Biomechanical analysis of bursal-sided partial thickness rotator cuff tears

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Background: Treatment of partial thickness supraspinatus tendon tears is controversial with no clearly defined treatment algorithms based on severity of tears. This study aims to evaluate the relationship between depth of partial thickness tears and strain.

Methods: Bursal-sided partial thickness tears were created at 1 mm increments in depth at the anterior portion of the supraspinatus tendon to 3/4 tendon width on ten fresh-frozen shoulder specimens. The supraspinatus muscle was dynamically loaded from 0-50N, and strain recorded at both the anterior and posterior portions of the tendon.

Results: Strain in the intact posterior portion increased monotonically with tear depth and supraspinatus force. Strain in the torn anterior portion decreased with increasing tear thickness and loading force. At 60% thickness tear, strain was significantly higher ($P = 0.023$) in the intact posterior portion compared to intact tendon. As the tear thickness exceeded 50% tendon thickness, the strain in the intact tendon rapidly increased nonlinearly.

Conclusions: Biomechanical results herein suggest increasing potential for tear propagation in the transverse plane with increasing depth of tears, and biomechanically supports repairs of grade III (>50% thickness).

Level of evidence: Basic science study.

Keywords: Rotator cuff; rotator cuff tear; supraspinatus tendon; partial thickness tear; dynamic loading; tendon strain

The supraspinatus muscle is a primary abductor of the arm, and is most commonly torn in partial thickness rotator cuff tears.\textsuperscript{8} Partial thickness rotator cuff tears (PTRCT) are a common sports and age related phenomena.\textsuperscript{17,29} PTRCTs of the supraspinatus tendon can be classified based on location as bursal-sided, articular-sided, or intratendinous. Factors contributing to formation of PTRCTs include sub-acromial impingement as a main proponent of bursal sided tears and intrinsic age related phenomena as an important contributor to articular sided tears.\textsuperscript{5,23,12} Articular or bursal sided partial thickness supraspinatus tears have been historically difficult to treat due to the lack of agreement on
accepted treatment algorithms. Nonoperative and various operative options have been tried with inconsistent results.\textsuperscript{3,6,7,11,21} Conservative treatment is effective in reducing inflammation in all stages of rotator cuff tendon pathology,\textsuperscript{19} but a satisfactory result from conservative care alone is successful in less than half of degenerative partial thickness tears.\textsuperscript{2}

A recent study with long follow-up described poor results when acromioplasty & debridement were used to manage partial thickness tears, including up to 35% of patients progressing to full thickness tears within 5 years.\textsuperscript{11} With failure of nonoperative treatment and in the absence of other clinical pathology, surgeons have been limited to the existing literature regarding the decision for repair versus debridement and acromioplasty.

Several studies have recommended or described favorable clinical results when using 50% thickness tendon tear as a threshold for repair of bursal-sided tears.\textsuperscript{14,20,24,30,31} For tears less than 50%, conservative treatment consisting of subacromial decompression without arthroscopic repair yielded satisfactory results at a minimum 1-year follow-up.\textsuperscript{20} Despite consensus among many orthopaedic surgeons that a tear thickness of 50% warrants repair,\textsuperscript{31} a biomechanical analysis on the supraspinatus tendon to support this practice has not been previously performed. A biomechanical analysis of the bursal-sided partially torn tendon may elucidate the underlying mechanisms behind the outcomes observed in clinical practice when using 50% thickness tears as a threshold for repair. Furthermore, such a study can provide quantitative insight regarding the behavior of a bursal-sided partially torn supraspinatus tendon among the whole range of thickness tears, from an intact tendon to a fully torn tendon.

The purposes of this study were to 1) examine the strain in both the torn portion and the remaining intact portion of the partially torn supraspinatus tendon when subject to dynamic loading along increasing levels of partial thickness tears, and 2) subsequently evaluate if a cutoff for repair of a partial thickness supraspinatus tendon of 50% is biomechanically justified.

