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A Biomechanical Analysis of Shoulder Muscle Excursions During Abduction, After the Treatment of Massive Irreparable Rotator Cuff Tears Using Superior Capsular Reconstruction (SCR), Bursal Acromial Reconstruction (BAR), and SCR with BAR

Michael Labib[1], Farid Amirouche[2,3], Sonia Pradhan[2], Aimee Bobko[2] and Jason Koh[3]

Abstract

Introduction: Current understanding of the biomechanical effects of treatment options for irreparable rotator cuff (RC) tears is lacking. This study examines how shoulder muscle lengths and excursions are affected by superior capsular reconstruction (SCR), bursal acromial reconstruction (BAR), and SCR with BAR, following a complete supraspinatus tear.
Method: Six fresh-frozen cadaveric shoulders were examined. Deltoid and RC muscle lengths were measured at 0, 30, 45, 60, and 90° of shoulder abduction under six conditions: (1) intact, (2) partially torn supraspinatus, (3) completely torn supraspinatus, (4) SCR, (5) SCR with BAR, and (6) BAR. Muscle excursions from 0–90° of abduction were then calculated.
Results: Subscapularis muscle lengths after SCR, BAR, and SCR with BAR were significantly greater (post-hoc Tukey HSD test; $p < .01$) compared to the other conditions. Supraspinatus, infraspinatus, teres minor, and deltoid lengths were not significantly different (ANOVA test; $p > .01$) between the conditions. All muscle excursions remained statistically similar between the conditions (ANOVA test; $p > .01$).
Conclusion: These findings demonstrate that the use of SCR, BAR, or SCR with BAR for a complete supraspinatus tear, may increase subscapularis muscle length while maintaining other shoulder muscle lengths. An increase in subscapularis length can allow for more effective subscapularis muscle strengthening and increased compensatory function in the long term. Additionally, all shoulder muscle excursions are preserved after partial or complete supraspinatus tears and after SCR, BAR, or SCR with BAR. Therefore, these surgical treatments can initially normalize shoulder muscle function during 0–90° of abduction, after an irreparable supraspinatus tear.

Keywords

rotator cuff injury, supraspinatus tear, superior capsular reconstruction, bursal acromial reconstruction, shoulder, muscle excursion, arthroplasty

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Introduction

The rotator cuff (RC) consists of the supraspinatus, infraspinatus, teres minor, and subscapularis muscles.[1] Abduction of the shoulder joint from 0–90° primarily involves the supraspinatus muscle controlling the initial 15° while the deltoid facilitates abduction from 15–90°.[1] The infraspinatus and teres minor are primarily external rotators, and the subscapularis is primarily an internal rotator of the

[1]Royal College of Surgeons in Ireland, Dublin, Ireland
[2]Department of Orthopaedics, University of Illinois, Chicago, IL, USA
[3]Department of Orthopaedics, NorthShore University HealthSystem, Evanston, IL, USA

Corresponding Author:
Farid Amirouche, Department of Orthopaedics, University of Illinois Chicago, E-190 Medical Sciences Building, MC 844, 835 S. Wolcott Avenue, Chicago, IL, USA.
Email: Amirouch@uic.edu

glenohumeral joint.[1,2] However, these muscles are also involved in stabilizing the joint and aid in abduction.[3,4]

The supraspinatus is the most commonly torn RC muscle.[5] Typically, a degenerative supraspinatus tear begins at the anterior insertion of the tendon then gradually extends posteriorly, resulting in a complete tear.[5] When a supraspinatus is completely torn, the other RC muscles maintain joint motion and stability,[2] while the deltoid becomes the primary shoulder abductor.[1]

Although conservative and surgical treatments for RC tears have significantly improved, 30% of all RC tears are categorized as massive and irreparable, posing an extreme challenge for surgeons.[6] Massive, irreparable RC tears are generally defined as RC lesions larger than 5 cm or tears encompassing two or more tendons.[7] Other factors affecting repairability include muscle fatty degeneration (Goutallier stage III–IV), muscle atrophy (greater than Thomazeau stage III), acromiohumeral distance less than 6–7 mm, and tendon retraction (Patte stage III or more). Treatment strategies for irreparable RC tears include physical therapy, debridement, partial repair, tendon transfer, reverse shoulder arthroplasty (RSA), superior capsular reconstruction (SCR), and bursal acromial reconstruction (BAR).[7,8] RSA is generally the most researched treatment strategy for irreparable tears[9] while superior capsular reconstruction (SCR) and bursal acromial reconstruction (BAR) are fairly new options. Although RSA has proven to provide appropriately indicated patients with good-excellent outcomes, some patient groups suffer from complications and less favourable outcomes.[10] SCR and BAR are both new and less invasive surgical alternatives for massive, irreparable RC tears that target specific patient groups.[10,11] SCR using allografts has become a favourable arthroscopic surgical technique for younger patients due to improved postoperative outcomes compared to other techniques.[2,12] It is limited to younger, symptomatic patients without moderate to severe rotator cuff arthropathy (Hamada classification type $\geq$3), nerve or deltoid dysfunction, glenohumeral osteoarthritis, and a torn or irreparable subscapularis.[10,13] BAR is a less expensive and challenging alternative to SCR and other RC tear surgical treatment options.[8] Compared to alternative approaches, it also provides patients with the advantage of a faster postoperative recovery.[8] The proposed indications for BAR are elderly patients (age $\geq$ 75 years) with painful, well-compensated, irreparable RCTs with minimal glenohumeral degenerative arthropathy.[8,11] However, one study described that younger patients with a preserved joint and pseudoparalysis can be indicated for SCR with a BAR. This provides them with the advantage of a potential head depressor effect due to the double thickness of graft material to a standard SCR.[11]

