

Infraspinatus Muscle Fiber Moment Arms During Abduction

A Biomechanical Comparison of Values for Intact Rotator Cuff, Supraspinatus Tear, Superior Capsular Reconstruction, and Reverse Total Shoulder Arthroplasty

Diego M. Barragan Echenique,* MD, Martine T. Dolan,*[†] BS, Jason L. Koh,^{‡§} MD, Benjamin A. Goldberg,* MD, and Farid Amirouche,*[‡] PhD

Investigation performed at the University of Illinois Hospital & Health Sciences System, Chicago, Illinois, USA

Background: Lines of action of the superior, middle, and inferior infraspinatus muscle fibers work together to produce moment arms that change throughout abduction in an intact shoulder, after a supraspinatus tear, and after superior capsular reconstruction (SCR) and reverse total shoulder arthroplasty (rTSA).

Purpose: To use moment arm values to indicate the efficacy of SCR and rTSA to restore infraspinatus function during shoulder abduction.

Study Design: Descriptive laboratory study.

Methods: A total of 5 human cadaveric shoulders placed in a testing apparatus were each actively abducted (0°-90°) under the following 4 conditions: intact, complete supraspinatus tear, SCR, and rTSA. The 3-dimensional coordinates of points were tracked along the origin and insertion of the superior, middle, and inferior infraspinatus fibers during abduction. Moment arm values were calculated using the origin-insertion method to determine abduction contribution of infraspinatus fiber sections. Analysis of variance and post hoc Tukey testing were used to compare differences in moment arms between the 4 conditions and between fiber sections.

Results: In the intact condition, the superior infraspinatus fibers had an abduction moment that decreased with elevation until shifting to adduction. Conversely, the middle and inferior fibers had an adduction moment that turned to abduction (mean moment arm values from 0° to 90°: inferior, from -5.9 to 19.4 mm; middle, from -4.7 to 15.9 mm; superior, from 5.6 to -5.1 mm; $P < .05$). After a supraspinatus tear, superior fibers lacked any torque, and inferior and middle fibers lost adduction potential (inferior, from 4.8 to 14.0 mm; middle, from -0.2 to 9.6 mm; superior, from 1.0 to 0.7 mm; $P < .05$). SCR restored the initial superior fiber abduction moment (5.6 mm at 0°; $P < .05$); middle and inferior fibers had some restoration but were weaker than intact fibers. Loss of abduction moment in all fibers was seen with rTSA (inferior, from -9.6 to -1.6 mm; middle, from -10.5 to -3.6 mm; superior, from -1.7 to -4.6 mm; $P < .05$).

Conclusion: Infraspinatus fiber groups had different and inverse moment arms during scapular plane elevation. SCR most closely resembled the intact shoulder, whereas rTSA transformed the infraspinatus into an adductor.

Clinical Relevance: These results support the efficacy of SCR at restoring biomechanical muscle function and suggest that the changes in moment arms for each fiber group be considered when choosing treatment modalities and rehabilitation protocols after rotator cuff tear.

Keywords: rotator cuff; infraspinatus; reverse total shoulder arthroplasty; supraspinatus tear; superior capsular reconstruction; moment arm; muscle fibers

The rotator cuff (RC) is formed by the subscapularis, supraspinatus, infraspinatus, and teres minor muscles and their tendinous attachments, all of which help to provide dynamic stability and create rotational movement at the glenohumeral joint.⁸

The insertion of a muscle relative to its origin determines the direction of the force vector and thus the action of the muscle force and power during contraction. The infraspinatus muscle is primarily an external rotator of the shoulder and compresses the glenohumeral joint. Yet biomechanical and anatomic studies have suggested that the infraspinatus muscle also can function as a shoulder abductor and humeral elevator in the scapular plane, particularly when the arm is internally rotated.^{11,19} Kato et al¹¹ noted that the infraspinatus muscle is composed of a distinct transverse portion located directly underneath the scapular spine and a distinct oblique region located caudally to that region. Kato et al further concluded that due to their location and innervation, the transverse fibers of the infraspinatus muscle were likely to be closely associated with those of the supraspinatus muscle. This region of the infraspinatus may become even more vital for shoulder abduction when a supraspinatus tear occurs.¹¹ Additionally, other cadaveric studies and studies using electromyography have illustrated 3 distinct subregions within the infraspinatus that are innervated differently, thus allowing independent activation to produce coordinated rotational action at the glenohumeral joint.^{3,7,13}

The current surgical solutions for irreparable RC tears include either superior capsular reconstruction (SCR) or reverse total shoulder arthroplasty (rTSA). SCR involves placing a graft into the cuff defect and provides a superior constraint on the glenohumeral joint.^{17,23} This results in more stabilization of the joint, allowing the other muscles to function more effectively.¹⁶