### Materials and methods

#### Specimen characteristics

Ten fresh-frozen upper extremities were used for testing. Seven male and three female specimens with an average age of 63.3 (range, 52-77 years) comprised the testing group.

#### Set-up

After the removal of all overlying soft tissue, the specimens were prepared for testing. All muscles, with the exception of the deltoid, supraspinatus, infraspinatus, teres minor, subscapularis, and long head of the biceps, were removed. The biceps was sectioned distally to allow for loading of the muscle belly. The deltoid was elevated from its origins and the acromion was partially excised to allow better visualization and access to the supraspinatus tendon. Careful macroscopic examination was undertaken to ensure absence of cuff tendon pathology.

Each muscle was elevated partially from its origin (with the exception of the biceps which was detached distally). The deltoid was divided into 3 distinct sections (anterior, middle, and posterior) as were the subscapularis (upper, middle, and lower) and infraspinatus (upper, middle, and lower) muscles. Individual muscle bellies were then wrapped proximally and secured with fiberglass mesh to allow for loading along its line of action with an amplitude proportional to its physiological cross-sectional area\textsuperscript{15,10} to maintain the glenohumeral joint and the supraspinatus tendon in a physiological position.

The scapula was mounted rigidly onto an aluminum plate and secured with 3 bolts, taking care to minimally disrupt any overlying muscle. The humerus was centered into an aluminum tube and secured using screws with sharpened tips. Muscle bellies were then loaded along their line of action though the cable affixed to the mesh. Cables were run through pulleys and eyebolts as needed to ensure the proper line of action was maintained. Muscles were loaded to 2% of their maximal force proportional to their cross-sectional area\textsuperscript{15,10} to maintain the glenohumeral joint and the supraspinatus tendon in a physiological position.

With the arm fixed at 30° of glenohumeral abduction in the scapular plane, 2 differential variable reluctance transducers (DVRT; Microstrain, Burlington, VT) were affixed with barbs and 4-0 prolene suture to the anterior and posterior portions of the
corresponds to a 45 increments divided by the measured tendon thickness. Subsequent comparison and analysis of each specimen thickness at the full thickness tear site were recorded with a digital protocol was completed, tendon width, tear width, and tendon dimensions, until a full thickness tear was created. After the loading during the experiment.

Protocol

The glenohumeral joint was fixed at 30° of elevation, which corresponds to a 45° angle of arm elevation assuming a shoulder rhythm of 2:1 glenohumeral and scapular elevations. Thirty-degree glenohumeral elevation represents a middle position in the supraspinatus contribution to the shoulder abduction range. The supraspinatus tendon was pre-loaded dynamically for 20 cycles to 10 N. Next, the supraspinatus tendon was loaded dynamically up to 50 N for 5 cycles.

Partial thickness tears were then created in the supraspinatus tendon proper, lateral to the attached DVRTs and medial to the bone-tendon junction, by sharply cutting the supraspinatus tendon initially from its most anterior portion to 3 quarters of the tendon width as measured by a digital caliper (Figure 2). Cuts were made at 1-mm depth increments. Depth increments were measured with a digital caliper from the tips of multiple #11 blade scalpels, with tape applied proximally from the marked measurement as a guide. Multiple blades were marked such that lengths from 1 mm to 8 mm were available at 1-mm increments. For each depth increment, the attached supraspinatus muscle was loaded accordingly up to 50 N for 5 cycles, with the strain recorded from the average of the last 3 cycles; 50 N was chosen as a conservative value that balanced 2 factors: allowing for high enough force while also preventing failure and tearing of the loaded muscle or tendon during the experiment.

Loading of each specimen was performed at 1-mm cut increments, until a full thickness tear was created. After the loading protocol was completed, tendon width, tear width, and tendon thickness at the full thickness tear site were recorded with a digital caliper. Subsequent comparison and analysis of each specimen data were based on the percentage derived from the 1-mm cut increments divided by the measured tendon thickness.

