Patterns of Strain and the Determination of the Safe Arc of Motion after Subscapularis Repair—A Biomechanical Study

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Abstract

This study characterizes the strain patterns and safe arcs for passive range of motion (ROM) in the superior and inferior subscapularis tendon in seven cadaveric shoulders, mounted for controlled ROM, after deltopectoral approach to the glenohumeral joint, including tenotomy of the subscapularis tendon 1 cm medial to its insertion on the lesser tuberosity. The tenotomy was repaired with end-to-end suture in neutral rotation. Strain patterns were measured during passive ROM in external rotation (ER), ER with 30° abduction (ER+30), abduction, and forward flexion in the scapular plane (SP) before and after surgery. Percentages were calculated from 35 trials corresponding to five trials of each motion across seven specimens. With ER of 0-30°, 89% of trials of superior subscapularis tendon and 100% of trials of inferior subscapularis tendon achieved strains >3%, with very similar patterns noted in ER+30. In abduction of 0-90°, 5.8% of trials of superior and 85.3% of trials of inferior tendon achieved >3% strain. With passive ROM in SP, 26.5% of trials reached 3% strain in superior tendon compared to 100% in inferior tendon. Strain patterns in abduction and SP differed significantly ($p < 0.001$). Selective tenotomy and repair of the superior subscapularis tendon with open reparative or reconstructive shoulder procedures, when feasible, may be favorable for protected early passive ROM and rehabilitation postoperatively.

Keywords: subscapularis tendon; tenotomy; strain; shoulder; range of motion

Level of Evidence: (Basic science)

INTRODUCTION

Many shoulder procedures, both arthroscopic and open, involve repair of the subscapularis tendon. These include, but are not limited to, surgical procedures in which a subscapularis tenotomy is performed for anterior shoulder stabilization procedures, glenohumeral exposure for shoulder arthroplasty, and large anterosuperior rotator cuff tears involving the subscapularis.[1-4] Previous authors have reported on the significance of shoulder instability following total shoulder arthroplasty due to subscapularis insufficiency with abnormal lift-off and belly-press examinations.[5] Partial or complete rupture of the subscapularis tendon after shoulder surgery remains a serious complication that may result in pain, weakness, and instability.[6-9] Proposed factors associated with postoperative subscapularis rupture or dysfunction following surgical repair include poor quality tissue, trauma, inappropriate physical therapy during the early postoperative period, and insufficient repair techniques.[5,10-13] In all cases, early range of motion (ROM) that stresses the repair to a point exceeding the strength of the repair should be avoided for an optimal outcome. A rehabilitation protocol describing a safety zone in which postoperative motion exercises can be performed without applying any amount of tension that would impair healing of the repaired rotator cuff has not been described. There are variations to rehabilitation protocols, specifically the timing of when ROM exercises should be initiated.[14,15] Some surgeons are moving towards earlier ROM to prevent some of the more devastating complications, including stiffness and arthrofibrosis, however these have focused on repair of either supraspinatus and infraspinatus tendons.[16,17] Various authors have described initial placement of the operative extremity in a sling for up to 6 weeks, with no passive external rotation beyond neutral or 30 degrees,[18,19] whereas some protocols involve earlier motion.[17,20,21] However, the exact amount and specific arc of motion that is safe for the repaired subscapularis taken down for exposure of the glenohumeral joint or following isolated arthroscopic repair, remains unknown. Furthermore, previous authors have clearly described the subscapularis footprint insertional anatomy and demonstrated that there are clear differences within the upper and lower portions of the musculotendinous unit at the insertion. To our knowledge no literature evaluates the clinical or biomechanical significance of differences between the upper and lower anatomic insertions.[22] By evaluating strain within the upper and lower portions of the tendon, we aimed to address the following questions: 1) Should external rotation be limited beyond neutral in all patients in the postoperative period? 2) On the basis of strain patterns within the repaired subscapularis tendon, can passive range-of-motion exercises within the scapular plane or coronal plane be initiated without compromising the integrity of the repair? We hypothesized that strain patterns in the superior and inferior subscapularis tendons are significantly different and therefore a safe ROM postoperatively that does not interfere with the integrity of the repair may vary depending on tear location.

MATERIALS AND METHODS

Eight fresh-frozen cadaveric upper extremities (bilateral specimens from 3 males and 1 female, average age 59 yrs, range 54-64 yrs) were obtained from our institution's Anatomical Donations Program. Standard radiographs were obtained for all specimens. Any specimen with glenohumeral osteoarthritis and large or massive rotator cuff tears was excluded, leaving seven specimens for subsequent study and analysis. The specimens were stored at -20 °C and thawed overnight at room temperature prior to testing. Testing and reconstruction were performed at room temperature and completed within 24-48 hours of thawing. No specimens were found to have any disruption or evidence of tear within the subscapularis musculotendinous unit.