The importance of muscle length measurement for preoperative shoulder arthroplasty planning was previously described by Pitocchi et al. Automated methods with statistical shape models and computed tomography have been used to measure deltoid and RC muscles preoperation. Measuring muscle excursion during surgery and post-operation has also been discussed as a potential prognostic factor of muscle recovery after tendon injury.[14,15] Jeon et al. identified that eight weeks post-operation, muscle excursion recovers by 0.6% of the percentage of measured muscle excursion during tendon repair surgery.[14] In addition, Chung et al. found that maintenance of muscle excursion, eight weeks after tenotomy, was critical in protecting against muscle contracture.[15] Many studies have shown that a change in a muscle's excursion can also have a large effect on the amount of muscle force produced[16] and muscle excursion has also been identified as proportionate to serial sarcomere number.[17–19] Since SCR and BAR affect glenohumeral positioning,[11,20] identifying how they affect deltoid and RC muscle lengths and excursions is essential to understanding the different treatment options and optimizing patient recovery post-operation.

Biomechanical studies generally investigate the effects of irreparable RC tear treatment options on muscle moment arms and abduction forces.[2,21,22] However, there is a scarcity of research on the biomechanical effects of RC tears and newer treatment options. One study compared the excursion demands of the teres minor and infraspinatus muscles during abduction after a non-offset and offset reverse total shoulder arthroplasty.[23] In addition, Wagner et al described the importance of maximizing excursion during arthroscopically-assisted latissimus dorsi and lower trapezius transfer for RC tears.[24] However, there is no existing literature on the effects of an SCR and BAR for irreparable RC tears on deltoid and RC muscle excursion. This biomechanical study examines the change in excursions that the deltoid and RC muscles undergo following an SCR, BAR, and SCR with BAR, for a complete irreparable supraspinatus tear.

Materials and Methods

Specimen Preparation

Six fresh-frozen cadaveric shoulders were used for this study. The shoulders were thawed, and all overlying soft tissues were carefully removed. During dissection, the shoulders were visually examined to ensure they did not have any deformities, prior RC injury or surgeries, or presence of osteoarthritis. The joint capsule, coracoacromial ligament, four RC muscles and the tendinous heads of the pectoralis major, latissimus dorsi and three heads of the deltoid were preserved. Tendinous muscle insertions were secured using sutures. The medial two-thirds of the scapulae were fixed in a block of Plaster of Paris mold and mounted to a custom biomechanical experimental apparatus (Figure 1)

Experiment Setup

Nylon strings were attached to each muscle insertion site and passed through a pulley system with free-hanging weights on the other side of the apparatus (Figure 1). The loading protocol

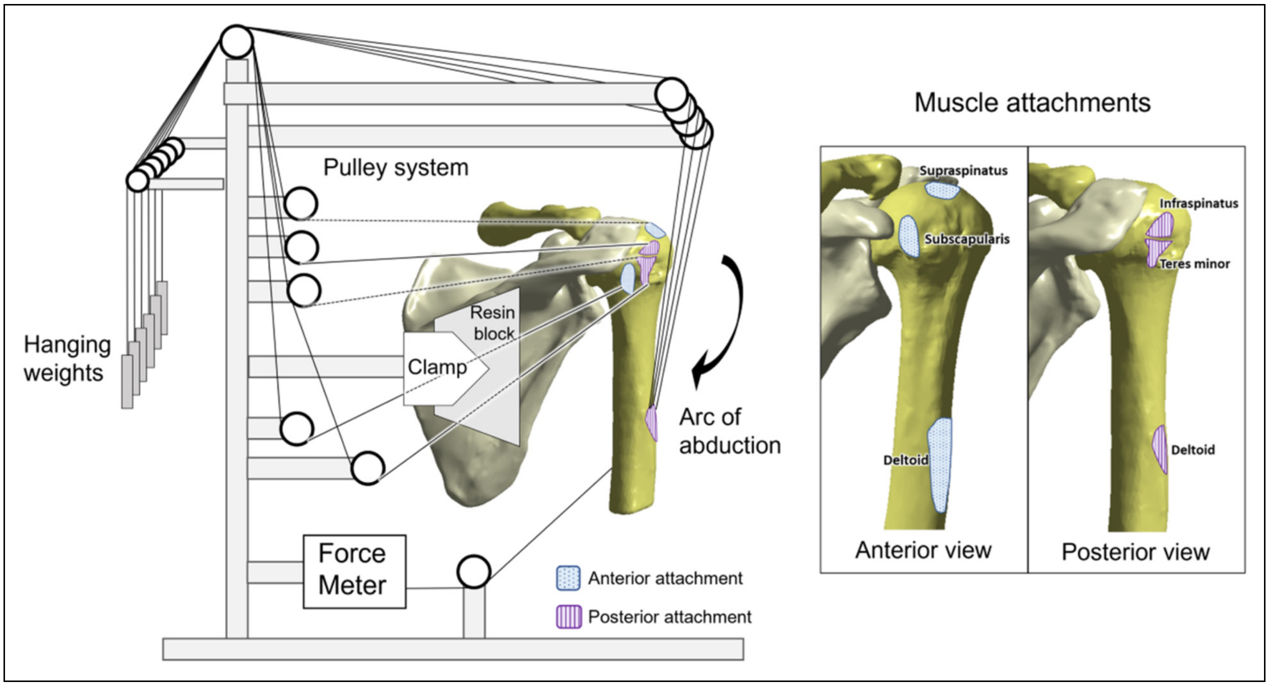

Figure 1. Shoulder experiment apparatus design along with Optotrak Certus placement. The deltoid and each of the four rotator cuff muscles have labeled attachment points. Static weights were employed in the pulley system to balance the glenohumeral joint during abduction.

used for the experimental frame was based on the recommendations of Mihata et al.: 5 N for teres minor, 5 N for infraspinatus, 10 N for pectoralis major, 10 N for latissimus dorsi, 10 N for supraspinatus, 10 N for subscapularis, and 40 N for the deltoid.[25,26] In addition, the deltoid was loaded with an additional 40 N before the abduction to create an abduction moment.

