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The anterior deltoid's importance in reverse shoulder arthroplasty: a cadaveric biomechanical study

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Background: Frequently, patients who are candidates for reverse shoulder arthroplasty have had prior surgery that may compromise the anterior deltoid muscle. There have been conflicting reports on the necessity of the anterior deltoid thus it is unclear whether a dysfunctional anterior deltoid muscle is a contraindication to reverse shoulder arthroplasty. The purpose of this study was to determine the 3-dimensional (3D) moment arms for all 6 deltoid segments, and determine the biomechanical significance of the anterior deltoid before and after reverse shoulder arthroplasty.
Methods: Eight cadaveric shoulders were evaluated with a 6-axis force/torque sensor to assess the direction of rotation and 3D moment arms for all 6 segments of the deltoid both before and after placement of a reverse shoulder prosthesis. The 2 segments of anterior deltoid were unloaded sequentially to determine their functional role.
Results: The 3D moment arms of the deltoid were significantly altered by placement of the reverse shoulder prosthesis. The anterior and middle deltoid abduction moment arms significantly increased after placement of the reverse prosthesis ($P < .05$). Furthermore, the loss of the anterior deltoid resulted in a significant decrease in both abduction and flexion moments ($P < .05$).
Conclusion: The anterior deltoid is important biomechanically for balanced function after a reverse total shoulder arthroplasty. Losing 1 segment of the anterior deltoid may still allow abduction; however, losing both segments of the anterior deltoid may disrupt balanced abduction. Surgeons should be cautious about performing reverse shoulder arthroplasty in patients who do not have a functioning anterior deltoid muscle.
Level of Evidence: Basic Science Study, Biomechanics, Cadaver Model.
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Keywords: Reverse total shoulder arthroplasty; shoulder reconstruction; deltoid; flexion; abduction; moment arms; cadaveric study

Reverse shoulder arthroplasty represents an increasingly useful tool for the treatment of rotator cuff arthropathy,[4,7,11,27] complex proximal humerus fractures,[18,29] and revision shoulder arthroplasty.[6,19,21] The reverse total shoulder prosthesis medializes the center of rotation of the glenohumeral joint and in doing so increases recruitment of deltoid muscles fibers.[5,8,10] This increases the moment arm and resultant mechanical torque about the shoulder due to the position of the glenoid component. A functional deltoid is critical to a successful outcome after a reverse total shoulder arthroplasty.

The anterior deltoid is seen as a vital structure to maintain during surgical exposures, and its disruption has been associated with functional weakness.[16,20,23] A recent case series of anterolateral deltoid muscle ruptures after

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reverse total shoulder arthroplasty in a patient population that had undergone a previous open rotator cuff repairs demonstrated the importance of the anterior deltoid to a successful clinical outcome. The patients in this series all had significant declines in their functional outcome after anterolateral deltoid rupture occured.[28] This report seems to support the concept that the anterior deltoid is vital for a successful outcome after reverse shoulder arthroplasty. However, Glanzmann et al reported a successful reverse shoulder arthroplasty after a previous deltoid muscle flap transfer,[9] suggesting that the entire deltoid may not be necessary for a successful outcome after this procedure. These diverging reports underscore the importance to clearly elucidate the role of the anterior deltoid before and after reverse shoulder arthroplasty.

The purpose of our study is to investigate the moment arms in all planes of movement of the glenohumeral joint (flexion, abduction, and rotation) in both the native shoulder and following reverse shoulder arthroplasty utilizing a laterally based glenosphere. Additionally, we sought to better elucidate the necessity of the anterior deltoid for function of the reverse shoulder arthroplasty.