In the current study, we used moment arm values to indicate the efficacy with which different RC tear treatments restore anatomic shoulder function during abduction. Additionally, we built on previous research to determine how infraspinatus fiber bundles contribute to resulting muscle function. The purpose of this study was to determine (1) how lines of action of the superior, middle, and inferior muscle fibers of the infraspinatus work together to produce abduction moment arms and (2) how the moment arms produced by these fibers change along the abduction arc in an intact shoulder, after a supraspinatus tear, and after reconstruction with SCR and rTSA. We hypothesized that the superior, middle, and inferior muscle fibers of the infraspinatus would have different moment arms and that these values would change after RC tear and repair through SCR and rTSA.

METHODS

Cadaver Preparation

A total of 5 frozen human cadaveric shoulders were purchased by our institution; they were thawed and screened to ensure the absence of osteoarthritis, deformities, prior trauma, or surgery. The shoulders then underwent careful dissection to remove soft tissue. The capsule and 4 RC muscles, coracoacromial ligament, and tendinous insertions of the deltoid, latissimus dorsi, and pectoralis major were preserved. All tendinous insertions of the muscles were secured using sutures before stabilizing the medial aspect of the scapula in a plaster of paris mold while allowing exposure of the lateral third.

Experimental Apparatus

The scapula was fixed in an experimental apparatus that permitted some adjustment of the fixed scapula to different angles to facilitate higher degrees of shoulder abduction. The machine device was designed and weighted according to the protocol described by Mihata et al^{14,17} and as used in other similar cadaveric studies.^{6,21,22} This experimental frame allowed the glenohumeral joint to be stabilized through force applied to the insertion sites of the muscles. The tendon attachments were connected to a pulley system and attached to free-hanging weights exerting the force vectors depicted in Figure 1. The deltoid was loaded with a force of 40 N. The latissimus dorsi, pectoralis, subscapularis, and supraspinatus were loaded with 10 N each, and the teres minor and infraspinatus were loaded with 5 N each per the loading protocol described by Mihata et al.^{14,17} No force was placed on the biceps muscle. To observe proximal migration of the humeral head, only muscles that inserted on the humeral head or shaft were loaded.

Testing Models

Each shoulder was sequentially tested under 4 different conditions: intact anatomy, irreparable supraspinatus tear, SCR, and rTSA.

To produce an irreparable supraspinatus tear, an incision was made along the entirety of the supraspinatus tendon insertion at the humerus under direct visualization to avoid transecting any fibers other than those of the supraspinatus tendon. SCR was performed with a 2- to 4-mm thick

[†]Address correspondence to Martine T. Dolan, BS, Department of Orthopaedics, University of Illinois at Chicago, 835 S Wolcott Avenue, E270 MSS MC 844, Chicago, IL 60612, USA (email: dolan8@uic.edu).

^{*}Department of Orthopaedic Surgery, University of Illinois, Chicago, Illinois, USA.

[‡]Orthopaedic and Spine Institute, Department of Orthopaedic Surgery, Northshore University HealthSystem, an Affiliate of University of Chicago Pritzker School of Medicine, Evanston, Illinois, USA.

[§]Department of Orthopaedics, Shoulder and Elbow Surgery, University of Chicago, Chicago, Illinois, USA.

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Ethical approval was not sought for the present study.

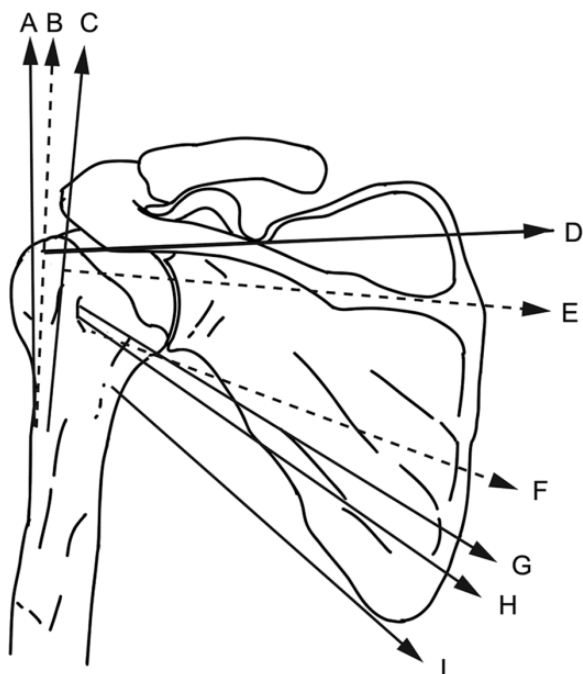


Figure 1. Force vectors acting on the shoulder to stabilize it in a neutral position. The lines depict the orientation of the strings attached to the insertion points of different muscles that act on the shoulder. The lines are labelled to represent the forces exerted by different muscles as follows: A, anterior deltoid; B, middle deltoid; C, posterior deltoid; D, supraspinatus; E, pectoralis major; F, subscapularis; G, infraspinatus; H, teres minor; and I, latissimus dorsi.