The frontal plane of the shoulder was motion captured during abduction using digitized points tracked, in 3-dimensional space, utilizing a 3-camera Optotrak Certus (Northern Digital Inc., 2006), two Orthopedic Research Pin markers, and First Principles software. The digital points tracked for this study were chosen on the origin and insertion of the deltoid and each of the four RC muscles. An additional digital point was added on the humerus to capture angular displacement when the shoulders were abducted. The placement of these points is shown in Figure 2. Each shoulder was then manually abducted in a breaking motion from 0° to 90° with holds at 30, 45, 60, and 90° under six different conditions: (1) intact RC, (2) partial supraspinatus tear, (3) complete supraspinatus tear, (4) SCR, (5) SCR + BAR, and (6) BAR only. The points that were digitized and tracked with Optotrak are mentioned in Table 1.

Excursion Calculation

The digital points tracked along the origin and insertion of each muscle were output as 3-dimensional coordinates in relation to specific markers. Muscle excursions were calculated for different combinations of muscle fibers for each muscle. The displacement formula $((x-x')^2+(y-y')^2+(z-z')^2)$ was used to get the length of each muscle as it travelled from 0° to 90° of abduction. The muscle trends may be positive, showing lengthening or negative, showing shortening. The trends may also be parabolic, increasing at lesser angles and stabilizing curves at higher grades. Although the supraspinatus was completely torn in some conditions, its length and excursion were assumed by measuring the distance from the fibers' origin and insertion sites. These measurements are not biomechanically nor clinically relevant for the following conditions: complete tear, SCR, SCR with BAR, and BAR.

Statistical Analysis

Deltoid and RC muscle data were imported into Microsoft Excel (version 2107) and Astasa (Vasavada, 2016). Mean muscle lengths were calculated at all abduction angles were calculated after each condition. Mean muscle excursions from 0–90°, were calculated for the muscles after each condition. Conditions were then compared using one-way ANOVA and post-hoc Tukey testing on mean muscle length and excursion values.

Results

Supraspinatus

BAR resulted in the highest mean supraspinatus muscle length (171.92 mm), followed by SCR with BAR (169.82 mm), SCR (166.62 mm), complete RC tear (149.64 mm), partial

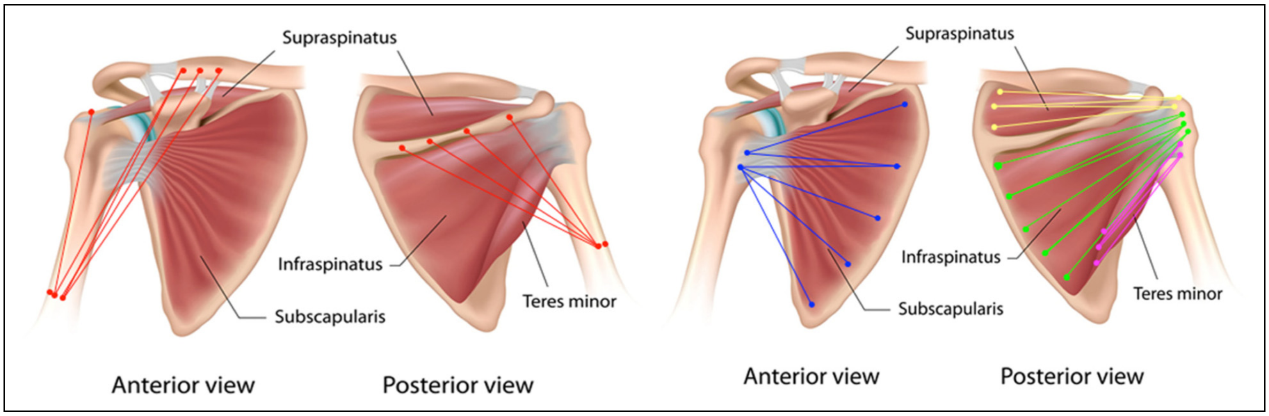

Figure 2. This figure identifies the digitized points tracked with Optotrak. Several points were digitized at the origin and insertion of each muscle. For the deltoid (red), eleven points were digitized (8 at origin and 3 at insertion). For the supraspinatus (yellow), five points have been digitized (3 at the origin and 2 at the insertion). For the infraspinatus (green), eight points were digitized (5 at the origin and 3 at the insertion). For the teres minor (pink), five points have been digitized (3 at the origin and 2 at the insertion). For the subscapularis (blue), seven points were digitized (5 at the origin and 2 at the insertion). These digitized points were used to track muscle measurements from 0°–90° of shoulder abduction. The vector lines between origin and insertion points show the muscle fibre bundle lines that were measured to calculate muscle lengths. For the larger muscles, vector lines have been drawn across fibre bundles to account for the crossover of fibres.

supraspinatus tear (148.63 mm), then lastly the intact RC (147.85 mm) (Table 2). However, these differences were not significantly different (ANOVA test; $p = .766$). The complete supraspinatus tear had the greatest muscle excursion, shortening by (−)107.61 mm from 0–90°, followed by the partial tear (−105.23 mm), intact RC (−94.55 mm), SCR (−93.22 mm), SCR with BAR (−85.24 mm), and finally BAR (−73.70 mm). The differences in muscle excursion between these conditions were not significant (ANOVA test; $p = .938$).

