each image, making it feasible to quantify the shear stiffness along the muscle.

While our preliminary study measured the local muscle tissue stiffness in each of the four quadrants, clinically it would be even more ideal to predict the extensibility of the muscle as a whole based on the stiffness measurements of each of its subzones. Although not included in the present study, we are currently developing an algorithm to calculate the whole muscle extensibility based on summation of weighted contributions of the four quadrants. Contribution of each quadrant to the whole muscle extensibility would be a function of pennation angle, physical cross-sectional area (PCSA), average fiber length, and the SWE stiffness measurement in the quadrant. We anticipate pennation angle, PCSA and average fiber length are measurable from B-mode ultrasound images, a hypothesis to be examined in our next future study.

There are two limitations in the present study: First, as a preliminary study, its sample size was very small. Future investigations aimed at confirming the value of SWE and B-mode ultrasound in this application will be necessary with a significantly larger number of subjects. Second, this preliminary study only assessed the normal subjects instead of rotator cuff muscles with tendon rupture. Whether the pennation angle and muscle architecture of rotator cuff muscle in patients with torn tendon would be different from that of the normal subjects or not, as well as whether such difference (if any) would affect the SWE stiffness measurements, remains to be examined in future studies (Meyer et al., 2006; Zuo et al., 2012).

CONCLUSIONS

Based on the preliminary findings in the present study suggests SWE when combined with B-Mode ultrasound image is a feasible method to quantify local tissue stiffness of the rotator cuff muscles.

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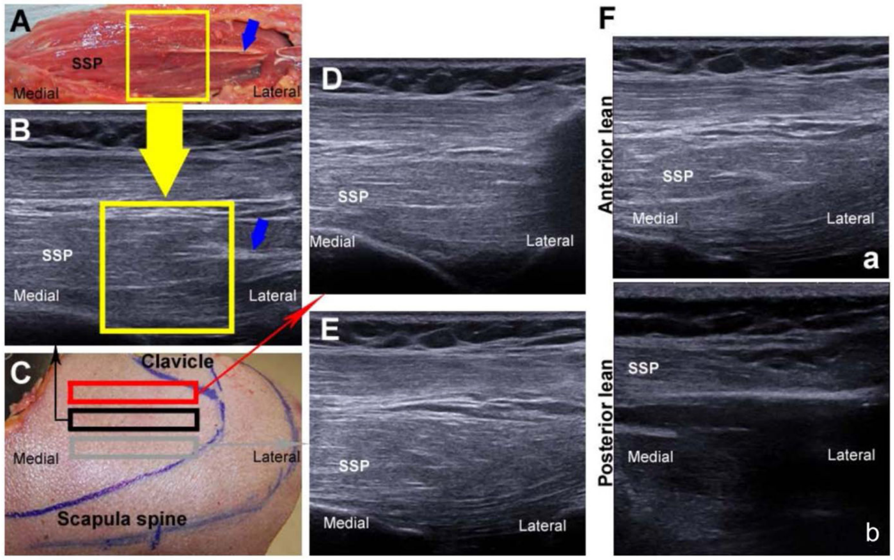

Fig. 1.

(Blue arrow: intramuscular tendon) A: Gross anatomy (coronal section) of right supraspinatus muscle, posterior view (Yellow box: center of supraspinatus muscle, and the same region as ultrasound image of B). B: Ultrasound image on which intramuscular tendon was observed when the probe was, perpendicularly to skin, positioned on the middle of the spine of scapula in mediolateral direction, and between clavicle and scapula spine in anteroposterior direction. C: Right cadaveric shoulder, superior view. Black box means the probe positioning where intramuscular tendon was observed when the probe was, perpendicularly to skin, positioned on the middle of the spine of scapula in mediolateral direction, and between clavicle and scapula spine in anteroposterior direction (Position A). Red and gray boxes show the probe positioning 1 cm anterior and posterior from black box (Position A), respectively. D: Ultrasound image on 1 cm anterior. The intramuscular tendon disappeared. E: Ultrasound image on 1 cm posterior. The intramuscular tendon disappeared. F: When the probe was inclined by more than approximately 20° to anterior direction, or approximately 20° to posterior direction from Position A, the intramuscular tendon also vanished in all ultrasound images.