ArthroFLEX acellular dermal allograft (Arthrex). The graft was secured to both the infraspinatus and the subscapularis with 2 side-to-side interrupted stitches on both the anterior and posterior portions of the graft. Suture anchors were used to attach the graft to the glenoid and coracoid process. Subsequently, the graft was attached laterally to the greater tuberosity using suture anchors. Afterward, the allograft was removed, and the glenoid and humerus were prepared for rTSA. The Aequalis Ascend system (Tornier) was used to implant a short stem with a 132° neck-shaft angle and a 12.5° reversed insert, producing a 145° neck-shaft angle. A 36 + 0 mm glenosphere was used with a size 25 glenoid baseplate component, and the stem was placed at 10° of retroversion.

Data Collection and Moment Arm Calculation

The 3-camera Optotrak Certus (Northern Digital) was used with First Principles software (Version 1.2.4; Northern Digital) to motion capture the anterior plane of each shoulder during abduction along the scapular plane. The Optotrak tracks 3-dimensional points over time and determines the coordinates. Before each shoulder was abducted, we chose digital marking points to be tracked by the Optotrak. These included 6 points evenly spread along the origin of infraspinatus at the scapula and 3 points evenly spread along

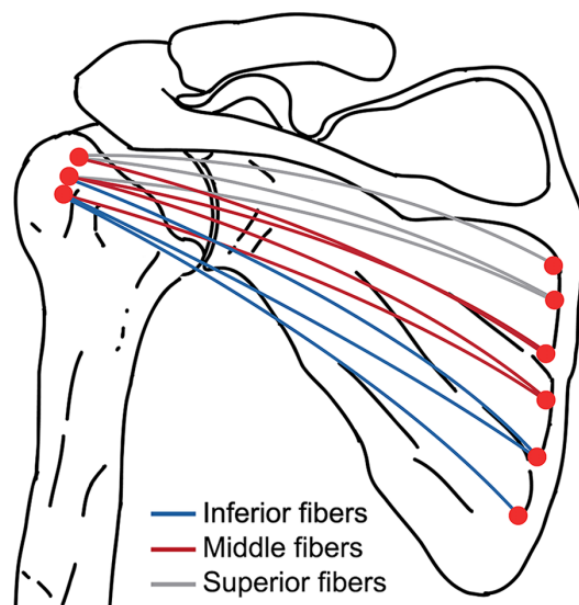


Figure 2. The red dots on this illustration represent the digitized points on the infraspinatus that were tracked with the Optotrak. A total of 9 points on the infraspinatus were digitized (6 points at its origin and 3 points at its insertion). The lines drawn between the insertion and the origin points of a muscle were drawn along fiber bundle lines to show the assumed direction of the force between 2 points. In addition, force action lines were drawn across fiber bundles to account for the crossover of fibers.

the insertion of the muscle's tendon on the humerus. In addition, 2 points were tracked on either side of the humeral head to calculate the joint's center of rotation throughout shoulder abduction. This produced a dynamic center of rotation used in the moment arm calculations at every abduction angle. Last, a point was tracked at the deltoid tuberosity on the humerus to calculate the angular displacement of the arm during the abduction.

Under each of the 4 shoulder testing conditions, the shoulder was manually abducted from 0° to 90° as the Optotrak captured coordinates of the labeled points. Because these were 3-dimensional points, a vector could be calculated between 2 chosen points. Using the 6 points along the origin of the infraspinatus and 3 points along the insertion, we calculated 10 different vectors to span the breadth of the infraspinatus muscle, as shown in Figure 2. Each vector was calculated as a segment between a single origin point and a single insertion point. Once each vector was calculated, the calculated center of rotation was used to determine the moment arm using the origin-insertion method.¹⁰ This moment arm calculation was conducted for each vector at every angle between 0° and 90° of abduction, allowing the output of 10-moment arm value sets that contained calculated moment arm values throughout the entire abduction movement for each shoulder specimen. Each shoulder was trialed 3 times for each condition to obtain average moment arm values that were used to create the