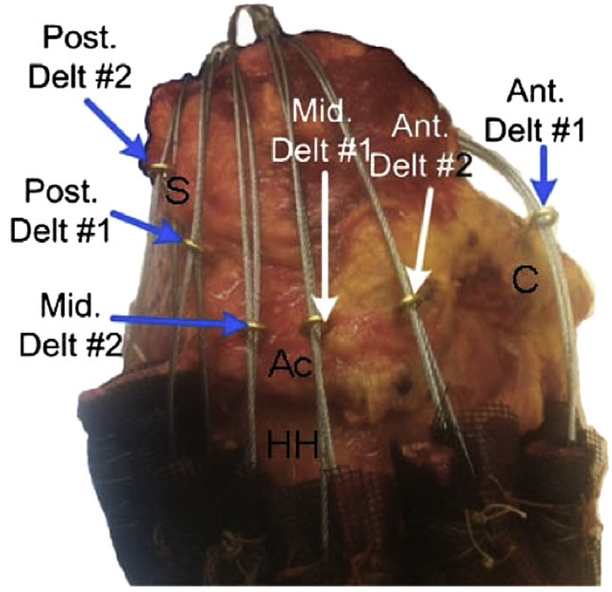

Figure 1 Six portions of deltoid labeled. *C*, the clavicle; *Ac*, the acromion; *HH*, humeral head; *S,* scapular spine.

Materials and methods

Specimen preparation

Eight fresh-frozen cadaveric right shoulders, 6 male and 2 female, with ages ranging between 46 and 68 years were obtained. The specimens were stored at -20°C and thawed for 24 hours before testing. Specimens were excluded from use if they were found to have prior surgery or deltoid muscle compromise.

The skin, subcutaneous, and adipose tissues were removed around exposing the underlying muscles. The planes dividing the anterior (clavicular head), middle (acromial head), and posterior (posterior scapular spine head) deltoid were defined. Each segment was measured and divided evenly into 2 portions, making 6 total portions of the deltoid that was then sharply removed from the scapular spine, acromion, and clavicle. The anterior most portion of the anterior deltoid was labeled anterior deltoid #1, the next portion anterior deltoid #2, etc. (Fig. 1).

Nylon mesh was sewn into each of the deltoid segments as well as the latissimus dorsi and pectoralis major with 0 Vicryl suture (Ethicon, Somerville, NJ, USA). A stainless steel cable of 1.6 mm in diameter was sutured to the Nylon mesh. The origin of each deltoid muscle segment was noted, and an eyelet was placed at the site to guide excursion of the muscle. The cables were threaded through the eyelets prior to mounting the specimen on the experimental apparatus. The clavicle was pinned to the acromion in its anatomic position.

Experimental apparatus

The scapula was firmly mounted to a customized metal plate with plates, and screws. The plate was placed with the glenoid vertical, and the center of rotation of the humeral head in line with a 6-axis force/torque (F/T) sensor (JR3, Inc., Woodland, CA, USA). Metal struts extended from the sensor to a platform where the humerus was fixed inside a metal cylinder with screws, which, in turn, was clamped to the apparatus (Fig. 2). The position of the humerus relative to the 6-axis F/T sensor center was noted with a digitizer (Immersion, San Jose, CA, USA) both before (the anatomical or native specimen) and after surgery (the prosthetic specimen) to minimize the error due to the possible offset between the center of rotation and the 6-axis F/T sensor. A 3D Flock of Bird motion sensor (Ascension Technology, Burlington, VT, USA) provided the 6 degree-of-freedom positions and angles of the humerus during the experiment.

The cables sewn into the muscles were then passed through eyelets at the measured midpoint of each muscle portion's insertion and onto pulleys that were connected to free hanging weights. The weight applied to the each portion of deltoid was approximately 10% of the maximum force, which can be generated by each portion, estimated by published physiological cross sectional areas of the deltoid.[2,13,15,26] A precision linear motor (LinMot, Spreitenbach, Switzerland) was attached to a selected cable to generate individual dynamic force, up to 60 N, with constant low velocity to each of the deltoid segments to determine their 3D mechanical actions. The pectoralis major and latissimus dorsi were each loaded with 10 N of weight statically throughout the experiment.

