Prediction of Extensibility of the Supraspinatus Musculotendinous Unit using Ultrasound Image with Shear Wave Elastography

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Introduction: Rotator cuff tears are the most common cause of shoulder pain and related disability. Surgery is performed if the conservative treatment fails. Unfortunately, re-tear rates for massive tears are generally high, especially in more severe cases with larger tissue defects. Large or massive tears often re-tear following surgery for several reasons. Over time, the tendon retracts, leaving a large defect. However, not only is the tissue gap a problem, but also the nature of the muscle changes. Alterations in the length-tension relationship of the tendon and muscle result in intrinsic changes in the muscle quality. Fatty infiltration of the muscle itself occurs, alterations in the pennation angle of the muscle occur, and the end result is decreased compliance and increased stiffness. As a result, large passive tensile loads are required to bring torn tendons together for repair. These excessive tensile forces upon abnormal tissue with poorly compliant and stiff muscles can lead to gap formation and failure at the repair site and ultimately failure of the repair, seen in 40-70% of all cases.

Though it is clear that the tension required for repair increases with time since injury, there is much individual variation. Thus, individualized assessment of muscle geometry, as well as morphological and material properties, are necessary to assist in pre-surgical planning and monitoring recovery throughout the rehabilitation process. MRI and ultrasound imaging techniques have been utilized for rotator cuff assessment in the past, though primarily to simply assess gross muscle size, tear size, and presence and extent of fatty infiltration. Our long-term goal is to develop a non-invasive tool for acquiring the information on passive stiffness of rotator cuff muscles for pre-surgical planning and thus improving the treatment outcome. We aim to achieve this goal by adopting a novel ultrasound based technology called Shear Wave Elastography (SWE). The SWE provides quantitative in vivo measurement of tissue stiffness by evaluating shear wave propagation speed, which is inherently related to tissue mechanical properties. The purpose of this study was to determine if this unique and innovative approach that combines B-Mode ultrasound imaging along with SWE to quantify structural properties could be used to predict the extensibility of the rotator cuff muscle on cadaveric specimens with cuff tears of varying sizes.

Methods: Specimen Preparation: Eleven fresh-frozen shoulders from six men and five women with a mean age at the time of death of sixty-seven years were used. The size and distribution of rotator cuff tears across the eleven specimens were as follows: tear size (number of shoulder), small (1), medium (3), large (1), massive (1), and intact/no tear (5). Each scapula was disarticulated from the thorax, and the humerus was cut at med-shaft. The specimens were kept frozen until testing and thawed overnight to room temperature before the experiment. A fiberglass rod was inserted into the medullary canal of
the humeral shaft and cemented. The scapula was secured in a custom-designed shoulder experimental device.

Measurement of B-Mode ultrasound imaging: The muscle geometric and morphological measurements were made via B-Mode images obtained with the Aixplorer®. The muscle geometry and morphology, such as the muscle pennation angle and cross sectional area, were measured and calculated. The pennation angle was measured on both the superficial and deep regions, respectively. The measurement values were obtained through software ImageJ (National Institutes of Health, MD).

Muscle Material Properties by Shear Wave Elastography: To assess the material properties of the muscle (along muscle fiber direction), shear wave speed maps were acquired with SWE on the same machine 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 for both the superficial and deep muscles. For each ultrasound measurement, 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 shear wave propagation velocity within the ROI was monitored and recorded for later analysis to calculate the shear modulus.

Measurement of extensibility of the supraspinatus musculotendinous unit: The specimens were tested using an electromagnetic tracking device and force transducer. A skin incision was made parallel to the lateral border of the acromion. The deltoid was taken off the acromion, and the rotator cuff was exposed by splitting the deltoid. An electromagnetic tracking device enabled the measurement of the 3-dimensional position and orientation of sensors that were rigidly fixed to the medial scapular spine and the lateral edge of supraspinatus tendon. Anatomical coordinate systems were defined. The margins of the tear in the supraspinatus tendon were identified. For those specimens with intact tendons or small tears, the supraspinatus tendon was detached from the humeral head insertion. The sensor was attached at the tendon edge using string sutured to tendon, and a load cell connected to the end of the string in series. The supraspinatus tendon was then axially stretched along the direction of muscle line under forces at a rate of about 1 N/sec, increasing to 30 N while the distance between the medial scapular spine and the lateral edge of the supraspinatus tendon and displacement force were recorded.

Data analysis: Stepwise multiple linear regression was used to determine significant independent predictors of the muscle extensibility. In addition, a regression analysis was performed to investigate the relationships between the tendon displacement, tendon loading, length of the supraspinatus, and SWE modulus of the superficial and deep muscles.

Results: We found a positive correlation between SWE modulus of superficial muscle and muscle structural stiffness \((R=0.953, p<0.0001)\) (Table 1). SWE modulus of deep muscle was also correlated with the stiffness \((R=0.731, p=0.0008)\). On the other hand, there was a significant negative correlation between the displacement of the supraspinatus tendon and the SWE modulus of the superficial muscle \((R=-0.953, p<0.0001)\) and deep muscle \((R=-0.852, p<0.0001)\). No correlation was found between the length of the supraspinatus musculotendinous unit and the SWE modulus of the superficial muscle \((R=0.022, p=0.806)\) or deep muscle \((R=0.0008, p=0.664)\), or the tendon displacement \((R=0.005, p=0.842)\) (Fig. 1).

Discussion: There were high correlations between SWE modulus and superficial muscle and extensibility of supraspinatus musculotendinous unit. SWE ultrasound can predict the extensibility of the
supraspinatus musculotendinous unit independent of the size of the supraspinatus tendon, and may be able to be used as a pre-surgical planning for rotator cuff repair.

**Significance:**

<table>
<thead>
<tr>
<th>Measure</th>
<th>R</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear wave elastography modulus on superficial muscle</td>
<td>0.9531</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Shear wave elastography modulus on deep muscle</td>
<td>0.7307</td>
<td>0.0008</td>
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<tr>
<td>Cross sectional area</td>
<td>0.2205</td>
<td>0.0131</td>
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<td>Superficial pennation angle</td>
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<td>0.07907</td>
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<tr>
<td>Deep pennation angle</td>
<td>0.3034</td>
<td>0.14506</td>
</tr>
</tbody>
</table>

*R = Correlation coefficient. P = p value.*

**ORS 2015 Annual Meeting**

**Paper No:** 0169