Each cadaveric upper extremity was amputated medial and inferior to the scapular body as well as the mid-humerus to obtain the entire shoulder girdle. A standard deltopectoral approach was used to identify the subscapularis tendon, after which all soft tissues anterior to the subscapularis tendon were removed for data collection and analysis. This included select portions of the acromion and coracoid process that would obstruct the motion-capture system from collecting data throughout the various shoulder arcs of motion.

The scapular portion of the shoulder specimen was then mounted onto a customized machined fixture (Fig. 1). The previously potted portion of the distal humerus was then fixed with one of two custom-made fixtures, specifically one for internal rotation, external rotation, and 30 degrees of abduction with external rotation, as well as a second fixture for abduction and forward flexion in the scapular plane. The humeral rod was attached to the arc of the apparatus using a linear-bearing slide to permit axial sliding. The bicipital groove was positioned to face anteriorly, so as to ensure a consistent starting position with each shoulder specimen in the neutral position.

Motion-tracking sensors were placed within the upper and lower portions of the subscapularis tendon within the tendinous insertion onto the humeral lesser tuberosity. The Optotrak Certus™ motion-capture system (Northern Digital Inc., Waterloo, Ontario, Canada) and MotionMonitor software (Innovative Sport Training, Inc., Chicago, Illinois) were used to collect the positions of two markers placed within the upper portion of the subscapularis tendon and two markers placed within the inferior portion of the tendon throughout the arc of internal rotation, external rotation, abduction and external rotation, abduction in the coronal plane, and forward flexion in the scapular plane.

Following measurement of marker positions within the intact subscapularis musculotendinous unit in all previously described arcs of motion, a standard tenotomy was performed perpendicular to the fibers as they traversed from the medial scapular body to the lesser tuberosity insertion, approximately 1-2 cm medial to the insertion, leaving a cuff of tendon laterally for repair as described by Caplan et al.[23] The Optotrak markers were placed approximately 5 cm apart , and ultimately the tenotomy left approximately 2.5 cm of tissue on each side.

The subscapularis tendon was repaired using a Mason-Allen suture technique with 0 Ethibond suture (Arthrex, Inc., Naples, Florida). This suture technique was chosen based on previous studies regarding gapping and biomechanical strength of various rotator cuff suture repair techniques.[24-27] This grasping stitch has been reported to have favorable results in minimizing gap formation and cyclic failure after rotator cuff repair.[25,27] The repair was performed with the forearm directly anterior in neutral rotation, the same position that the arm was in for the subscapularis tenotomy. This was made possible by placing a guidewire in the bicipital groove; the neutral arm/forearm position was indicated when the guidewire was perpendicular to the arm (facing directly anterior).[28]

Spacing of the Optotrak transducers ensured that one transducer would be on either side of the repaired tendon to allow for measurement within the intact or repaired portion of the tendon. The Optotrak sensors were secured to the subscapularis tendon with glue and 3.0 nylon (Ethicon) suture to secure the Optotrak cords away from the field of motion capture.

To calculate strain, Optotrak data were then imported to a customized MATLAB program, which then calculated the strain values within the upper and lower portions of the subscapularis tendon. The cumulative sum of each Optotrak marker length change, frame by frame, was calculated as $e = \sum \frac{l_{i+1}-l_i}{l_{i+1}}$. We had two markers in the superior portion of the tendon, measured displacement between those markers and calculated strain; we similarly did this in the inferior portion of the tendon as well. Therefore, there is one measurement for superior tendon strain, and one measurement for inferior tendon strain.

Five trials of each ROM were conducted on both the intact and then the repaired portion of the subscapularis tendon in the following order: (1) internal rotation with the arm neutral, (2) external rotation with the arm neutral, (3) external rotation with the arm at 30 degrees of abduction, (4) abduction to 90 degrees in the coronal plane, and (5) forward flexion to 90 degrees in the scapular plane.

To simulate a typical passive range of motion protocol, the research testing assistant moved the shoulder through the various ranges described above with a controlled rate utilizing a timer throughout each arc of motion. Each specimen trial run through the arc of motion was performed in a 5-second interval. Preconditioning was performed in all specimens within 5 cycles in the external rotation arc of motion, from approximately 0 degrees to 30 degrees, for both intact and repaired tendon. The shoulder position was then changed after internal rotation, external rotation, and external rotation with 30 degrees abduction to the second custom mounting device so as to allow for the final two arcs of motion of abduction and forward flexion in the scapular plane (Fig. 1).

Statistical Analysis

Strain patterns were defined with marker plots throughout the arc of motion, and absolute strain of greater than 3% was defined as clinically concerning for failure.[29,30] These analyses and investigations were conducted using the procedures available in SPSS v. 21.0 (IBM Corp., Armonk, New York). Categorical data were examined in contingency tables, with inferential testing using the chi-square test. The superior and inferior tendons were matched and examined for differences in proportions of strain patterns (<3, 0-30, and >30 trials with >3% strain, out of 35 trials) across seven subjects with five measurements for each subject. The multiple measurements, as well as cells with less than 5 responses, were controlled for within the chi-square test by use of the McNemar-Bowker test for K > 2 categories to reduce the inflation of type-I error.