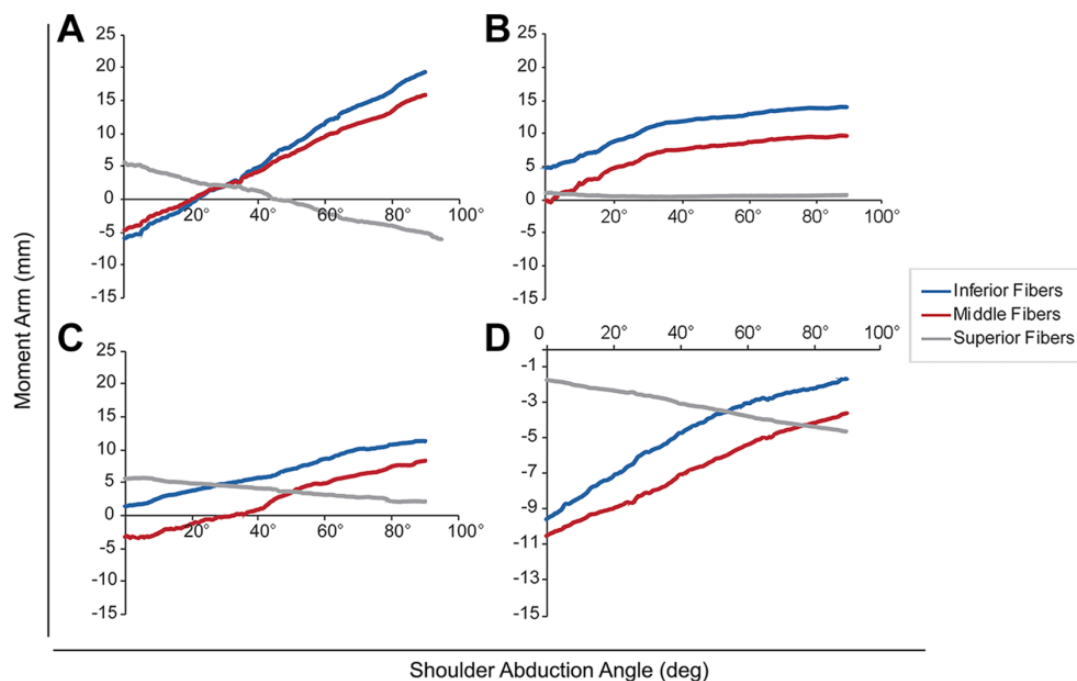


Figure 3. Mean moment arm values for the inferior, middle, and superior infraspinatus fibers plotted through 0° to 90° of shoulder abduction across the 4 study conditions: (A) intact, (B) complete supraspinatus tear, (C) superior capsular reconstruction, and (D) reverse total shoulder arthroplasty. Negative values indicate adduction moment.

10–moment arm value sets. Additionally, because the 5 shoulders underwent each condition, the average of these 5 was used to create the final 10–moment arm value sets for each condition.

Statistical Analysis

The 10–moment arm value sets, corresponding to the moment arms calculated from the 10 vectors spread over the breadth of the muscle area, were then divided based on the orientation of the fibers of the infraspinatus. In total, 3 superior fiber vectors ran transversely, 4 middle fiber vectors ran obliquely, and 3 inferior fiber vectors ran obliquely along the muscle. Next, the moment arm value sets in each fiber group were averaged, creating 3 moment arm value sets (superior, middle, and inferior) for each shoulder condition across 0° to 90° of shoulder abduction.

An analysis of variance (ANOVA) was used to compare moment arm values between each of the 4 study conditions, according to infraspinatus fiber type and at abduction angles of 0°, 30°, 60°, and 90°. Next, post hoc Tukey test identified significant differences in comparison to the intact shoulder. A second ANOVA was performed to detect significant differences in moment arm values between the inferior, middle, and superior fibers for each of the 4 conditions and according to the 4 specified abduction angles. In addition, post hoc Tukey testing identified significant differences among the fiber types. The threshold for statistically significant differences was set at $P < .05$. All statistical analyses were performed using SPSS for Windows (Version 27; IBM).

RESULTS

The mean moment arm values for the superior, middle, and inferior fibers of the infraspinatus throughout 0° to 90° of abduction are displayed in Figure 3 for all 4 testing conditions: intact, complete supraspinatus tear, SCR, and rTSA. The mean moment arm values at select abduction angles (0°, 30°, 60°, 90°) are highlighted in Figure 4.

In the intact condition, the superior fibers that were oriented transversely across the infraspinatus muscle initially showed a mean abduction moment value of 5.63 ± 1.18 mm at 0° of abduction. This abduction moment trended downward until it shifted to an adduction moment at 45° and reached a peak mean value of 5.095 ± 1.27 mm at 90° of abduction. The inferior and middle fibers, which are obliquely oriented along the muscle, demonstrated an inverse function to that of the superior fiber; they initially had a mean adduction moment of 5.9 ± 5.6 mm and 4.7 ± 3.2 mm, respectively, at 0° of abduction that decreased and shifted to a mean abduction potential of 19.4 ± 5.9 mm and 15.9 ± 6.6 mm, respectively, as the arc of motion approached 90°.

