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Quantifying extensibility of rotator cuff muscle with tendon rupture using shear wave elastography: A cadaveric study

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ABSTRACT

Surgical repair for large rotator cuff tear remains challenging due to tear size, altered muscle mechanical properties, and poor musculotendinous extensibility. Insufficient extensibility might lead to an incomplete reconstruction; moreover, excessive stresses after repair may result in repair failure without healing. Therefore, estimates of extensibility of cuff muscles can help in pre-surgical planning to prevent unexpected scenarios during surgery. The purpose of this study was to determine if quantified mechanical properties of the supraspinatus muscle using shear wave elastography (SWE) could be used to predict the extensibility of the musculotendinous unit on cadaveric specimens. Forty-five fresh-frozen cadaveric shoulders (25 intact and 20 with rotator cuff tear) were used for the study. Passive stiffness of 4 anatomical regions in the supraspinatus muscle was first measured using SWE. After detaching the distal edge of supraspinatus muscle from other cuff muscles, the detached muscle was axially pulled with the scapula fixed. The correlation between the SWE modulus and the extensibility of the muscle under 30 and 60 N loads was assessed. There was a significant negative correlation between SWE measurements and the experimental extensibility. SWE modulus for the anterior-deep region in the supraspinatus muscle showed the strongest correlation with extensibility under 30 N ($r = 0.70$, $P < 0.001$) and 60 N ($r = 0.68$, $P < 0.001$). Quantitative SWE assessment for the supraspinatus muscle was highly correlated with extensibility of musculotendinous unit on cadaveric shoulders. This technique may be used to predict the extensibility for rotator cuff tears for pre-surgical planning.

1. Introduction

A rotator cuff tear is the most common cause of shoulder pain and disability of shoulder function, especially in the middle-aged and elderly population (Minagawa et al., 2013; Moosmayer et al., 2009; Tempelhof et al., 1999). Patients who failed conservative treatment may require surgery in order to restore shoulder function and/or to reduce pain (Caldwell et al., 1997; Gazielly et al., 1994; Harryman et al., 1991). Surgical options for rotator cuff tears are highly individualized, including debridement alone, direct repair of smaller defects, partial repair, augmentation with a patch or tendon transfer to cover the defect, or shoulder arthroplasty (Bedi et al., 2010).

As notable characteristics, a detached rotator cuff tendon can retract over time, increasing the size of the initial tear (Safran et al., 2011). Moreover, it may change cuff muscles properties. With a deteriorated length-tension relationship of the musculotendinous structure, intrinsic changes in muscle quality, fatty infiltration, and/or degeneration may occur, resulting in a decrease in extensibility and an increase in stiffness (Hersche and Gerber, 1998; Meyer et al., 2006; Safran et al., 2005). Consequently, large passive tensile loads are required to bring torn tendons onto the footprint region for repair (Berth et al., 2010; Ward et al., 2006). The subsequent excessive tensile stresses on the repaired tendon-bone structure, combined with abnormal tissue properties with poor extensibility, may cause repair failure with gap formation in the repair site, as reported in 17–57% of re-tear cases (Bartl et al., 2012; Iannotti et al., 2013; Zumstein et al., 2008).

In the clinical setting, individualized assessment of biomechanical parameters for extensibility of rotator cuff structures, as well as morphological parameters are necessary to assist in pre-surgical planning and monitoring recovery throughout the rehabilitation process. Computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound imaging techniques have

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been utilized for rotator cuff assessment in the past; however, mainly to assess gross muscle and tear size, and/or the presence/absence and extent of fatty infiltration (Bedi et al., 2010; Maman et al., 2009; Meyer et al., 2006; Yamaguchi et al., 2001). In this study, we aimed to develop a non-invasive tool to acquire the rotator cuff muscles' extensibility for pre-surgical planning thus improving treatment outcome. To achieve this goal, we adopted a novel ultrasound technique, shear wave elastography (SWE). SWE can provide quantitative *in vivo* measurements of soft tissue elasticity, or stiffness, by measuring shear wave propagation speed, which is inherently related to the elastic modulus (Garra, 2007). The technique is fast, convenient and applicable to a variety of clinical scenarios in which other approaches would potentially be inadequate; thus, it has been used successfully for breast cancers diagnosis (Athanasiou et al., 2010) and liver fibrosis staging (Ferraioli et al., 2014). In addition, quantitative assessments of the mechanical properties of skeletal muscles have also been investigated in *in vivo* and *in vitro* studies (Akagi et al., 2015; Hatta et al., 2016a; Hirata et al., 2015; Hug et al., 2013).

Therefore, this ultrasound technique to quantify the mechanical properties of skeletal muscles structures may be used to predict the extensibility of the supraspinatus muscle. We hypothesized that the mechanical properties, measured by SWE, of the supraspinatus muscle could be correlated to the extensibility of the supraspinatus musculotendinous unit.