Trajectory plots were created for visual aid with utilization of graphics interchange format (GIF) to allow for representation of the markers throughout each arc of motion.

RESULTS

The results from seven cadaveric specimens were utilized for analysis. For one of the specimens, only 4 trials were performed due to researcher error, thus we had 34 trials for analysis. With external rotation (ER) from 0 to 30 degrees, 89% (31/35) of the trials in the superior portion of the tendon experienced greater than 3% strain, and 100% (35/35) of the trials in the inferior portion of the tendon achieved greater than 3% strain, with very similar patterns noted in ER with 30 degrees abduction (ER+30) (Table 1). In abduction (AB) from 0 to 90 degrees, only 5.8% (2/34) of trials of the superior tendon and 85.3% (29/34) of trials of the inferior tendon achieved greater than 3% strain. With passive ROM in the scapular plane (SP), only 26.5% (9/34) of trials reached 3% strain in the superior tendon compared to 100% (34/34) of trials achieving at least 3% strain within the inferior tendon. These results are summarized in Table 1. There was a statistically significant difference between the strain patterns in both abduction $X^2(2, N = 34) = 36.4$, $p < 0.001$, and scapular plane $X^2(2, N = 34) = 39.0$, $p < 0.001$ between the upper and lower portion of the subscapularis tendon. Strain vs. angle graphs and three-dimensional marker plots demonstrate visual representation of either compression or strain throughout the trial runs in ER, ER+30, AB, and SP (Figs. 2-4).

DISCUSSION

The subscapularis musculotendinous unit, with its origination from the subscapularis fossa of the scapular body and insertion into the humeral lesser tuberosity, comprises the anterior rotator cuff, providing active internal rotation of the humerus and stability to the glenohumeral joint.[31] Electromyelogram studies have confirmed that upper and lower portions of the tendon, innervated by the upper and lower subscapularis nerves, respectively, demonstrate different levels of activation that may play a role in dynamic rehabilitation.[32] Tenotomy of the entire subscapularis tendon is very often required for access during total shoulder arthroplasty, however the tendon is often split or the upper portion may be taken down for open stabilization and reconstructive glenoid procedures such as the Latarjet-Patte procedure. Traumatic tears have been classified and similarly can involve the entire upper and lower portion of the tendon or a partial disruption of the upper portions of the tendon alone.[33]

Limited studies have assessed a defined “safe” shoulder range of motion following repair of the rotator cuff musculature but have primarily evaluated repair of the supraspinatus.[34] Previous studies have identified increased strain following supraspinatus repair with greater than 30 degrees of elevation in the coronal or scapular plane and external rotation greater than 60 degrees.[34] Other studies have demonstrated that humeral rotation can further alter gap formation and strain in the repaired supraspinatus tendon. The importance of early postoperative range-of-motion exercise has been emphasized by various authors, with proposed benefits including avoidance of scar formation above the repaired rotator cuff as well as adhesions of the subacromial bursa, contracture of the capsule, and muscle degeneration from long-term immobilization.[35,36] These benefits, however, have not been clearly demonstrated with early range of motion protocols in randomized clinical trials.[17]

Our study is the first, to our knowledge, to identify and address the strain patterns within the subscapularis of the rotator cuff and specifically attempt to define a safe arc of motion that would protect the integrity of any subscapularis repair. Within external rotation and external rotation plus 30 degrees of abduction, there was a linear increase in strain within the upper and lower portions of the repaired subscapularis tendon. Thus current protocols that limit any external rotation beyond neutral, often with a shoulder immobilizer, do protect the integrity of the repair. However, in our study we began to see a statistically significant difference in patterns of strain between the upper and lower portions of the subscapularis tendon in the arc of abduction and forward flexion in the scapular plane. Specifically, the upper portion of the tendon experienced significantly less strain, less than 3% in 94% (32/34) of specimens in abduction and 74% (25/34) of specimens in the scapular plane. With increasing angles of abduction, the upper portion of the tendon actually underwent compression, whereas the inferior markers continued to lengthen. Similarly in forward flexion in the scapular plane, there was very little lengthening and overall strain within the upper portion of the subscapularis tendon, whereas the inferior portion of the tendon continued to experience a more linear strain pattern throughout the arc of motion. Therefore, the results of the current study suggest that a traumatic partial tear of the upper portion of the subscapularis or open stabilization surgery in which the lower portion of the subscapularis tendon is preserved may have a greater arc of safe passive abduction and forward flexion in the scapular plane postoperatively.