Infraspinatus

The complete supraspinatus tear resulted in the greatest mean infraspinatus muscle length (198.86 mm), followed by the partial tear (194.26 mm), intact RC (193.13 mm), SCR with BAR (187.00 mm), BAR (185.53 mm), and lastly SCR (181.37 mm) (Table 2). These differences were not significantly different (ANOVA test; $p = .0902$). The intact RC resulted in the longest mean muscle excursion (−21.71 mm) from 0–90° at −21.71 mm, followed by SCR (−20.37 mm), SCR with BAR (−15.75 mm), the partially torn RC (−11.11 mm), complete supraspinatus tear (−8.91 mm), and finally BAR (−0.46 mm). These differences were not significantly different (ANOVA test; $p = .989$).

Teres Minor

The complete supraspinatus tear resulted in the most significant mean teres minor length (172.10 mm), followed by the partial tear (170.34 mm), intact RC (169.24 mm), SCR + BAR (159.05 mm), SCR (158.44 mm) and finally BAR (149.76 mm) (Table 2). Differences between the mean teres minor lengths were not significant (Anova test; $p = .382$). All conditions displayed an upward trend in muscle length, over shoulder abduction until 60° (Figure 3). However, intact RC, partial RC tear, complete RC tear and SCR with BAR had a slight decline in mean muscle length from 60–90°. Mean muscle excursion was greatest after BAR (51.66 mm), followed by the complete tear (47.74 mm), SCR with BAR (43.35 mm), SCR (43.07 mm), the partially torn RC (41.49 mm) and the intact RC (31.23 mm). The differences between teres minor muscle excursions after the six conditions were not significant (Anova test; $p = .961$) (Table 3).

Subscapularis

The greatest average subscapularis muscle length was found after SCR with BAR (195.10 mm), followed by BAR (191.43 mm), SCR (188.46 mm), intact RC (134.86 mm), partial RC tear (132.61 mm), then complete RC tear (130.88 mm). The six conditions were identified as significantly different (ANOVA test; $p = 1.12 \times 10^{-09}$). SCR, BAR, and SCR with BAR had significantly different muscle lengths (post-hoc Tukey HSD test; $p < .01$) compared to the intact RC, partial RC tear, and complete supraspinatus tear, but not between themselves (Table 4). The complete supraspinatus tear resulted in the largest subscapularis excursion (41.85 mm), succeeded by SCR (37.19 mm), the intact RC (36.25 mm), the partially torn RC (33.55 mm), SCR with BAR (32.96 mm) and lastly BAR (31.76 mm). However, these conditions did not result in significantly different subscapularis muscle excursions (ANOVA test; $p = .999$) (Table 3).

Deltoid

A complete supraspinatus tear resulted in the highest mean deltoid muscle length (144.00 mm), succeeded by the partial tear (142.90 mm), intact RC (139.74 mm), SCR

Table 1. Muscle Fiber Combinations.

Muscle	Origin	Insertion	Fiber combinations
Supraspinatus	3 points O1, O2, O3 (ant. and post.)	2 points I1, I2 (ant. and post.)	Ant. • O1-I1 • O2-I1 Post. • O2-I2 • O3-I2
Subscapularis	5 points O1, O2, O3, O4, O5 (top to bottom)	2 points I1, I2 (diagonal)	Sup. • O1-I1 • O2-I1 Mid. • O2-I2 • O3-I2 Inf. • O4-I2 • O5-I2
Infraspinatus	5 points O1, O2, O3, O4, O5 (top to bottom)	3 points I1, I2, I3 (sup. To inf.)	Sup. • O1-I1 • O2-I1 Mid. • O2-I2 • O3-I2 • O4-I2 Inf. • O4-I3 • O5-I3
Teres minor	3 points O1, O2, O3 (top to bottom)	2 points I1, I2 (sup. To inf.)	Sup. • O1-I1 • O2-I1 Inf. • O2-I2 • O3-I2
Deltoid	5 points O1, O2, O3 (ant. del 3), O4 (mid deltoid 1), O5, O6, O7, O8 (post. Deltoid 4	3 points I1, I2, I3 (ant. and post.)	Ant. • O1-I1 • O2-I1 • O3-I1 Mid. • O3-I2 • O4-I2 Post. • O5-I3 • O6-I3 • O7-I3 • O8-I3
Center of humeral head (center of shoulder joint)	first point of subscapularis insertion	second point of supraspinatus insertion	(I-SUBSCAP + I-SUPRA)/2

Points at the origin and insertion of the deltoid and each rotator cuff muscles were digitized and tracked using Optotrak. The fiber combinations examined for each muscle were named based on origin and insertion points. Abbreviation: O, origin; I, insertion; Ant, anterior; Post, posterior; Sup, superior; Mid, middle; Inf, inferior.