Data analysis

In order to compare all specimen under dynamic loading, stress and strain values obtained at 30 N load for each specimen’s loading cycle were used for data analysis. To calculate stress, we assume a rectangular shaped cross-section of the supraspinatus tendon (Figure 3) and evenly distributed stress over the cross-sectional area. Thus the supraspinatus tendon stress was calculated as follows:

\[ \sigma = \frac{f}{WT - lt} \]

where \( \sigma \) represents the stress, \( f \): pulling force, \( W \): width of tendon, \( T \): thickness of tendon, \( l \): width of cut, and \( t \): depth of cut. Strain was then calculated by dividing the changes in length by the initial length. Because each specimen had a different supraspinatus tendon thickness, comparisons of stress or strain based on specific percentage thickness tears were not possible. To allow for comparison at discrete percentage thickness tears, a 2nd-order polynomial curve was fit on data for stress and strain with respect to the depth of cut. Using such a model, stress or strain values at specific percentage thickness tears were comparable across the specimens via interpolation. Also to allow for comparison, stress and strain values with respect to percentage thickness tears were analyzed at a fixed supraspinatus load of 30 N. In this experiment, multiple measurements on the same dependent variable were made for each specimen. Thus a repeated measures analysis of variance procedure (SPSS; LEAD Technologies, Inc., Haddonfield, NJ) was appropriate to analyze the effects of percentage thickness cut as the independent variable and strain as the dependent variable. A P value of less than .05 was considered statistically significant for the difference in means for strain at each percentage thickness cut.

Results

Trends in experimental data

As the partial thickness tear of the supraspinatus tendon increased, the strain in the remaining intact posterior portion increased monotonically. In contrast, the strain decreased in the torn anterior portion of the tendon. With increasing percentage thickness tears, the strain in the intact posterior portion increased nonlinearly while the strain in the torn anterior portion decreased nonlinearly (Figure 4).

Results with curve fitting

The 2nd-order curve fit showed consistent trends across different pulling force magnitudes (Figure 5). After curve fitting, the strain values for each 10% thickness tear interval for all specimens at 30 N supraspinatus load were obtained and pooled (Figure 6). As the strain in the intact posterior portion increased nonlinearly with percentage thickness tear, the difference in mean strain in the posterior portion at 60% thickness tear compared to that at 0% thickness tear was statistically significant (\( P = .023 \)). Of note, at 50% thickness tear the difference in mean strain resulted in \( P = .056 \). The differences in mean strain in the posterior portion between the intact tendon and all percentage thickness tears are presented in the Table I.
The observed behavior between strain, pulling force, and percentage thickness tear can be appreciated by analyzing the stress in the intact portion in light of the rectangular supraspinatus model explained. As the depth of tear increases, the remaining cross-sectional area of the intact portion decreases; therefore, the stress on the remaining intact portion increases. An increase in percentage thickness tear (depth) on the intact portion results in a nonlinear increase in the stress (Figure 7).

Discussion

Although many orthopaedic surgeons agree that a 50% thickness bursal sided tear of the supraspinatus tendon warrants repair, there is not enough scientific evidence to support this claim as a standard. The purpose of this study was to examine the strain of the partially torn supraspinatus tendon and elucidate a biomechanical basis behind a 50% thickness tear as a reasonable cutoff for repair.

The method of fixing the glenohumeral joint to 30° of elevation is justified as follows: Nightingale et al. used dynamic modulus of elasticity as a measure of tissue stiffness to monitor changes in tissue properties with cyclic loading and abduction, and showed no significant change in dynamic modulus with cyclic loading in the 0-30° abduction range. Furthermore, testing at significantly larger abduction angles could introduce tear propagation, as Reilly et al. have shown significant increase in strain in partially torn articular sided supraspinatus tears at 120° abduction compared 0° abduction. We used a maximum value of 50 N to load the supraspinatus tendon in order to prevent failure during the experiment. In a biomechanical cadaveric study of failure loads under tension of the supraspinatus tendon, Itoi et al. reported that the posterior portion of the tendon had the lowest ultimate load at failure than did

![Figure 4](image1.png)  
**Figure 4** Recorded strain values (%) with respect to the supraspinatus loading force (N) for one specimen. Each curve corresponds to a different percentage depth of cut in the anterior side of the supraspinatus tendon for the same specimen. A, Intact posterior side of the supraspinatus tendon. B, Torn anterior side of the supraspinatus tendon.

