INTRODUCTION
Rotator cuff tears are common shoulder disorders, with the supraspinatus tendon most frequently affected. More than 300,000 surgeries are performed each year with re-tear rates ranging from 25-90% [1]. Methods to improve repair strength and surgical outcomes are necessary. Successful repairs of the rotator cuff are dependent both upon the intrinsic musculoskeletal properties as well as surgical technique. Technical developments such as double row and transosseous-equivalent repairs increase pressurized contact at the insertion footprint [2] but necessitate additional anchors and suture passes through the tendon. While numerous laboratory studies have compared single to double row rotator cuff fixation properties by repairing tendon to bone [3-5], little is known regarding suture retention properties of the medial and lateral regions of the tendon (independent of fixation technique) in both intact and torn states. A more complete understanding of the regional collagen fiber functional and architectural properties may facilitate surgical planning. Therefore, the present investigation evaluated the mechanical capacity of intact and torn human supraspinatus tendons to retain a suture with both lateral and medial placements.

METHODS
Specimens: Twenty fresh frozen human cadaveric shoulders (five left-right pairs and ten unpaired shoulders, mean age 74 ± 10 years) were obtained from LifeLegacy Foundation (Tucson, AZ, USA). Supraspinatus tendons were sharply resected from their insertion sites on the humeral head, and randomized into either medial or lateral groups (i.e., contralateral tendons were not tested for the same region). The distribution of specimens for mechanical testing was (a) four intact and five torn tendons for medial region testing and (b) four intact and four torn tendons for lateral region testing. The remaining three shoulders were utilized for ultrastructural analysis.

Mechanical testing: Testing was performed on an electromechanical materials testing system (MTS Insight 5, Eden Prairie, MN, USA). A custom freezer clamp was used to grip the muscle while taking precaution to maintain the tendon temperature above 15°C. Two #2 FiberWire (Arthrex, Naples, FL, USA) sutures, trisecting the width of the tendon, were placed at either 10mm from the free margin (lateral) or at the musculotendinous junction (medial). A standard suture length of 6mm was used in each test, with each suture looped over adjustable fixtures attached to the testing platform. The sutures were loaded in a direction parallel to the predominant tendon fiber orientation. The tendon was preloaded to 5N for 1min in order to establish its initial length, followed by cyclic preconditioning between 5N and 30N for 50 cycles. Finally, a pull to failure test was applied at a rate of 1mm/s. The following mechanical parameters were quantified from the force-displacement curve (0-10mm portion only) of each failure test: maximum load, linear stiffness (steepest slope spanning 30% of data points), and energy (area under curve). A paired t-test was used to compare properties of medial to lateral placement in contralateral specimens, while unpaired t-tests were used for statistical comparison of torn and intact medial row placements. Statistical significance was assumed for p<0.05.

Transmission electron microscopy (TEM): ~3mm cubes from medial and lateral regions of each supraspinatus tendon were fixed, embedded, sectioned transversely at 100nm and stained. Digital images were collected at 150k magnification using an electron microscope (Model JEM-1220, JEOL, Tokyo, Japan). Collagen fibril diameters were measured [6,7] using ImageJ software (NIH, USA).

RESULTS
Biomechanics: No significant differences were noted between medial and lateral regions of intact tendons. In contrast, the lateral region of torn supraspinatus tendons was significantly (p<0.05) weaker than the medial. For the medial tendon, maximum load (282 ± 53N) and energy (1700 ± 160N-m) of intact tendons were similar (p>0.4) to those of torn tendons (262 ± 48N and 1568 ± 283N-m, respectively) (Table 1). For the lateral tendon, maximum load (256 ± 46N) and energy (1527 ± 251N-m) of intact tendons were significantly higher (p>0.04) than those of torn tendons (155 ± 60N and 932 ± 209N-m, respectively).

TEM: Mean collagen fibril diameter was larger (p=0.04) in the medial (63 ± 14 nm) compared with lateral (26 ± 3nm) tendon region. In addition, as depicted in Figure 1, the medial region exhibited a wider distribution range of collagen fibril diameters (40–100nm) than the lateral (20–45nm). Fibril area fraction tended to be larger (p=0.058) in the medial (63 ± 7%) than the lateral tendon (49 ± 4%). (Table 2)

DISCUSSION
The current study demonstrates that the medial and lateral regions of the intact supraspinatus tendon exhibit similar biomechanical properties with respect to suture retention. Interestingly, the presence of a tear altered the suture pullout characteristics of the lateral, but not the medial supraspinatus tendon. Among torn tendons, the lateral supraspinatus exhibited a significantly inferior mechanical response compared with the medial region (Table 1). This finding confirms clinical observations that tendon pathology and matrix degeneration initiates near the supraspinatus tendon insertion (i.e., critical zone) [1].

The superior pullout resistance of the medial row may provide a strain shielding effect for the lateral row following double row repair [3]. A structural basis for the superior suture retention properties of the medial row is evident from the TEM data; namely, the larger collagen fibrils as well as greater fibril area fraction (i.e., density) of the medial supraspinatus tendon may provide a more robust matrix for resisting suture migration.

While clinical factors such as musculotendinous integrity (e.g., retraction, atrophy) warrant strong consideration for surgical decision making, our ultrastructural and biomechanical results appear to provide a scientific rationale for double-row rotator cuff repair. Histologic analyses are currently being conducted to supplement the data reported herein.

Table 1: Biomechanical properties

<table>
<thead>
<tr>
<th></th>
<th>Fiber Diameter (nm)</th>
<th>Area Fraction (%)</th>
</tr>
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<tbody>
<tr>
<td>Medial part</td>
<td>63 ± 14</td>
<td>63 ± 7</td>
</tr>
<tr>
<td>Lateral part</td>
<td>26 ± 3</td>
<td>49 ± 4</td>
</tr>
</tbody>
</table>

* p<0.05 between medial and lateral aspects

Table 2: Ultrastructural data

<table>
<thead>
<tr>
<th></th>
<th>Medial</th>
<th>Lateral</th>
<th>Medial</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Load (N)</td>
<td>282 ± 53</td>
<td>256 ± 46</td>
<td>262 ± 48</td>
<td>155 ± 60</td>
</tr>
<tr>
<td>Energy (N-mm)</td>
<td>1700 ± 160</td>
<td>1527 ± 251</td>
<td>1568 ± 283</td>
<td>932 ± 209</td>
</tr>
</tbody>
</table>

* p<0.05  medial>lateral for torn;  #  p<0.05  intact>torn for lateral

REFERENCES

ACKNOWLEDGEMENTS
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