Experimental protocol

After mounting the scapula and humerus onto the apparatus, the humerus was placed at 0° of abduction and neutral rotation with respect to the epicondylar axis. Its position relative to the 6-axis force sensor was digitized. Weight was added to the cables, and the linear motor sequentially cycled through each segment (starting with anterior deltoid #1, ending with posterior deltoid #2) of the deltoid within pre-defined maximum pulling force limit (the 10% of maximum pulling force of each portion of deltoid) while the free weight remained on the other portions providing a physiologic static load to the joint. The 3D moment arm was

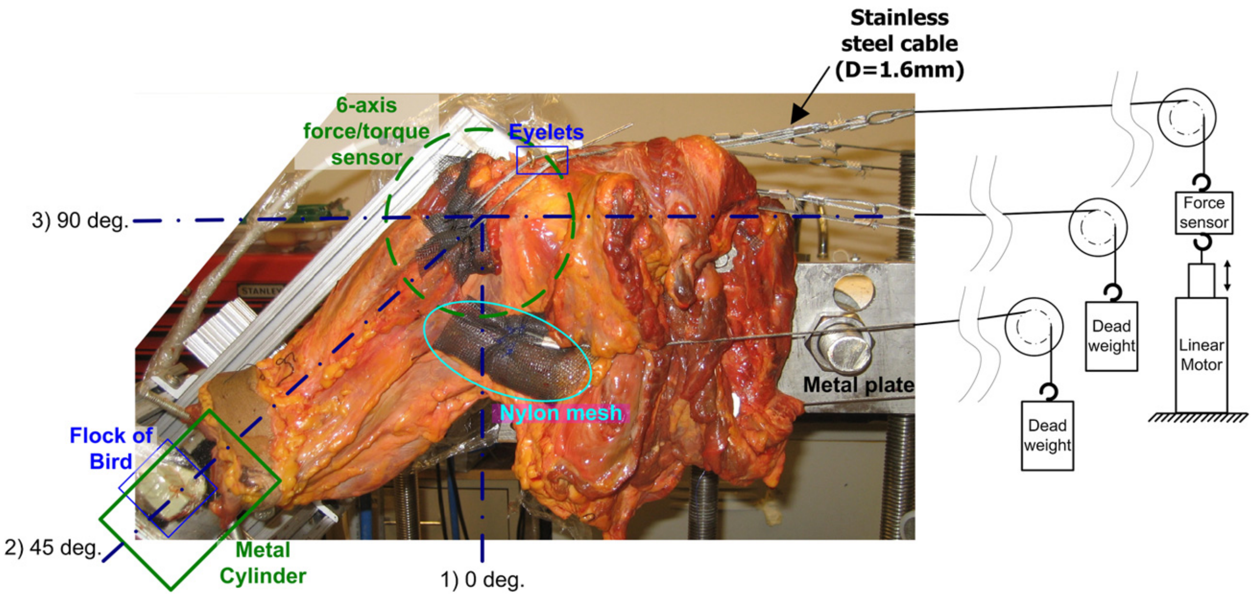

Figure 2 Experimental setup for right shoulder. Note *H* denotes the base of the humeral shaft and *SB* is the scapular body attached to the metal plate. This figure demonstrates the different positions (0, 45, and 90°) that the specimen was tested at. Note the 6-axis force/torque sensor directly behind the glenohumeral joint that captures the moments about the joint.

determined for each deltoid segment. Next, all muscles were reloaded with free weights, while measuring the changes in the moments while the anterior most 3 portions of the deltoid (anterior deltoid #1 and #2, middle deltoid #1) were sequentially unloaded. The position and angle of the humerus was then captured via the Flock of Bird motion sensor. This entire procedure was repeated at 45° and 90° of glenohumeral abduction equivalent to 135° of arm abduction when accounting for theoretical scapulothoracic motion.[12]

Next, the humerus was placed in a neutral position and released from its clamping while weights hung on each segment. This allowed the humerus to move into a position of equilibrium that was measured with the Flock-of-Bird motion sensor. We then sequentially unloaded the anterior deltoid and the anterior portion of the middle deltoid while measuring the change in position of the distal humerus.