There are several limitations to our study. The first is that the tissue quality among the cadaveric specimens may have been variable. Traumatic tears and degenerative rotator cuff tears may involve tissue of varying quality, and thus the overall viscoelastic nature of each individual specimen likely differed. Second, removal of soft tissue and structures (including the coracohumeral ligament) anterior to the subscapularis tendon, and changes within the remaining biceps brachi, having no distal attachment, may alter the amount of strain experienced within the subscapularis tendon. Third, although our customized jig and mounting device was based on a previous model that worked well for our specific testing,[34] our device did not allow for normal scapulothoracic motion and ultimately may not have simulated the exact patterns of dynamic strain across the shoulder girdle. Lastly, strain depends on rate given the viscoelastic nature of tendons and collagen fibrils, and although we attempted to control the rate of motion throughout our experiment, the shoulder was manually taken through the arc of motion. Thus minor differences in rate between trials and specimens may have altered strain. Furthermore, although we aimed to place the markers, tenotomy, and repair the same distance apart for each specimen with measurements, there may have been minor discrepancies among specimens, and thus strain measurements may have altered depending upon distance and soft tissue stretch between the intact and repaired portion of the tendon.

CONCLUSION

Our study has clear implications for the nature of postoperative rehabilitation following subscapularis tears or surgical procedures that require tenotomy of the whole, or a portion, of the subscapularis tendon. The results of our study suggest that repairs of the superior, or upper portion, of the subscapularis tendon may be favorable for an early range-of-motion protocol with a therapist if passive range of motion is within the "safe zone" involving abduction from 0 to 90 degrees as well as forward flexion in the scapular plane from 0 to 90 degrees. If, however, a subscapularis repair involves the inferior, or lower half, of the tendon, it remains important to limit elevation of the extremity in abduction and forward flexion in the scapular plane, as this would increase strain within the repair and leave the potential for failure. Furthermore, external rotation within any plane should be avoided, even with limited tenotomies, as this places strain across any repair. Earlier ROM and avoidance of a prolonged period of complete immobilization in a sling/shoulder immobilizer for 4-6 weeks may ultimately limit postoperative arthrofibrosis and stiffness, and lead to improved outcome measures and shoulder function.

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FIGURE CAPTIONS

Figure 1. (A) Mounting device for investigating simulated rehabilitation range of motion in cadaveric shoulder specimens, shown during pretrial testing. The distal humerus was previously potted and then fixed with one of two custom-made fixtures, specifically one for internal rotation, external rotation, and 30 degrees of abduction with external rotation, and a second fixture for abduction and forward flexion in the scapular plane. The humeral rod was attached to the arc of the apparatus using a linear-bearing slide to permit axial sliding. The bicipital groove was positioned to face anteriorly, so as to ensure a consistent starting position with each shoulder specimen in the neutral position. (B) Close-up view of a mounted specimen showing tenotomy and markers.

Figure 2. Marker positions were used to calculate the strain at intervals of 5 degrees throughout the range of motion. During abduction, 29/34 trials experienced negative strain, or compression, in the superior tendon, and 29/34 reached 3% strain in the inferior aspect of the tendon. Each color represents trials from one specimen.

Figure 3. (**A**) Trajectory plot of the strain markers in external rotation, with the blue rectangle representing the position of the markers during their initial placement (tendon at rest), the green and pink rectangles representing separate time points of the markers along the arc of motion, and the red rectangle representing the final placement at the end of the arc of motion. (**B**) The same trajectory plot of the external rotation strain markers looking from distal to proximal up the humerus, demonstrating strain and lengthening as the tendon moves over the humeral head (blue representing initial marker placement and red final marker placement).

Figure 4. Marker positions were used to calculate the strain at intervals of 5 degrees throughout the range of motion. The average and standard deviation of each five-trial block was plotted against angle with each color representing a different specimen. Average across all specimens is shown with orange diamonds. (**A**) External rotation, (**B**) external rotation + 30 degrees of abduction, (**C**) abduction, (**D**) forward flexion in the scapular plane.

Appendix Table 1. Summary of strain measurements across intact subscapularis tendon for all trials.

	Strain Measurements Across Intact Tendon		**Subscapularis**
	Trials >3% Strain	Trials <3% Strain	Trials With Compression
ROM Superior Tendon			
ER 0-30°	28/35 (80%)	7/35 (20%)	0/35
ER+30, Abduction 0-30°	30/35 (85.7%)	0/35	5/35 (14.3%)
Abduction 0-90°	7/35 (20%)	3/35 (8.6%)	25/35 (71.4%)
Scapular Plane 0-90°	12 (34.3%)	2 (5.7%)	21/35 (60%)
ROM Inferior Tendon			
ER 0-30°	26 (74.3%)	9 (25.7%)	0/35

ER+30, Abduction 0-30°	30/35 (85.7%)	5/35 (14.3%)	0/35
Abduction 0-90°	25/35 (71.4%)	9/35 (25.7%)	1/35 (2.9%)
Scapular Plane 0-90°	35/35 (100%)	0/35	0/35

Notes: ER = external rotation, ROM = range of motion.

Table 1. Summary of strain measurements across the subscapularis repair within the superior and inferior portions of the tendon for all trials. The categories included those trials in which greater than 3% strain was obtained, those in which strain was measured but did not achieve 3%, and finally those in which compression was noted across the repair.