After a supraspinatus tear, the torque-producing potential of the superior fibers was significantly reduced and remained constant throughout the arc of motion. In contrast, the middle and inferior fibers lost their adduction potential and saw a levelling off of mean abduction moment, producing an overall reduction in maximum abduction potential compared with the intact shoulder.

After SCR, the abduction function of the superior fibers was restored with a mean moment arm value of 5.6 ± 1.8 mm at 0° of abduction. Still, the adduction function

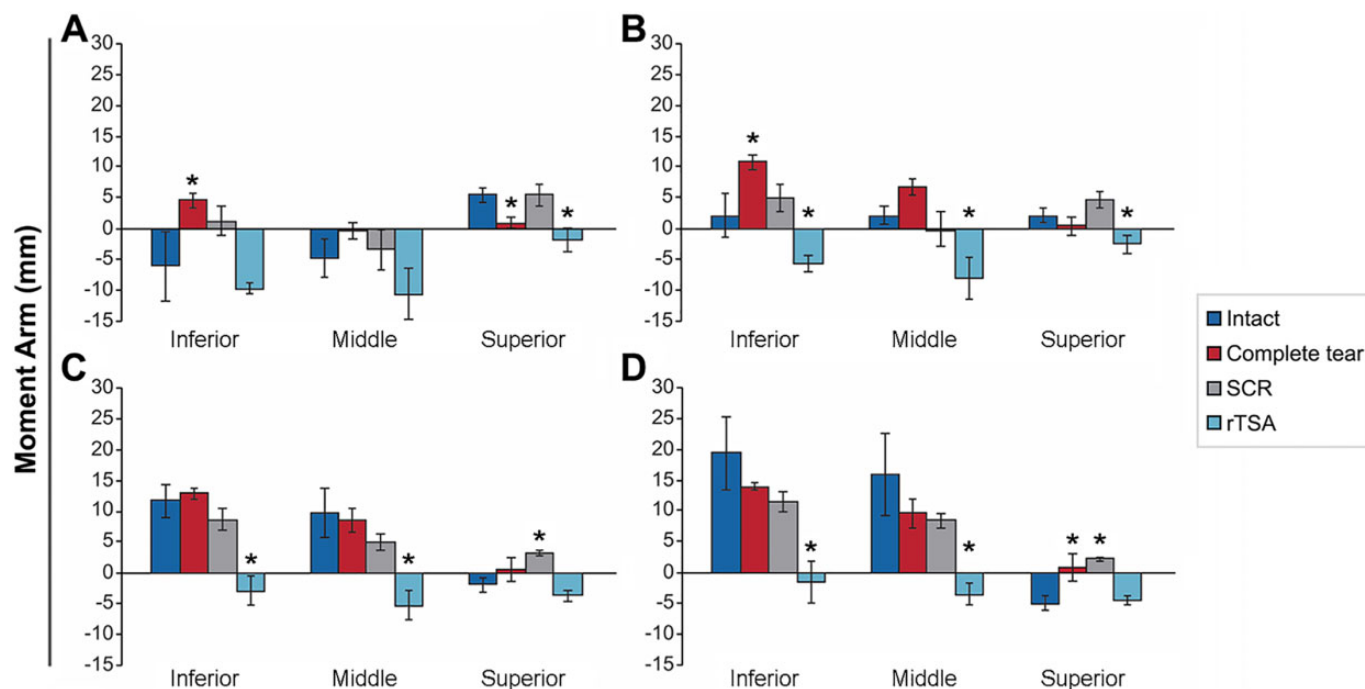


Figure 4. Comparison of mean moment arm values across the 4 study conditions (intact, complete tear, superior capsular reconstruction [SCR], and reverse total shoulder arthroplasty [rTSA]), according to infraspinatus fiber type. Values are stratified according to shoulder abduction angle: (A) 0°, (B) 30°, (C) 60°, and (D) 90°. Negative values indicate adduction moment. *Significantly different moment arm value compared with the intact shoulder under that specific angle and condition ($P < .05$).

that was present in the later phase of humeral abduction was lost. The middle and inferior fibers also saw a slight restoration of their function, although the moment arms were not as prominent as in the intact shoulder and were able to gain only a moderate mean abduction moment of 8.3 ± 1.3 mm and 11.3 ± 1.6 mm, respectively, at 90° of abduction.