The senior author (M.D.S.) implanted a reverse total shoulder (RSP, DJO Surgical, Austin, TX, USA) (32 - 4 glenosphere, 32 standard shell and polyethylene liner) while the scapula remained mounted to the apparatus to minimize the error because of remounting. During the surgical approach, the rotator cuff was excised to simulate the environment of a massive rotator cuff tear that predominates in this patient population.[4,24] The surgical technique of the DJO Encore prosthesis was followed including cutting the humerus in 30° of retroversion. We attempted to tension the prosthesis such that the shoulder could be ranged without instability, but that there was no undue tension on the deltoid or attached acromion. The aforementioned entire protocol was repeated with the implanted reverse total shoulder prostheses in the specimen.

Data analysis

Three-dimensional mechanical actions, including moment arms in flexion/extension, abduction/adduction, and internal/external rotation, were estimated from each specimen both before (the native specimen) and after surgery (prosthetic) using the measured 3D torques and pulling forces. The exact same method for measuring the moment arms was used in each phase of the study.

To investigate the role of each portion of deltoid, direction of rotation (DOR) was computed from the measured 3D moments with respect to a moving coordinate system (Fig. 2) located at the glenohumeral joint center with the following 3 orthogonal axes: *u* axis being the internal rotation axis parallel to long axis of humerus; *w* axis the adduction axis always in frontal and sagittal plane; and *v* axis, the flexion axis, orthogonal to both *u* axis and *w* axis. By using the DOR, one can clarify the role of a (portion of) muscle[30] and aid in comparison of muscle portions. DOR is computed as follows:

$$DC_u = \frac{M_u}{\sqrt{M_u^2 + M_v^2 + M_w^2}},$$

$$DC_v = \frac{M_v}{\sqrt{M_u^2 + M_v^2 + M_w^2}}, \text{ and}$$

$$DC_w = \frac{M_w}{\sqrt{M_u^2 + M_v^2 + M_w^2}},$$

where DC_u, DC_v, and DC_w denote 3 components of DOR: M_u, M_v, and M_w denote internal rotation, flexion, and adduction moment measured, respectively. With respect to the *u*-*v*-*w* coordinate system about the shoulder (Fig. 2), if a portion of muscle only functions as an abductor, then DOR must be $DC_u = 0$, $DC_v = 0$, and $DC_w = 1$. If $DC_u = 1$, the portion of the muscle's role is internal rotation with its rotation axis coinciding with the internal rotation axis and if close to -1 external rotation. If $DC_u = 0$, it has no mechanical action in internal or external rotation with its rotation axis perpendicular to the internal rotation axis. Similarly, DC_v is a flexor if close to 1, and an extensor if close to -1; DC_w is an adductor if close to 1, and an abductor if close to -1. Thus, by examining DOR of each portion of deltoid, one can define the role of each portion of

Table I Direction of rotation before and after surgery

Shoulder angle (deg)	Portion of deltoid	Preoperative	Postoperative
0	ant 1	Int. rotator-Flexor-Adductor	Flexor-Abductor
	ant 2	Flexor-Abductor	Abductor
	mid 1	Extensor-Abductor	Extensor-Abductor
	mid 2	Extensor-Abductor	Extensor-Abductor
	post 1	Ext. rotator-Extensor	Extensor-Abductor
	post 2	Ext. rotator-Extensor	Ext. rotator-Extensor
45	ant 1	Flexor-Abductor	Flexor-Abductor
	ant 2	Flexor-**Abductor**	**Abductor**
	mid 1	Extensor-Abductor	Extensor-Abductor
	mid 2	Extensor-Abductor	Extensor-Abductor
	post 1	Ext. rotator-Extensor	**Extensor**-Abductor
	post 2	Ext. rotator-Extensor-Adductor	Extensor-Adductor
90	ant 1	Flexor-**Abductor**	Flexor-**Abductor**
	ant 2	Extensor-**Abductor**	**Abductor**
	mid 1	Extensor-Abductor	Extensor-**Abductor**
	mid 2	Extensor-Abductor	Extensor-Abductor
	post 1	Int. rotator-Extensor-Abductor	Int. rotator-Extensor-Abductor
	post 2	Int. rotator-Extensor	Int. rotator-Extensor