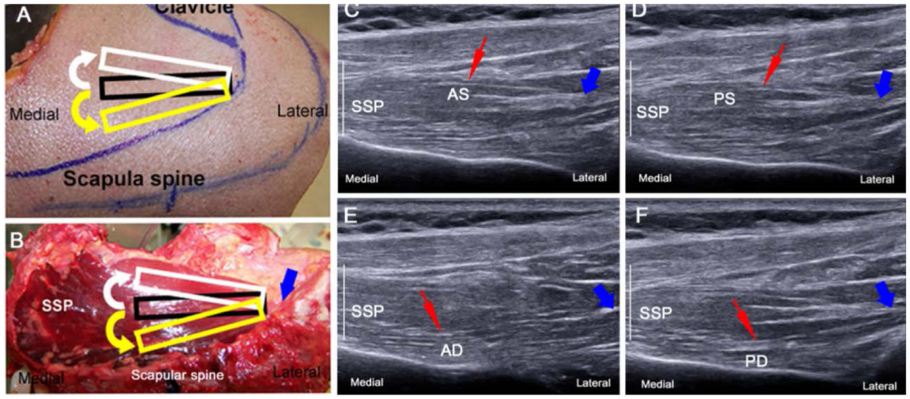

Fig. 2.

A: Right cadaveric shoulder, superior view. Black box shows the probe orientation where intramuscular tendon was observed when the probe was, perpendicularly to skin, positioned on the middle of the spine of scapula in mediolateral direction, and between clavicle and scapula spine in anteroposterior direction (Position A). The probe positioning was rotated centering around the intramuscular tendon to anterior direction (white box), or posterior direction (yellow box) from Position A. The muscle fiber orientation within each quadrant (AS or PS) was determined by rotating the ultrasound probe orientation until the muscle fiber displayed in the B-mode ultrasound screen reached its maximal length. B: Gross anatomy of right supraspinatus muscle, superior views (Blue arrow: intramuscular tendon, SSP: supraspinatus). The probe positioning of AS or PS meant anterior or posterior muscle fibers. C: Ultrasound images for anterior superficial muscle. (Red arrow: muscle fiber, Blue arrow: Intramuscular tendon) D: Ultrasound images for posterior superficial muscle. E: Ultrasound images for anterior deep muscle. F: Ultrasound images for posterior deep muscle. The muscle fibers mostly run parallel on each images and observed from origin of muscle to intramuscular tendon on allquadrants (C, D, E, F).