	Strain Measurements Across Repaired Subscapularis Tendon		
	Trials >3% Strain	Trials <3% Strain	Trials With Compression
ROM Superior Tendon			
ER 0-30°	31/35 (88.6%)	4/35 (11.4%)	0/35
ER+30, Abduction 0-30°	35/35 (100%)	0/35	0/35
Abduction 0-90°	2/34 (5.8%)	32/34 (94%)	0/34
Scapular Plane 0-90°	9/34 (26.5%)	25/34 (73.5%)	0/34

ROM Inferior Tendon			
ER 0-30°	35/35 (100%)	0/35	0/35
ER+30, Abduction 0-30°	33/35 (94.3%)	2/35 (5.7%)	0/35
Abduction 0-90°	29/34 (85.3%)	3/34 (8.8%)	2/34 (5.8%)
Scapular Plane 0-90°	34/34 (100%)	0/34	0/34

Notes: ER = external rotation, ROM = range of motion.

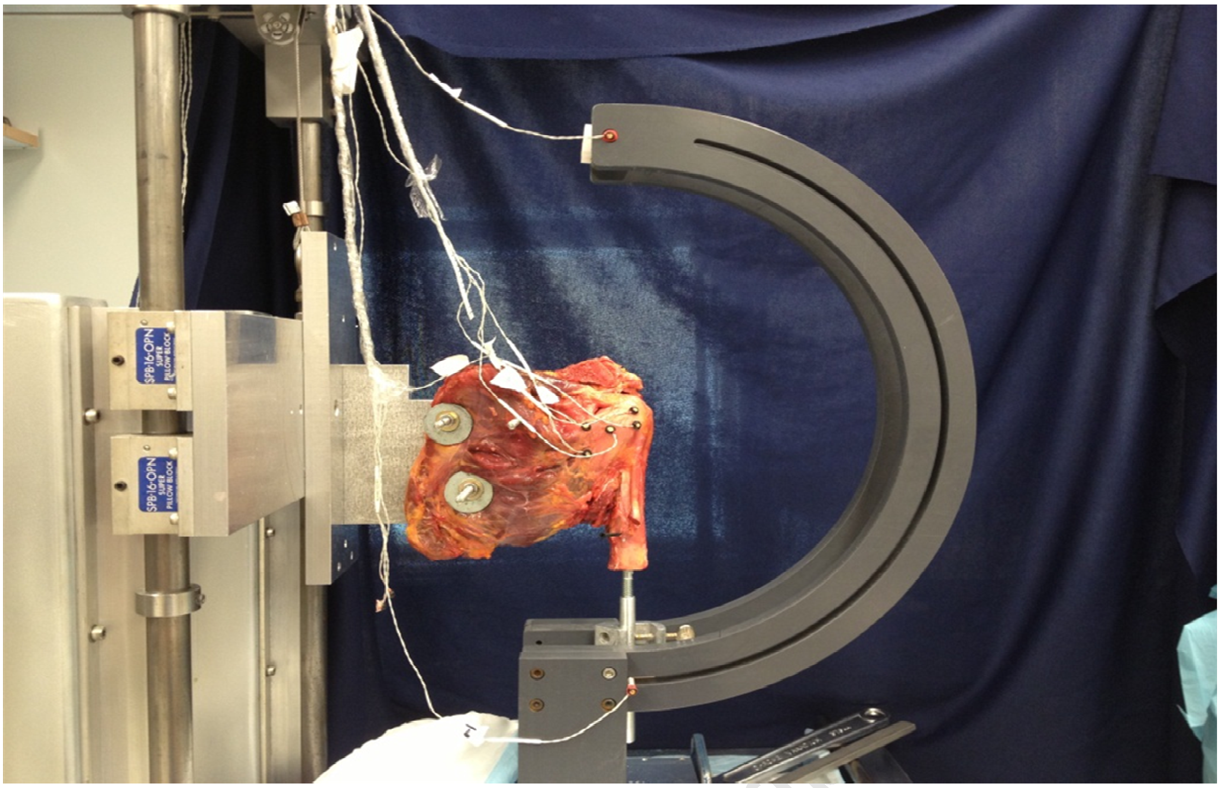


Fig1A .

Fig1B .