![Figure 5](image2.png)  
**Figure 5** Curve fitting of strain values to percentage thickness tear based on experimental data points in an intact posterior side of the supraspinatus tendon of a representative specimen. Each curve represents a different load value in the same specimen.
the middle or anterior portions. In their study, the posterior portion of the supraspinatus tendon had an ultimate load of 88.1 /C6 32.1 N. In our experiment, the posterior portion of the tendon was mostly intact, while the anterior portion was cut with progressively increasing depth; 50 N represents a force value that is well below the reported failure loads in the posterior tendon. Strain was chosen as the experimental variable because it can be used as a measure of tissue properties under load without causing significant damage in actual testing for propagation or failure. Several biomechanical studies have used strain as a measured variable in evaluating tissue responses.1,18,25,27

Several weaknesses are recognized in the current study. The use of cadaver specimens unfortunately limits the direct application to the in vivo state; however, an attempt was made to obtain specimens from an age appropriate population. In addition, the experiment was designed to closely emulate the in vivo situation, yet still allowing for the capability to carry out the appropriate biomechanical tests.

Furthermore, despite the lack of macroscopic tissue damage, torn tendons in vivo often show signs of intratendinous degeneration that were not visualized in this experiment. Reilly et al concluded that the load sharing through the supraspinatus tendon is altered by these intratendinous tears.27 Although 50% thickness tear is used as a cutoff in the treatment of both bursal and articular sided tears, one should use caution when applying the data herein for the treatment of articular sided tears due to different strain properties of bursal and articular sides of the supraspinatus tendon.13,26

The effect of cyclic loading on strain due to tissue stretching was not evaluated in this study. Hence, the authors took measures in assuring consistency between each experimental cycle. Each specimen was preconditioned with 20 cycles at 10 N prior to testing at each 1-mm-depth cut increment. The specimens were then tested with 5 cycles to 50 N. The strain values of the last 3 cycles were then averaged to account for possible strain changes with cyclic loading. Although sequential loading may potentially alter tissue properties, all modifiable aspects of each specimen were held constant (ie, position, DVRT placement) except for the increasing depth of cuts with each loading cycle.

Finally, this study was done under relatively low loads (maximum 50 N load) due both to inherent capacity of our motor and to ensure that the supraspinatus muscle would not rupture during analysis. Although the resultant low strain values presented in the data, the trends that were noted in this study may also be applicable under more physiological loads.

In our dynamic loading experiment, the intact posterior portion of the supraspinatus tendon was preferentially loaded as percentage thickness tear in the anterior portion increased. The strain values in the supraspinatus tendon from this experiment were within the range of those obtained by Reilly et al.26 At a fixed load, the strain of the torn anterior portion of the tendon decreased with increasing percentage thickness tear. The strain of the intact posterior portion of the tendon increased concomitantly with percentage thickness tear. A statistically significant difference in mean strain was evident at tears at or above 60%. The results herein support that partial thickness tears significantly increases strain in the remaining tendon in grade III4 partial thickness tears.

Biomechanical factors may contribute to poor clinical results30 of grade III partial thickness and their propagation into full thickness tears. In a 2-dimensional model finite element analysis of a bursal sided tear in the supraspinatus tendon, Sano et al28 explored the stress distribution of a bursal sided tear. At both 0° and 60° abduction, the highest tensile stress was observed at the deep site of partial thickness tear. These results show that bursal sided partial thickness tears propagating deeper into full thickness tears are due to the proportionately higher stress at the remaining deep portion of the tendon tear site. The results of our study elucidate mechanisms of propagation of partial thickness tears in the anterior-posterior dimension that Sano et al did not address with their model.