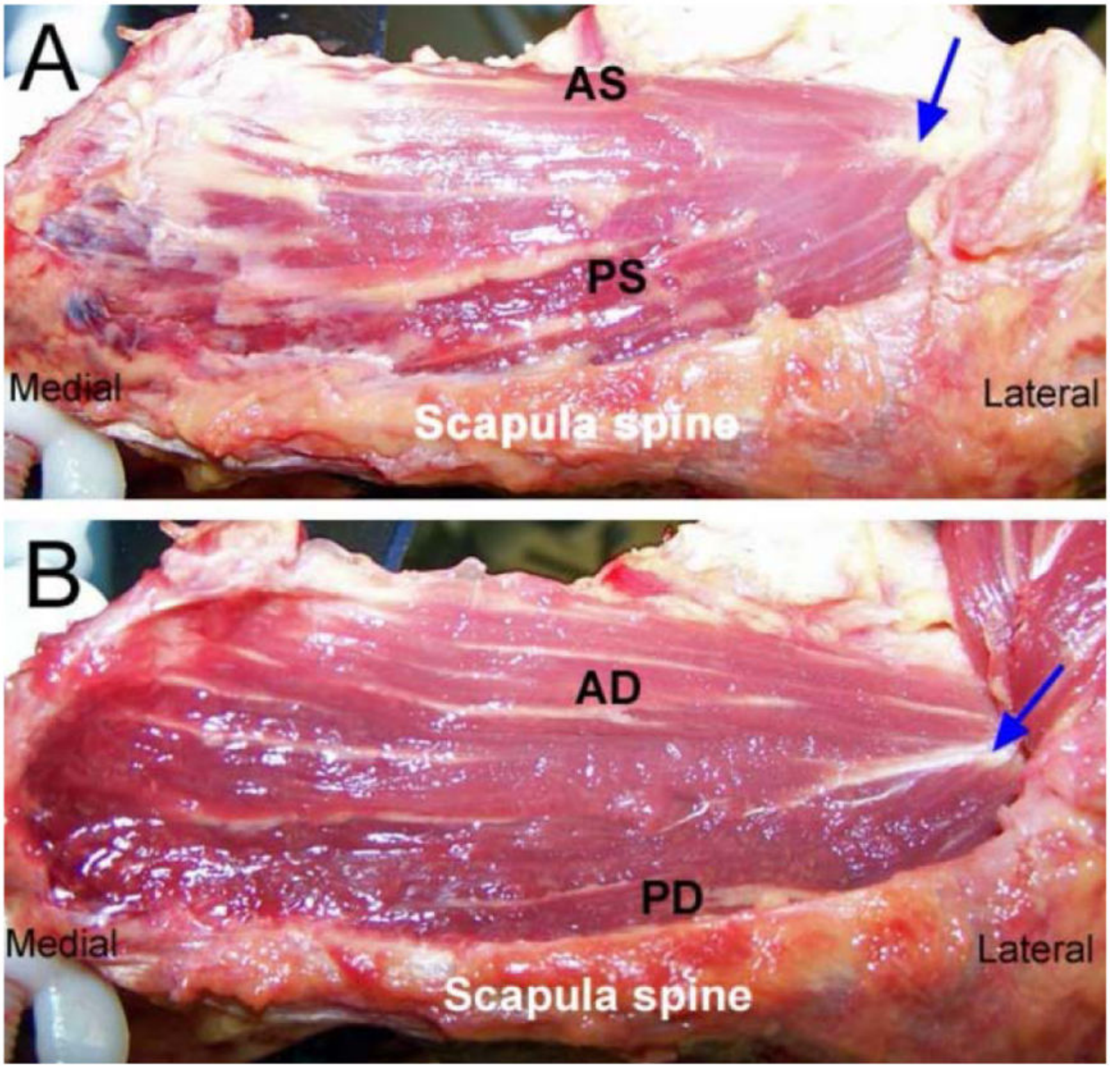

Fig. 3.
Gross anatomy of right supraspinatus muscle, superior views (Blue arrow: intramuscular tendon). A: Superficial supraspinatus muscle (AS: anterior superficial region, PS: posterior superficial region). B: Deep supraspinatus muscle (AD: anterior deep region, PD: posterior deep region).

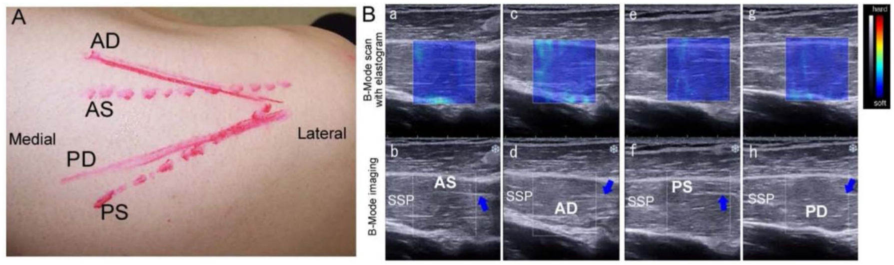

Fig. 4.

A: The probe's positions drawn on the skin of right shoulder B: Ultrasound imaging of human supraspinatus. B-Mode scan with overlaid elastogram (a, c, e, g) and B-Mode imaging (b, d, f, h). a, c, g, and f are same sections as b, d, f, and h, respectively. a and b are ultrasound imaging for anterior superficial muscle. c and d are ultrasound imaging for anterior deep muscle. e and f are ultrasound imaging for posterior superficial muscle. g and h are ultrasound imaging for posterior deep muscle. (AS: superficial region of anterior supraspinatus, SSP: supraspinatus, Blue arrow: intramuscular tendon, AD: deep region of anterior supraspinatus, PS: superficial region of posterior supraspinatus, PD: deep region of posterior supraspinatus).