(131.81 mm), BAR (128.28 m), and lastly, SCR with BAR (124.60 mm). However, the differences between the conditions were not significantly different (ANOVA test; $p = .573$) (Table 2). Generally, all the conditions had a downward trend in muscle length over shoulder abduction. However, the partial and complete supraspinatus tears had an increase in muscle length from 60–90° (Figure 3). From 0–90° of abduction, SCR with BAR had the biggest effect on mean muscle excursion (−67.74 mm), followed by SCR (−63.21 mm), BAR (−62.72 mm), the intact RC (−37.86 mm), the complete supraspinatus tear (−31.66 mm) and finally the partially torn RC (−26.84 mm). The differences in the deltoid muscle

Table 2. Mean Muscle Lengths and Anova Test p-Values in the six Experimental Conditions: Intact Supraspinatus, Partial Supraspinatus Tear, Complete Supraspinatus Tear, After Superior Capsular Reconstruction (SCR), After Bursal Acromial Reconstruction (BAR), and After SCR with BAR.

	Mean Muscle Lengths in mm (Standard Deviation)	ANOVA p-value for Muscle Length
Supraspinatus		
Intact	147.85 (75.47)	
Partial tear	148.63 (74.83)	$p = .766$
Complete tear	149.64 (77.09)	
SCR	166.62 (80.89)	
SCR + BAR	169.82 (68.01)	
BAR	171.92 (82.73)	
Infraspinatus		
Intact	193.13 (83.14)	
Partial tear	194.26 (75.22)	$p = .0902$
Complete tear	198.86 (78.72)	
SCR	181.37(79.06)	
SCR + BAR	187.00 (73.80)	
BAR	185.55(83.59)	
Teres Minor		
Intact	169.23 (101.64)	
Partial tear	170.34 (96.31)	$p = .382$
Complete tear	172.10 (98.52)	
SCR	158.44 (67.93)	
SCR + BAR	159.05 (66.32)	
BAR	149.76 (72.56)	
Subscapularis		
Intact	134.87 (35.72)	
Partial tear	132.61 (34.70)	$p < .01$ ($p = 1.12 \times 10^{-09}$)
Complete tear	130.88 (35.78)	
SCR	188.46 (57.68)	
SCR + BAR	195.10 (57.80)	
BAR	191.43 (64.44)	
Deltoid		
Intact	139.74 (43.24)	
Partial tear	142.90 (42.04)	$p = .573$
Complete tear	144.00 (41.70)	
SCR	131.81 (34.25)	
SCR + BAR	124.60 (32.70)	
BAR	128.28 (37.46)	

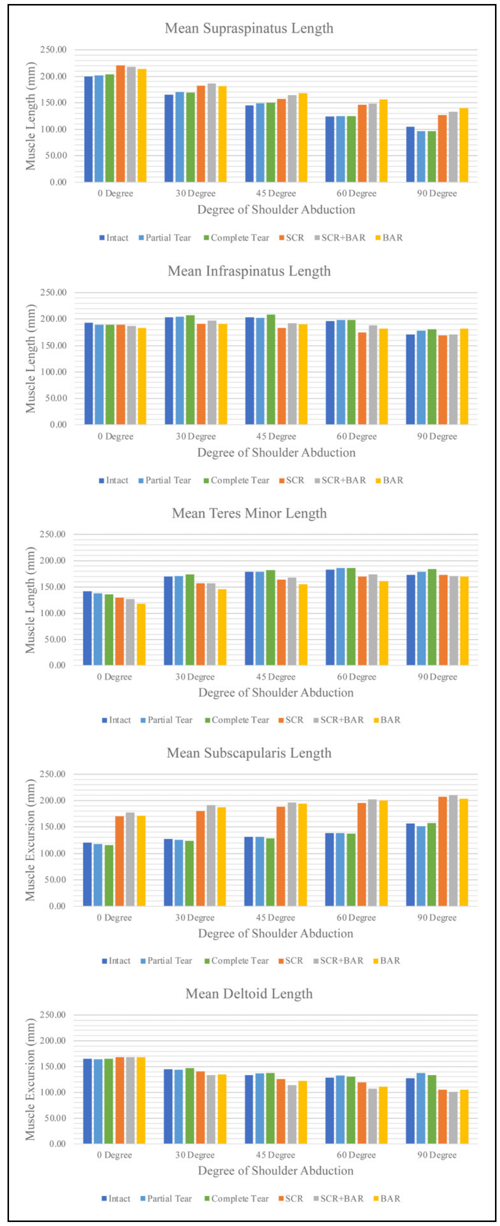

Figure 3. Mean muscle lengths of supraspinatus, infraspinatus, teres minor, subscapularis, and deltoid at 0, 30, 45, 60, and 90°.

excursions caused by the different conditions were not significant (ANOVA test; $p = .108$) (Table 3).

Discussion

This study examined the effect of SCR, BAR, and SCR with BAR on shoulder muscle lengths and excursions during glenohumeral abduction from 0–90°. Our findings indicate that the use of SCR, BAR, or SCR with BAR may increase subscapularis muscle length during shoulder abduction. Our results also suggest deltoid and RC muscle lengths during abduction can remain statistically similar to an intact RC after a partial or complete supraspinatus tear. Moreover, our findings show that deltoid and RC muscle excursions remain statistically similar when the supraspinatus is intact, partially torn, completely torn, or after SCR, SCR with BAR, and BAR. Dolan et al revealed similar results when identifying that after a complete supraspinatus tear, RC muscles may produce moment arms statistically indistinguishable from that of an intact RC.[27]

The use of SCR, BAR, and SCR with BAR showed no significant differences in deltoid, supraspinatus, infraspinatus, and

Table 3. Mean Muscle Excursions from 0°–90° and Anova Test *p*-Values in the six Experimental Conditions: Intact Supraspinatus, Partial Supraspinatus Tear, Complete Supraspinatus Tear, After Superior Capsular Reconstruction (SCR), After Bursal Acromial Reconstruction (BAR), and After SCR with BAR.