Based on a decrease in strain in the cut portion and a concomitant increase in strain in the intact portion with increased tear depth, we propose that the stress distribution from the anterior to posterior direction may lead to tear tears.
propagation. With increasing tear depth, there was a nonlinear 2nd-order rate of decrease in the strain at the torn anterior portion of the supraspinatus tendon with an accompanying 2nd-order increase in the strain at the intact posterior portion of the supraspinatus tendon. This behavior is most clearly seen in Figure 3, in which there is a noticeable spread in strain differences at the full thickness tear compared to that at 50% for both the anterior and posterior portions of the supraspinatus tendon. The results herein suggest that with increasing tear depth, the nonlinear strain increase in the posterior intact portion promotes higher susceptibility of partial tearing and tear propagation in the transverse plane. Due to tear propagation in the transverse plane, in addition to tear propagation to full thickness tears proposed in other biomechanical studies, patients with >50% thickness bursal sided tears may be at increased risk of developing both longer tears and full thickness tears. Nevertheless, the clinical relevance of increased tear length is unclear.

**Conclusion**

The data from this study suggest that partial thickness tears could potentially propagate in the transverse plane, especially at >50% thickness partial tears. From biomechanical data presented herein and stress distribution results seen in finite element models, bursal sided tears of over 50% thickness should warrant more concern to the surgeon. As the results from this study may imply tear propagation in the transverse plane in the antero-posterior direction, a formal stress analysis and the analyzing the biomechanical effects of the tear length in the transverse plane is a potential future study.

**References**


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**Table I** Comparison of mean strain between different percentage thickness cuts and the intact tendon. (* indicates statistically significant difference)

<table>
<thead>
<tr>
<th>(I) Percentage Thickness Cut</th>
<th>(J) Percentage Thickness Cut</th>
<th>Difference in Mean Strain (I-J)</th>
<th>Std. Error</th>
<th>Sig.(a)</th>
<th>95% Confidence Interval for Difference(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% (Intact Specimen)</td>
<td>10%</td>
<td>0.015</td>
<td>0.022</td>
<td>0.496</td>
<td>(0.065, 0.034)</td>
</tr>
<tr>
<td>20%</td>
<td>0.039</td>
<td>0.056</td>
<td>0.040</td>
<td>0.356</td>
<td>(0.210, 0.013)</td>
</tr>
<tr>
<td>30%</td>
<td>0.075</td>
<td>0.069</td>
<td>0.056</td>
<td>0.210</td>
<td>(0.114, 0.035)</td>
</tr>
<tr>
<td>40%</td>
<td>0.120</td>
<td>0.079</td>
<td>0.087</td>
<td>0.023</td>
<td>(0.131, 0.052)</td>
</tr>
<tr>
<td>50%</td>
<td>0.173</td>
<td>0.094</td>
<td>0.099</td>
<td>0.003</td>
<td>(0.202, 0.006)</td>
</tr>
<tr>
<td>60%</td>
<td>0.238(∗)</td>
<td>0.105</td>
<td>0.114</td>
<td>0.000</td>
<td>(0.353, 0.034)</td>
</tr>
<tr>
<td>70%</td>
<td>0.313(∗)</td>
<td>0.114</td>
<td>0.000</td>
<td>0.000</td>
<td>(0.437, 0.041)</td>
</tr>
<tr>
<td>80%</td>
<td>0.402(∗)</td>
<td>0.105</td>
<td>0.000</td>
<td>0.000</td>
<td>(0.525, 0.041)</td>
</tr>
<tr>
<td>90%</td>
<td>0.506(∗)</td>
<td>0.105</td>
<td>0.000</td>
<td>0.000</td>
<td>(0.626, 0.035)</td>
</tr>
<tr>
<td>100%</td>
<td>0.654(∗)</td>
<td>0.105</td>
<td>0.000</td>
<td>0.000</td>
<td>(0.742, 0.035)</td>
</tr>
</tbody>
</table>

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**Figure 7** Stress in the intact posterior side of a supraspinatus tendon in a representative specimen with respect to percentage depth of cut. Each curve corresponds to a different load value (N) for the same specimen.