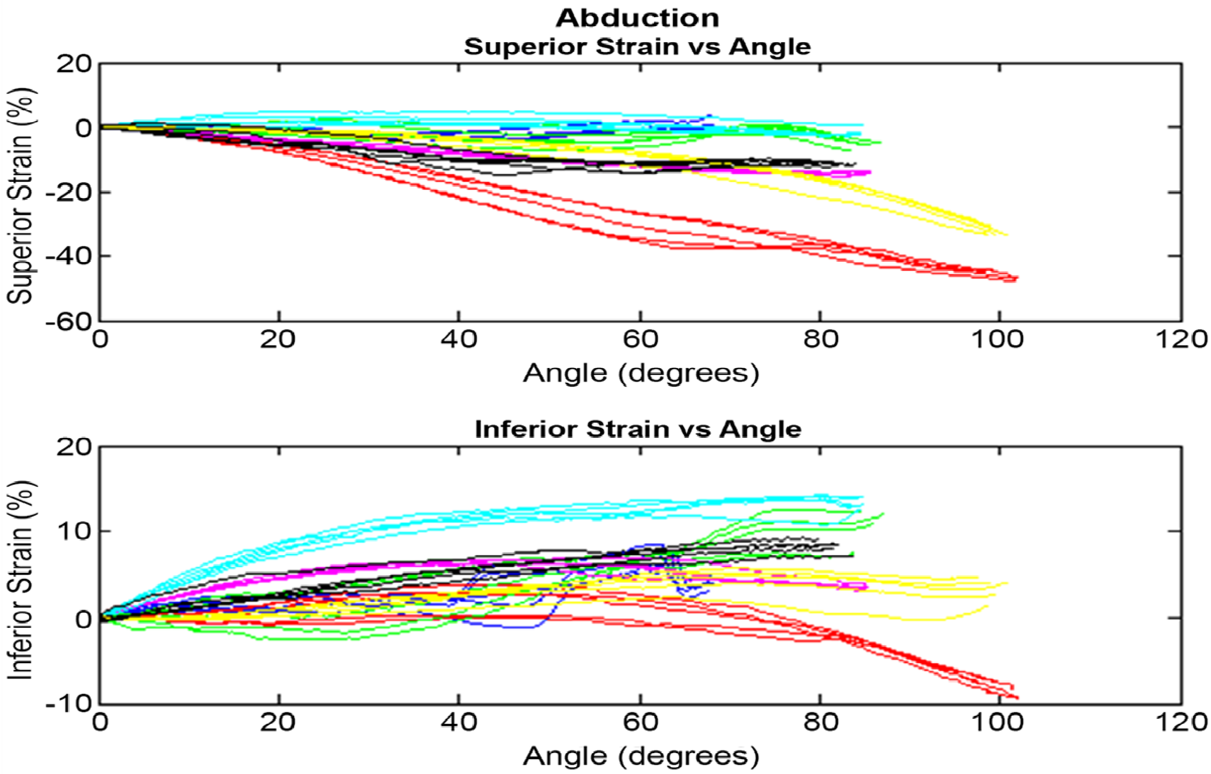
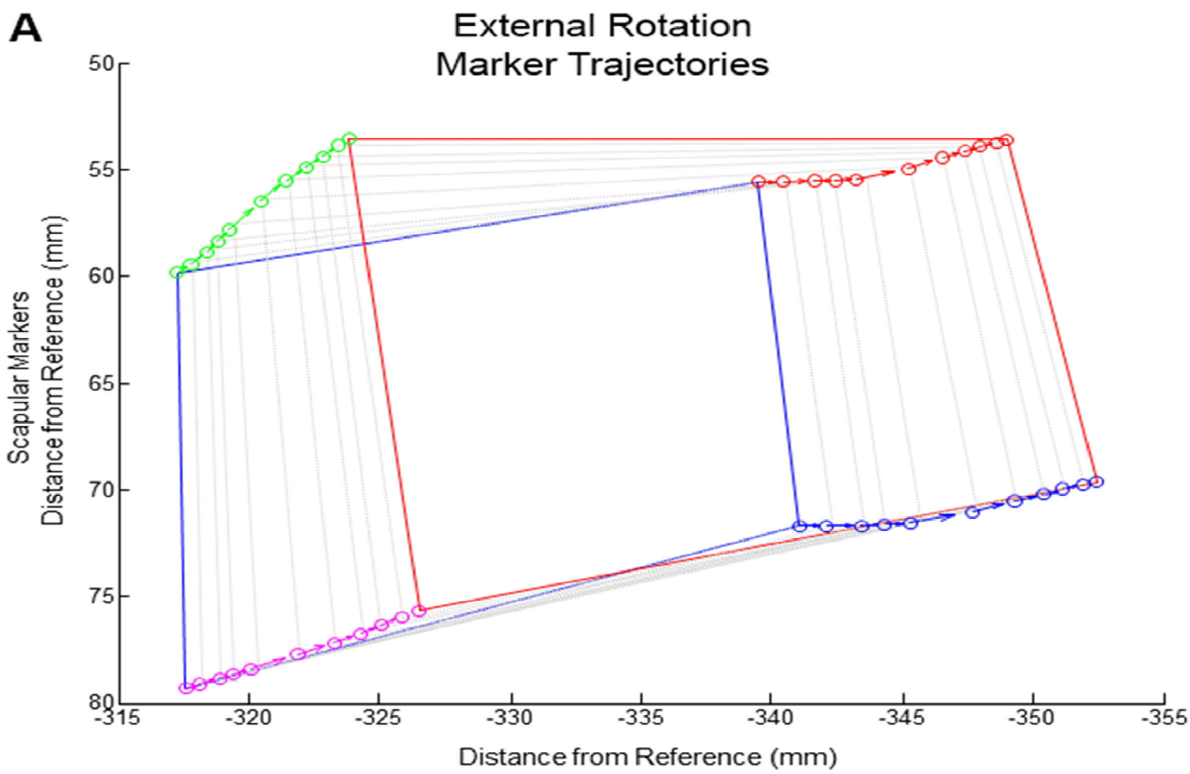

Abduction
Superior Strain vs Angle
Superior Strain (%)
Angle (degrees)
Inferior Strain vs Angle
Inferior Strain (%)
Angle (degrees)

Fig2 .