	Mean Muscle Excursions from 0°–90° in mm (Standard Deviation)	ANOVA *p*-value for Muscle Excursion
Supraspinatus		
Intact	−94.56 (76.96)	
Partial tear	−105.30 (77.85)	$p = .938$
Complete tear	−107.62 (82.16)	
SCR	−93.22 (28.61)	
SCR + BAR	−85.24 (34.06)	
BAR	−73.69 (51.57)	
Infraspinatus		
Intact	−21.71 (49.86)	
Partial tear	−11.11 (51.90)	$p = .989$
Complete tear	−8.91 (43.47)	
SCR	−20.37 (76.91)	
SCR + BAR	−15.75 (66.09)	
BAR	−0.46 (51.42)	
Teres Minor		
Intact	31.23 (38.32)	
Partial tear	41.49 (32.80)	$p = .961$
Complete tear	47.74 (28.64)	
SCR	43.07 (45.28)	
SCR + BAR	43.35 (43.63)	
BAR	51.66 (36.94)	
Subscapularis		
Intact	36.25 (19.71)	
Partial tear	33.55 (20.45)	$p = .999$
Complete tear	41.85 (38.15)	
SCR	37.19 (59.62)	
SCR + BAR	32.96 (58.35)	
BAR	31.76 (46.99)	
Deltoid		
Intact	−37.86 (28.03)	
Partial tear	−26.84 (21.56)	$p = .108$
Complete tear	−31.66 (28.83)	
SCR	−63.21 (42.13)	
SCR + BAR	−67.74 (35.04)	
BAR	−62.72 (29.76)	

Table 4. Post-hoc Tukey Testing was Performed for Subscapularis Muscle Lengths Only Since ANOVA did not Identify a Significant Difference Between all six Conditions, in the Other Muscles.

	Post-hoc Tukey HSD test *p*-values at 95% confidence
Subscapularis	
Intact versus Partial tear	.900
Intact versus Complete tear	.900
Intact versus SCR	.001
Intact versus SCR + BAR	.001
Intact versus BAR	.001
Partial tear versus Complete tear	.900
Partial tear versus SCR	.001
Partial tear versus SCR + BAR	.001
Partial tear versus BAR	.001
Complete tear versus SCR	.001
Complete tear versus SCR + BAR	.001
Complete tear versus BAR	.001
SCR versus SCR + BAR	.900
SCR versus BAR	.900
SCR + BAR versus BAR	.900

For example, there were no significant differences between SCR, BAR, and SCR with BAR, but all three conditions had substantial differences compared to intact, partial torn, and completely torn models.

teres minor muscle lengths during glenohumeral abduction. However, all three procedures resulted in significantly longer subscapularis muscle lengths during abduction than the intact, partially torn, and completely torn RCs. This finding is expected for SCR, given that the graft is stitched to the subscapularis. However, the graft is also sutured to the infraspinatus which did not significantly increase in length. This may also indicate that SCR increased the potential subscapularis compensatory function of shoulder abduction after a complete supraspinatus tear. BAR generally requires well-compensated shoulder function to be shown.[8] Given the anatomy of the BAR technique, the increase in subscapularis length was not anticipated. Mean subscapularis muscle length after BAR was also greater than that after SCR, but this difference was not statistically significant. Furthermore, the use of SCR with BAR was expected to result in an increased subscapularis muscle length, again because of the attachment of the SCR graft to the subscapularis. SCR with BAR resulted in a greater subscapularis muscle length than both BAR and SCR. However, the differences were again insignificant. It was also not anticipated that SCR, BAR, and SCR with BAR did not result in significantly different muscle excursions, given the significant increase in subscapularis muscle length they caused. Therefore, our findings indicate that SCR, BAR, and SCR with BAR significantly increase subscapularis muscle length, allowing for more efficacious subscapularis muscle strengthening and eventually increased subscapularis muscle compensatory function during abduction. However, directly after surgery, stabilizing and abduction function normally provided by the shoulder muscles, in the intact RC, is preserved.

Ward et al previously described that increasing RC muscle lengths may also allow for more efficacious muscle strengthening.[1] Thus, it can be implied that patients undergoing physical therapy and muscle strengthening after SCR, SCR with BAR, and BAR, may even experience increased compensatory abduction function by the subscapularis. Longitudinal muscle lengthening has also been shown to improve muscle power generating capacity in patients with reduced muscle extensibility.[28] Subscapularis repair is recommended for patients with irreparable RC tears, treated with reverse shoulder arthroplasty (RSA), due to shoulder muscle stiffness pre-and-post-operation.[29] Although subscapularis preservation or repair are also recommended for SCR and BAR, patients generally don't experience post-operative shoulder instability and muscle stiffness.[2,8] This may be explained by the significant increase in subscapularis length resulted by SCR, BAR, and SCR with BAR, which would provide patients with the ability to increase compensatory function and stability provided by the subscapularis.[8,11,20,30,31] Moreover, Halder et al. discussed the importance of the subscapularis in providing a depressor effect for dynamic stability;[32] thus, an increase in subscapularis muscle strength would also increase shoulder stability. This would suggest that SCR, BAR, and SCR with BAR may also increase dynamic shoulder stability by expanding the depressor function of the subscapularis. Future studies should further examine the effects of other surgical alternatives on shoulder muscle compensatory function and stability.