Finally, rTSA completely changed the function of the muscle fibers. All muscle fibers lost their abduction moments and had adduction moments only throughout shoulder abduction. However, as the shoulder moved closer toward 90° of abduction, the superior fibers had an increasing mean adduction moment arm of 4.6 ± 0.7 mm. The middle and inferior fibers had mean adduction moments of 10.5 ± 4.2 mm and 9.6 ± 1.0 mm, respectively, at 0°, which then trended upward slightly until reaching small mean adduction moments of 3.6 ± 1.7 mm and 1.6 ± 3.4 mm, respectively, at 90° of abduction.

Comparison of Moment Arms Between Shoulder Conditions

ANOVA showed significant differences in moment arm values between the 4 study conditions at all selected angles (0°, 30°, 60°, and 90°) ($P < .05$ for all). The results of the post hoc comparisons are shown in Table 1.

At the start of abduction, the inferior fibers showed significant differences in the complete tear condition at 0° and 30° of abduction. The rTSA model showed substantial differences starting at 30° of abduction. Once the shoulder

reached 60° and above, the rTSA was the only model with differences compared with the intact shoulder.

At the start of abduction, the middle fibers showed no significant differences. However, from 30° and beyond, rTSA was the only testing condition with substantial differences, whereas both a complete tear and SCR remained similar to the intact shoulder.

At the start of abduction, the superior fibers showed significant differences in the complete tear and rTSA conditions. The rTSA condition continued to show differences at 30°, but these diminished at higher abduction angles. From 60° and beyond, SCR showed significant differences compared with intact, and at 90°, the complete tear model again appeared to show significant differences.

Comparison of Moment Arms Among Fiber Types

ANOVA detected significant differences in moment arm values between inferior, middle, and superior fibers at the specified angles for each of the 4 conditions. The results of the post hoc comparisons are shown in Table 2.

For the intact shoulder, the superior fibers were significantly different from both the inferior and middle fibers throughout the entire shoulder abduction motion. After the complete supraspinatus tear, the inferior fibers were different from all other fibers at 0° of abduction, whereas all fibers were different from each other at both 30° and 60° of abduction. At 90° of abduction, the superior fibers were different from both the middle and inferior fibers.

TABLE 1
Mean Moment Arm Values Across All 4 Study Conditions by Infraspinus Fiber Type and Abduction Angle^a

	Inferior Infraspinus	Middle Infraspinus	Superior Infraspinus
0° of abduction			
Intact	-5.9 ± 5.6	-4.7 ± 3.2	5.6 ± 1.2
Complete tear	4.8 ± 1.2	-0.2 ± 1.4	1.0 ± 0.9
SCR	1.4 ± 2.4	-3.2 ± 3.3	5.6 ± 1.8
rTSA	-9.6 ± 1.0	-10.5 ± 4.2	-1.7 ± 1.8
30° of abduction			
Intact	2.1 ± 3.5	2.1 ± 1.5	2.1 ± 1.1
Complete tear	10.8 ± 1.1	6.7 ± 1.3	0.4 ± 1.5
SCR	4.8 ± 2.3	-0.1 ± 3.0	4.6 ± 1.3
rTSA	-5.8 ± 1.3	-8.1 ± 3.4	-2.6 ± 1.4
60° of abduction			
Intact	11.7 ± 2.7	9.6 ± 4.0	-2.0 ± 1.3
Complete tear	12.8 ± 0.8	8.6 ± 1.9	0.6 ± 2.0
SCR	8.6 ± 1.9	4.9 ± 1.3	3.2 ± 0.5
rTSA	-3.0 ± 2.4	-5.4 ± 2.3	-3.8 ± 0.9
90° of abduction			
Intact	19.4 ± 5.9	15.9 ± 6.6	-5.1 ± 1.3
Complete tear	14.0 ± 0.7	9.6 ± 2.4	0.7 ± 2.2
SCR	11.32 ± 1.6	8.3 ± 1.3	2.1 ± 0.3
rTSA	-1.6 ± 3.4	-3.6 ± 1.7	-4.6 ± 0.7

^aValues are expressed in millimeters as mean ± SD. Negative values indicate adduction moment. Bolding indicates statistically significant difference compared with intact condition ($P < .05$, post hoc Tukey test). rTSA, reverse total shoulder arthroplasty; SCR, superior capsular reconstruction.