A
External Rotation
Marker Trajectories
Scapular Markers
Distance from Reference (mm)
50
55
60
65
70
75
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-315
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-330
-335
-340
-345
-350
-355
Distance from Reference (mm)

Fig3AFINAL .

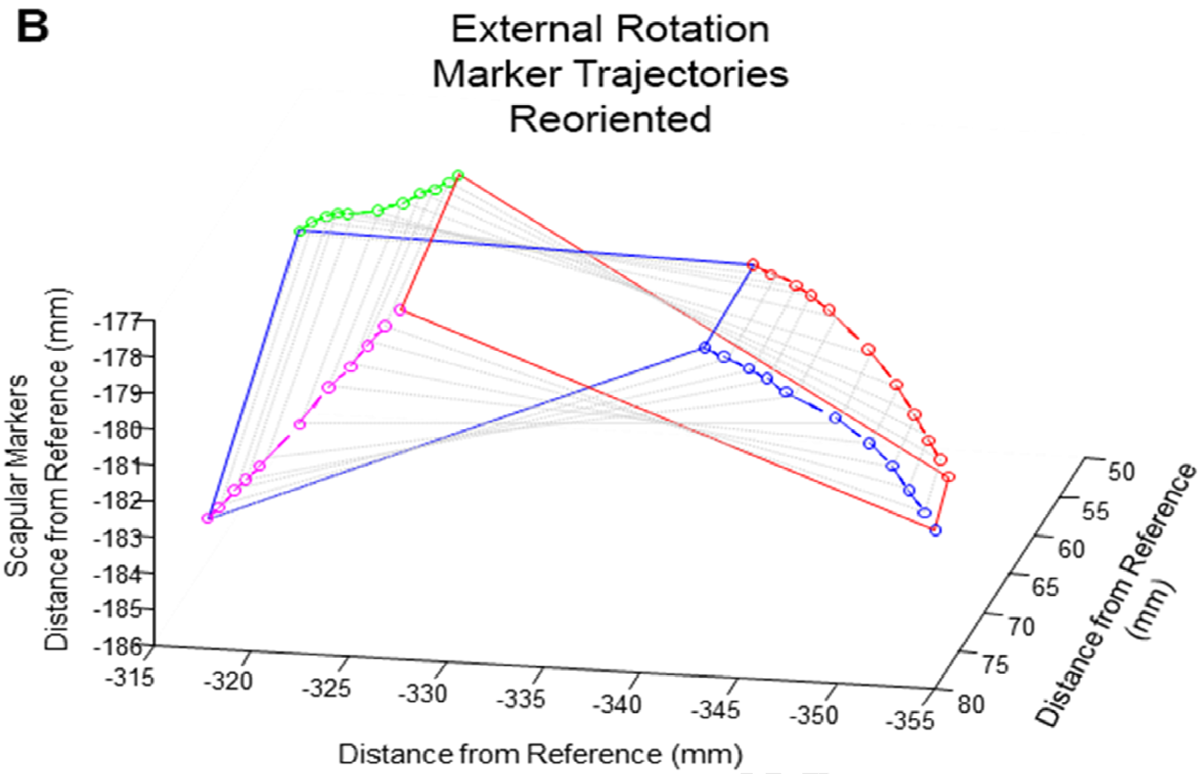
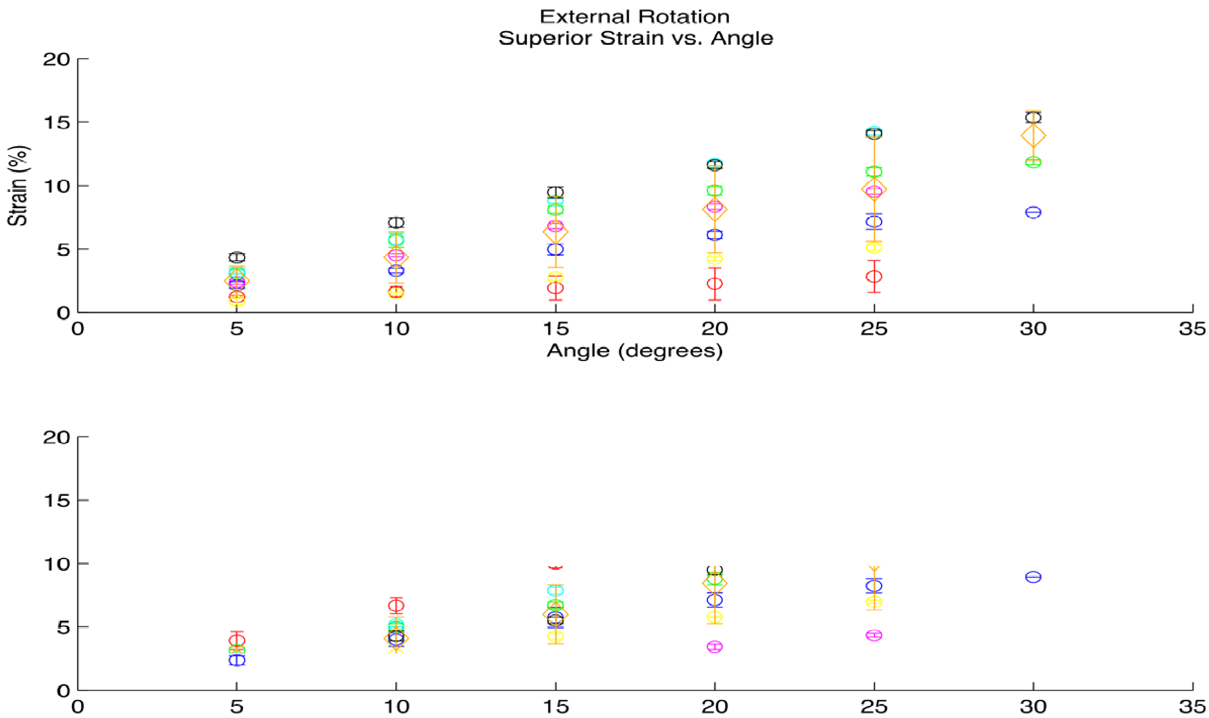