This study aimed to demonstrate the effects of SCR, BAR, and SCR with BAR on shoulder muscle lengths and excursions during abduction. This was examined to identify how treatment options affect shoulder muscle functionality after a complete supraspinatus tear. Our study did have several limitations, many of which are inherent to biomechanical cadaveric investigations. Firstly, McClure et al. demonstrated that the scapula is rotated upwards, posteriorly tilted, and externally rotated during abduction.[33] Therefore, our study was limited by the experimental apparatus, which held the scapula in a static position. Moreover, to control independent variables and improve reproducibility, our measurements were limited by static loading conditions used in accordance with previous biomechanical literature by Mihata et al.[13,25,26] and Williamson et al.[34] Measurement of muscle lengths and excursions was limited by defined vector lines of assumed force direction from muscle origins and insertions. In vivo, these forces are much more complex. As with all biomechanical studies, we were also limited to investigating the effects of the supraspinatus tears at time-zero, where no compensatory mechanisms or healing would have occurred. Furthermore, our findings are limited to massive tears of the supraspinatus while most tears classified as massive and irreparable involve multiple RC tendons.[35,36] Finally, our study was also limited by the small number of cadaveric shoulders examined. Although our results indicated some significant differences in subscapularis length and no significant differences in excursions between the six conditions, future studies should examine a larger sample size.

Conclusion

In conclusion, this study reveals that shoulder muscle lengths and excursions are maintained after a partial or complete supraspinatus tear. In addition, SCR, BAR, and SCR with BAR may increase subscapularis muscle length, thus providing patients with the potential to increase subscapularis compensatory function through more effective muscle strengthening. However, they retain deltoid and RC muscle excursions during 0–90° of shoulder abduction so immediate shoulder muscle stabilization and functionality is maintained statistically similar to the intact RC. Future research should confirm these findings in a clinical setting and explore the effect of these surgical techniques on muscle function, in vivo, over time.

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Declaration of Conflicting Interests

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Ethical Approval

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ORCID iD

Michael Labib https://orcid.org/0000-0001-7405-1474

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References

1. Ward SR, Hentzen ER, Smallwood LH, et al. Rotator cuff muscle architecture: implications for glenohumeral stability. *Clin Orthop Relat Res.* 2006;448:157–163.
2. Parsons IM, IV, Apreleva M, Fu FH, et al. The effect of rotator cuff tears on reaction forces at the glenohumeral joint. *J Orthop Res.* 2002;20(3):439–446. DOI: 10.1016/S0736-0266(01)00137-1.