2. Materials and methods

2.1. Specimen preparation

Forty-five fresh-frozen human cadaveric shoulders were harvested from 45 subjects after institutional review board approval from our institution. Twenty-four right shoulders and 21 left shoulders were used for this study. The specimens were kept frozen at −20 °C until testing and thawed overnight at room temperature before the experiment. After disarticulating the scapula from the thorax and cutting the humerus at the level of the midshaft, the scapula and a fiberglass rod inserted into the humeral medullary canal were both secured in a custom-designed experimental device, as previously described (Hatta et al., 2015). Based on the International Society of Biomechanics (ISB) recommendation, the scapula was fixed at 0° of upward/downward rotation considered as a neutral position (Schwartz et al., 2014; Wu et al., 2005). All soft tissues including skin, subcutaneous fat, and muscles within the cut level were kept intact during this process.

2.2. Supraspinatus muscle passive stiffness measurements

Passive stiffness of the supraspinatus (SSP) muscle was assessed using a commercial ultrasound system (Aixplorer; Supersonic Imagine Ltd., Aix-en-Provence, France) with a linear array transducer (2–10 MHz; Supersonic Imagine, Ltd.). Mechanical properties of the SSP muscle were obtained using a built-in-software and measured in kilopascal (kPa). Placement of the ultrasound transducer and measurement regions of the SSP muscle had been established in previous studies (Hatta et al., 2015; Itoigawa et al., 2015). Briefly, the SSP muscle was divided into 4 regions according to the muscle fiber orientation; anterior deep (AD), anterior superficial (AS), posterior deep (PD), and posterior superficial (PS). SWE measurements for each region were assessed independently on the plane parallel to the muscle fibers (Fig. 1). Regions of interest (ROI), represented by circular areas including the whole thickness of each muscle region, were used to obtain quantitative SWE moduli. To minimize technical variation due to probe positioning or probe pressure, SWE measurement values were obtained repeatedly 9 times based on a previous study (Hatta et al., 2015). Mean SWE values were then calculated for each region.

2.3. Musculotendinous unit extensibility measurement

After SWE measurements were obtained, a 10cm incision was made parallel to the lateral border of the acromion. The deltoid muscle was detached from the acromion to observe the rotator cuff tendon. The presence/absence of a rotator cuff tear and its size (width and length) were recorded. The specimens were then divided into two groups based on the presence or absence of a cuff tear. The size of the tear was classified into small, medium, large, or massive, according to the classification established by Post et al. (1983). Load and muscle displacement data were used to measure extensibility at 30 N and 60 N in mm. Extensibility was considered as the measured displacement, or deformation, of the musculotendinous unit with the applied loads (Giambini et al., 2017). To assess the extensibility of SSP musculotendinous unit, the distal edge of the supraspinatus tendon was cut in specimens with intact cuff or small tears. This process was not required in specimens presenting medium size or large tears, since the distal edge of the tendon was already detached from the greater tuberosity. After removing all the soft tissues and acromion, the shoulders were placed in a custom-designed experimental device which

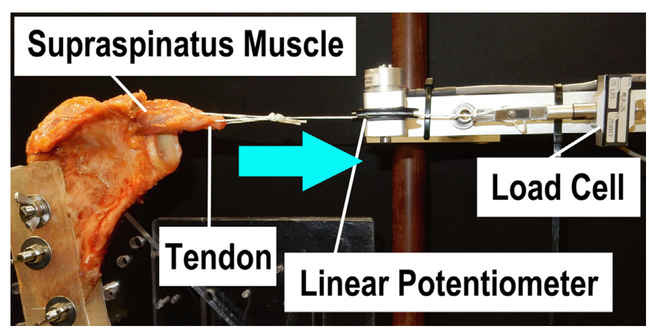

Fig. 2. Custom-designed device used for the assessment of extensibility.

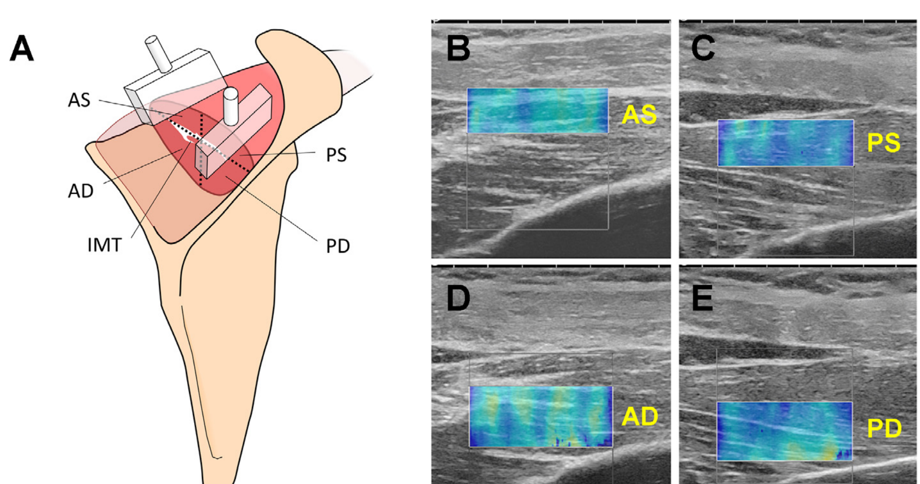

Fig. 1. Quadrisected regions of the supraspinatus muscle for SWE measurements. (A) Scheme of the placement of the ultrasound probe for the 4 muscular regions. SWE images for (B) anterior-superficial (AS), (C) posterior-superficial (PS), (D) anterior-deep (AD), and (E) posterior-deep (PD) muscular regions. IMT; intra-muscular tendon.

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