B
External Rotation
Marker Trajectories
Reoriented
Scapular Markers
Distance from Reference (mm)
-177
-178
-179
-180
-181
-182
-183
-184
-185
-186
-315
-320
-325
-330
-335
-340
-345
-350
-355
Distance from Reference (mm)
50
55
60
65
70
75
80
Distance from Reference (mm)

Fig3BFINAL .

A



External Rotation
Superior Strain vs. Angle
Strain (%)
Angle (degrees)

Fig4A, ER .

B

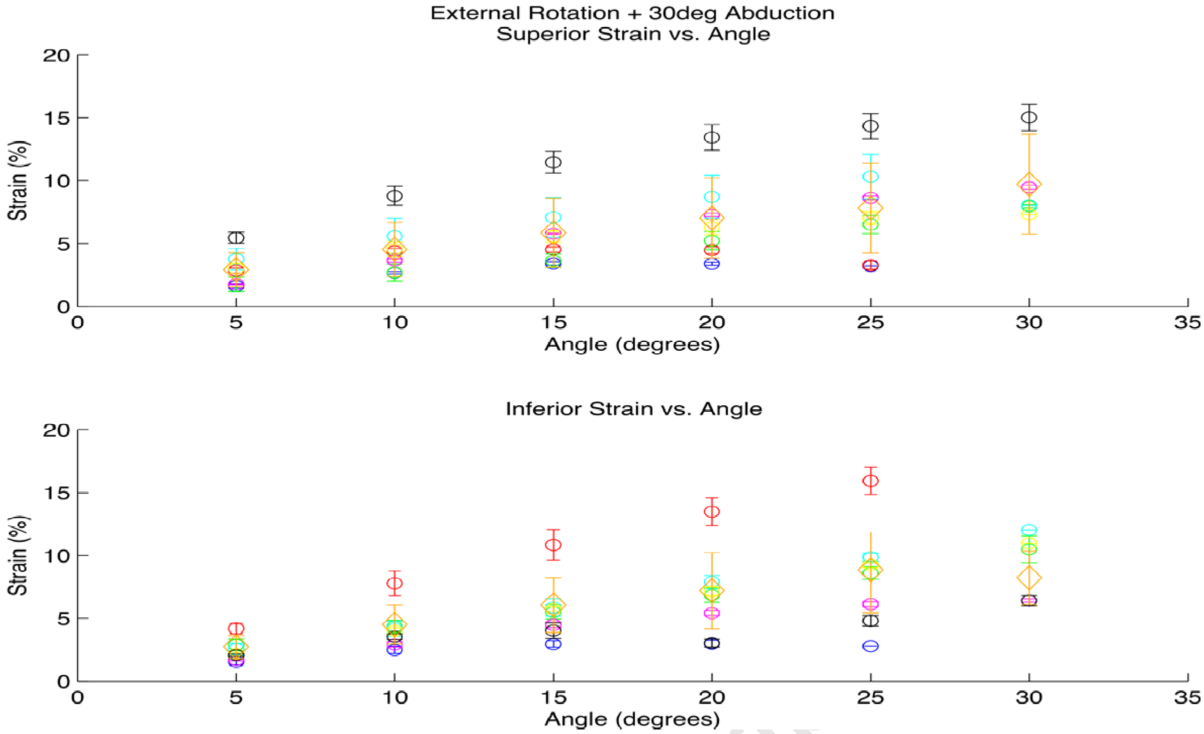

External Rotation + 30deg Abduction
Superior Strain vs. Angle
Strain (%)
Angle (degrees)
Inferior Strain vs. Angle
Strain (%)
Angle (degrees)

Fig4B, ER30 .

Fig4C Abd .

Fig4D SPAbd .