TABLE 2
P Values for Differences in Moment Arm Values Among Infraspinus Fiber Types by Study Condition^a

	Intact	Complete Tear	SCR	rTSA
0° of abduction				
Inferior vs middle	.901	.003	.127	.912
Inferior vs superior	.016	.016	.198	.034
Middle vs superior	.021	.438	.008	.015
30° of abduction				
Inferior vs middle	>.999	.010	.067	.472
Inferior vs superior	>.999	<.001	.989	.314
Middle vs superior	>.999	.001	.083	.051
60° of abduction				
Inferior vs middle	.667	.032	.022	.343
Inferior vs superior	.002	<.001	.004	.904
Middle vs superior	.004	.001	.273	.573
90° of abduction				
Inferior vs middle	.685	.056	.033	.509
Inferior vs superior	.002	<.001	<.001	.274
Middle vs superior	.003	.002	.001	.802

^aBolded P values indicate statistically significant differences among infraspinus fiber types ($P < .05$, post hoc Tukey test). rTSA, reverse total shoulder arthroplasty; SCR, superior capsular reconstruction.

After SCR, the middle and superior fibers were different from each other at 0° of abduction. At 60° of abduction, the inferior fibers were different from both the middle and superior fibers, and by 90° of abduction, all fibers were different from each other.

After rTSA, the only differences among fibers throughout abduction were seen at 0° of abduction when the superior fibers differed from the inferior and middle fibers.

DISCUSSION

This study showed that superior infraspinus fibers of the intact shoulder had an abduction moment that decreased with elevation until it shifted to adduction. Conversely, the middle and inferior fibers had an adduction moment that decreased until it turned to abduction. After a supraspinatus tear, superior fibers lacked any abduction torque; inferior and middle fibers of the infraspinus lost adduction potential ($P < .05$). SCR restored initial superior fibers to have an abduction moment ($P < .05$). Middle and inferior fibers had some restoration but were weaker than intact fibers. rTSA completely changed the function of muscle fibers, showing significant differences that caused loss of abduction moments in all fibers ($P < .05$).

These results confirm that individual groups of muscle fibers of different orientations within 1 muscle can make alternating contributions toward the variety of actions the muscle can perform. Our results also indicate that the function of the different fiber groups within the infraspinus muscle is variably affected after a supraspinatus tear or reconstruction with SCR and after rTSA. The roles of muscle fibers have been previously studied in the intact model. It has been speculated that different injuries would affect the torque-producing capacities of the RC muscles.¹ Ackland et al² demonstrated that rTSA inferomedially shifted

the center of rotation of the joint and thus changed the action and moment arms of different muscles and their fiber subgroups. Therefore, it is not surprising that rTSA most prominently affected the function and torque-producing potential of the infraspinatus muscle fibers.

Studies on the biomechanics of the infraspinatus of the intact shoulder have illustrated that it provides an abduction moment during shoulder abduction. One study found that at 15° of abduction, the infraspinatus had a 10-mm moment arm, which remained steady throughout the rest of shoulder abduction.¹² Similarly, our study showed that the infraspinatus has an abduction ability on the shoulder during that arc of motion, with this ability increasing at higher angles, particularly in the middle and inferior fibers. Our results were sensitive enough to demonstrate differences between superior and remaining fibers throughout the abduction movement. This resembled what Ackland et al¹ found when they divided the infraspinatus into superior and inferior sections and showed that the superior portion of the infraspinatus had a significantly larger abduction moment arm below 40° of abduction when compared with inferior infraspinatus fibers. These previous studies as well as the current study highlight the importance of understanding how broad muscles with differently oriented fibers may have different rotational actions on the joint that combine to produce a resulting overall motion. Analyzing these muscles according to their multiple fiber areas may increase the understanding of the resultant action produced on the joint.

When we analyzed the different testing conditions in this study, it was surprising that the SCR qualitatively imitated the intact infraspinatus moment arms most closely along the coronal arc of motion. We believe that most of the efficacy of the SCR relies on the widening of the acromiohumeral space. The position of the humeral head, which determines the center of rotation, dictates the orientation that the muscle fiber vectors have relative to the center of rotation and, therefore, the magnitude and direction of the moment arms that the fibers produced. We believe that the SCR restored the abduction moment arm of the superior fibers by positioning them closer to their original positions so that the fiber orientation had a geometry that would allow for an abduction torque. Following this logic, a partial RC repair would have a similar biomechanical effect as long as the repair restored the normal acromiohumeral distance. These findings are encouraging, mainly in terms of providing surgical options to young patients without arthritic changes, who may otherwise be candidates for rTSA. The future of SCR may be promising for patients who play sports or live an active lifestyle. Mihata et al^{15,18} found that patients who previously played recreational or competitive sports who underwent SCR for irreparable RC injury could fully return to their sports activity after surgery. Several studies depicted the return to intact shoulder motion from a biomechanical perspective and agreed with our results for the infraspinatus moment arms after SCR.²⁴

Additionally, it was surprising to see that the behavior of the moment arm of the middle fibers was counterintuitive.