3. Gasbarro G, Bondow B, Debski R. Clinical anatomy and stabilizers of the glenohumeral joint. *Ann Joint.* 2017;2(10).
4. Phadke V, Camargo P, Ludewig P. Scapular and rotator cuff muscle activity during arm elevation: a review of normal function and alterations with shoulder impingement. *Rev Bras Fisioter.* 2009;13(1):1–9. DOI: 10.1590/s1413-35552009005000012.
5. Kim HM, Dahiya N, Teefey SA, et al. Location and initiation of degenerative rotator cuff tears: an analysis of three hundred and sixty shoulders. *J Bone Joint Surg Am.* 2010;92(5):1088–1096. DOI: 10.2106/JBJS.I.00686.
6. Oh JH, Park MS, Rhee SM. Treatment strategy for irreparable rotator cuff tears. *Clin Orthop Surg.* 2018;10(2):119–134.
7. Kovacevic D, Suriani RJ, Jr., Grawe BM, et al. Management of irreparable massive rotator cuff tears: a systematic review and meta-analysis of patient-reported outcomes, reoperation rates, and treatment response. *J Shoulder Elbow Surg.* 2020;29(12):2459–2475. DOI: 10.1016/j.jse.2020.07.030.
8. Curtis DM, Pullen WM, Helenius K, et al. The evolution and role of the bursal acromial reconstruction. *Video J Sports Med.* 2021;1(2):26350254211001367. DOI: 10.1177/26350254211001367.
9. Dickerson P, Pill SG, Longstaffe R, et al. Systematic review of reversing pseudoparalysis of the shoulder due to massive, irreparable rotator cuff tears. *J Shoulder Elbow Surg.* 2020;29(7, Supplement):S87–S91. DOI: 10.1016/j.jse.2020.04.039.
10. Frank RM, Cvetanovich G, Savin D, et al. Superior capsular reconstruction: indications, techniques, and clinical outcomes. *JBJS Rev.* 2018;6(7):e10.
11. Ravenscroft M, Barnes MW, Muench LN, et al. Bursal acromial reconstruction (BAR) using an acellular dermal allograft as a surgical solution for the treatment of massive irreparable rotator cuff tears. *Arthrosc Tech.* 2021;10(3):e877–e885. DOI: 10.1016/j.eats.2020.11.002.
12. Tokish JM, Makovicka JL. The superior capsular reconstruction: lessons learned and future directions. *JAAOS – J Am Acad Orthop Surg.* 2020;28(13):528–537.
13. Mihata T, Lee TQ, Watanabe C, et al. Clinical results of arthroscopic superior capsule reconstruction for irreparable rotator cuff tears. *Arthroscopy.* 2013;29(3):459–470. DOI: 10.1016/j.arthro.2012.10.022.
14. Jeon SH, Chung MS, Baek GH, et al. The effect of muscle excursion on muscle recovery after tendon repair in a neglected tendon injury: a study in rabbit soleus muscles. *J Orthop Res.* 2011;29(1):74–78. DOI: 10.1002/jor.21212.
15. Chung MS, Baek GH, Oh JH, et al. The effect of muscle length and excursion on muscle contracture after tendon injury: a study in rabbit soleus muscles. *Injury.* 2007;38(10):1139–1145. DOI: 10.1016/j.injury.2007.05.008.
16. Arnold EM, Hamner SR, Seth A, et al. How muscle fiber lengths and velocities affect muscle force generation as humans walk and run at different speeds. *J Exp Biol.* 2013;216(Pt 11):2150–2160. DOI: 10.1242/jeb.075697.
17. Winters TM, Takahashi M, Lieber RL, et al. Whole muscle length-tension relationships are accurately modeled as scaled sarcomeres in rabbit hindlimb muscles. *J Biomech.* 2011;44(1):109–115. DOI: 10.1016/j.jbiomech.2010.08.033.
18. Takahashi M, Ward SR, Fridén J, et al. Muscle excursion does not correlate with increased serial sarcomere number after muscle adaptation to stretched tendon transfer. *J Orthop Res.* 2012;30(11):1774–1780. DOI: 10.1002/jor.22137.
19. Koh TJ, Herzog W. Excursion is important in regulating sarcomere number in the growing rabbit tibialis anterior. *J Physiol.* 1998;508 (Pt 1):267–280. DOI: 10.1111/j.1469-7793.1998.267br.x.
20. Hirahara AM, Adams CR. Arthroscopic superior capsular reconstruction for treatment of massive irreparable rotator cuff tears. *Arthrosc Tech.* 2015;4(6):e637–e641. DOI: 10.1016/j.eats.2015.07.006.
21. Rybalko D, Bobko A, Amirouche F, et al. Biomechanical effects of superior capsular reconstruction in a rotator cuff–deficient shoulder: a cadaveric study. *J Shoulder Elbow Surg.* 2020;29(10):1959–1966. DOI: 10.1016/j.jse.2020.03.007.
22. Walker DR, Struk AM, Matsuki K, et al. How do deltoid muscle moment arms change after reverse total shoulder arthroplasty? *J Shoulder Elbow Surg.* 2016;25(4):581–588. DOI: 10.1016/j.jse.2015.09.015.
23. Onstot BR, Jacofsky MC, Hansen ML. Muscle force and excursion requirements and moment arm analysis of a posterior-superior offset reverse total shoulder prosthesis. *Bull Hosp Jt Dis.* 2013;71(Suppl 2): S25–S30.
24. Wagner ER, Woodmass JM, Welp KM, et al. Novel arthroscopic tendon transfers for posterosuperior rotator cuff tears: latissimus dorsi and lower trapezius transfers. *JBJS Essent Surg Tech.* 2018;8(2):e12–e12. DOI: 10.2106/JBJS.ST.17.00062.
25. Mihata T, Bui CN, Akeda M, et al. A biomechanical cadaveric study comparing superior capsule reconstruction using fascia lata allograft with human dermal allograft for irreparable rotator cuff tear. *J Shoulder Elbow Surg.* 2017;26(12):2158–2166.
26. Mihata T, McGarry MH, Pirolo JM, et al. Superior capsule reconstruction to restore superior stability in irreparable rotator cuff tears: a biomechanical cadaveric study. *Am J Sports Med.* 2012;40(10):2248–2255.
27. Dolan MT, Patetta MJ, Pradhan S, et al. Evaluation of rotator cuff abduction moment arms for superior capsular reconstruction and reverse total shoulder arthroplasty. *Int Orthop.* 2021;45(7):1767–1774. DOI: 10.1007/s00264-021-05066-6.
28. Kruse A, Rivares C, Weide G, et al. Stimuli for adaptations in muscle length and the length range of active force exertion-A narrative review. *Front Physiol.* 2021;12:742034–742034. DOI: 10.3389/fphys.2021.742034.
29. Linderman SE, Johnson JE, Anderson DD, et al. Influence of subscapularis stiffness with glenosphere lateralization on physiological external rotation limits after reverse shoulder arthroplasty. *J Shoulder Elbow Surg.* 2021;30(11):2629–2637. DOI: 10.1016/j.jse.2021.04.039.
30. Noyes MP, Denard PJ. Arthroscopic superior capsular reconstruction: indications and outcomes. *Oper Tech Sports Med.* 2018;26(1):29–34. DOI: 10.1053/j.otsm.2017.10.005.
31. Pennington WT, Bartz BA, Pauli JM, et al. Arthroscopic superior capsular reconstruction with acellular dermal allograft for the treatment of massive irreparable rotator cuff tears: short-term clinical outcomes and the radiographic parameter of superior capsular distance. *Arthroscopy.* 2018;34(6):1764–1773. DOI: 10.1016/j.arthro.2018.01.009.

32. Halder AM, Zhao KD, Odriscoll SW, et al. Dynamic contributions to superior shoulder stability. *J Orthop Res.* 2001;19(2):206–212. DOI: 10.1016/s0736-0266(00)00028-0.
33. McClure PW, Michener LA, Sennett BJ, et al. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *J Shoulder Elbow Surg.* 2001;10(3):269–277. DOI: 10.1067/mse.2001.112954.
34. Williamson P, Mohamadi A, Ramappa AJ, et al. Shoulder biomechanics of RC repair and instability: a systematic review of cadaveric methodology. *J Biomech.* 2019;82:280–290. DOI: 10.1016/j.jbiomech.2018.11.005.
35. Greenspoon JA, Petri M, Warth RJ, et al. Massive rotator cuff tears: pathomechanics, current treatment options, and clinical outcomes. *J Shoulder Elbow Surg.* 2015;24(9):1493–1505. DOI: 10.1016/j.jse.2015.04.005.
36. Bedi A, Dines J, Warren RF, et al. Massive tears of the rotator cuff. *J Bone Joint Surg Am.* 2010;92(9):1894–1908. DOI: 10.2106/jbjs.I.01531.