When analyzing the moments of the fiber types relative to each other for the SCR (Figure 4A, gray bars), we noted that the middle fibers had an adducting moment, whereas the superior and inferior fibers had an abducting moment. This phenomenon was due to the geometry between the middle fiber vectors and the center of rotation. The middle fiber vectors lay more perpendicular to the center of rotation. Therefore, the moment direction was more sensitive to positional changes of the center of rotation: that is, the humeral head position. After the complete supraspinatus tear, the humeral head shifted upward so much so that the inferior fibers lay obliquely enough to produce an abduction moment arm. However, this upward humeral shift positioned the middle fibers even more perpendicular to the center of rotation, thus making their moment arm values near zero after a complete supraspinatus tear (Figure 4A, red bars). When the SCR widened the acromiohumeral distance, it restored the initial adduction moment arm of the middle fibers, as they required only a slight change in angle, given that they lay close to the perpendicular line to the center of rotation. Nevertheless, although the angle between the center of rotation and the inferior angles was obtuse by a small amount (thus reducing the magnitude of the abduction torque), the angle change was not sufficient to restore the adduction moment arm of the inferior fibers. For that to happen, the acromiohumeral distance would have had to be restored to the original position by the SCR, which was not the case.

The shift of moment arms after rTSA does not necessarily indicate inferiority to SCR, although the shoulder motion kinematics are different. These findings agree with *in vivo* kinematic studies showing that patients who underwent rTSA had different scapular kinematics during arm motion compared with healthy individuals.⁵ With activities of daily living, the scapulothoracic joint may compensate for the torque potential lost by the RC musculature during arm motion. It has been suggested that patients with complete pseudoparalysis after a massive RC tear often undergo rTSA as a treatment option.²⁵ However, early evidence shows that SCR can reverse pseudoparalysis while retaining the biomechanical functions of at least the infraspinatus muscle fibers.⁴

Moment arms of the RC muscles are not fully restored regardless of reconstruction technique. Thus, readjustment in muscle moment arms, not only of the whole muscle but also at the fiber level, should be considered when determining rehabilitation protocols and choosing treatment modalities. Similarly, given the evidence that different muscle fiber groups have different actions, it may be essential to consider the implications in disease states other than supraspinatus tears. It can be inferred that muscle action and moment arms across different arcs of motions will be affected for different injuries. For example, it is unknown how the behavior of the infraspinatus muscle fiber groups would change with a concurrent subscapularis tear or even with an injury unrelated to the RC, like a pectoralis major tear.

Limitations

The limitations of this study are typical for those involving cadaveric specimens.²⁶ Because the scapula was fixed into the experimental apparatus, only a slight adjustment of the apparatus could be used to obtain higher degrees of shoulder abduction. Therefore, scapulothoracic joint movement was not fully replicated, influencing moment arm values across the entire arc of abduction. It is challenging to replicate scapulothoracic position because it dynamically adjusts to shoulder abduction²⁰; however, future studies should aim to replicate unrestricted scapular movement as much as possible. Additionally, although our study's goal was to better understand how individual fiber groups contribute to joint rotation, the force vectors chosen are subject to human error. However, dividing a muscle into different fiber groups with different moments provides a more accurate and anatomic representation of the muscle power and strength than the alternate method of calculating a moment arm from a single line force vector that disregards fiber orientation.⁹ Being a cadaveric study, this experiment is also limited with respect to incorporating muscle activation. Although loading conditions were chosen to simulate in vivo shoulder movements, muscle activation would likely affect moment arm values. This holds true for force couples; for example, it is difficult to determine the role of the subscapularis–infraspinatus teres minor force couple, given that we did not measure the sagittal moment arm that these muscles exerted on the humerus during shoulder abduction. Therefore, further studies should be performed to determine this influence. Another limitation of the cadaveric nature of the study was that the RC tears were not induced by an injury but were transected. There are instances in which the complete tear includes a tear of the superior fibers of the infraspinatus. We did not transect these under visualization, and we did not histologically confirm that these were intact after the experiments were performed. The points that we created to make the vectors, however, were digital, and they would not have changed even if the fibers had been transected.

CONCLUSION

This study demonstrates that infraspinatus fiber groups (superior, middle, and inferior) have different and inverse moment arms resulting in different actions during scapular plane elevation. These changed after a massive RC tear, SCR, and rTSA. Of the 3 models tested, SCR moments had the closest resemblance to the moments of infraspinatus in the intact shoulder, whereas rTSA significantly altered the moment arms, resulting in the infraspinatus transforming into an adductor.

We believe that these results provide early evidence supporting the efficacy of SCR at restoring biomechanical muscle function and that they should be taken into consideration when choosing treatment modalities and rehabilitation protocols after RC tears. More studies and evidence, however, are needed to solidify these findings and provide clinical recommendations.

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