Small font size means weak action as an internal/external rotator, flexor/extensor, or adductor/abductor. Similarly, middle and **large** font sizes represent middle and **strong** action as an internal/external rotator, flexor/extensor, or adductor/abductor as defined by the DOR.

deltoid before and after surgery. Because it is a normalized measure, it is possible to make comparisons both between portions of deltoids and before and after surgery. Practically, we can use the angle between the rotation axis of a portion of deltoid muscle with the abduction axis to evaluate its role in abduction.

Statistical analysis using a paired student *t* test with the level of significance defined as $P < .05$ was performed after a normality test of each set of data for pre-post comparison. During the portion of the experiment when the anterior deltoid was unloaded, a 1 sample *t* test with significance level defined as $P < .05$ was performed for flexion moment change and adduction moment change.

Results

Direction of rotation (DOR)

The 3D mechanical action measured by DOR for each segment of the deltoid before and after the surgery is listed in Table I. The most inferior portion of the anterior deltoid (anterior deltoid #1) changed from an adductor to an abductor after implantation of the reverse shoulder prosthesis at 0° of glenohumeral abduction. There were no other significant changes in the DOR. Our model also reaffirms that the deltoid is an important flexor of the glenohumeral joint.

Moment arms

Although the DOR remained unchanged for most segments of the deltoid, increases in several moment arms were noted (Fig. 3, Table II). The anterior deltoid #1 increased its abduction moment ($P < .01$) and flexion moment ($P < .01$) in the postsurgical specimen (Table II). At 45° of glenohumeral abduction, all portions of the anterior and half of the middle deltoid experienced significant increases in their abduction moment arms ($P < .05$). At 90° of glenohumeral abduction, increases in moment arms were negligible.

Isolation of the anterior deltoid

Flexion and abduction moment change were examined under 3 different conditions: the first portion of the anterior deltoid unloaded, the entire anterior deltoid unloaded, and the anterior and first portion of the middle deltoid unloaded. This allowed us to determine the contribution of each portion of the anterior deltoid to flexion and abduction (Table III).

The flexion moment decreased significantly after the first portion of the anterior deltoid was unloaded, and all other portions of the deltoid remained loaded at 0° and 45° of abduction in all pre- and postsurgical specimens ($P < .05$). In the native specimen with the entire anterior deltoid and a portion of the middle deltoid unloaded, the flexion moment decreased ($P < .05$) due to the absence of important contributors (anterior and a portion of the middle deltoid) to flexion. After placement of the reverse total shoulder arthroplasty at 0° and 45°, when either a portion of the anterior deltoid or the entire anterior deltoid was unloaded, the flexion moments significantly decreased ($P < .01$).

Similar results occur when examining abduction moment arms. After placement of the reverse total shoulder arthroplasty, abduction was significantly decreased when any segment of the deltoid was unloaded at 0°. At 45°, no significant decrease in abduction occurred when only 1 portion of the anterior deltoid was unloaded, but became significant ($P < .01$) when the entire anterior deltoid was unloaded. At 90°, there were no significant changes in flexion; however, abduction decreased significantly when a portion of the anterior deltoid was unloaded ($P < .05$) and when the entire anterior and middle deltoid were unloaded ($P < .01$).

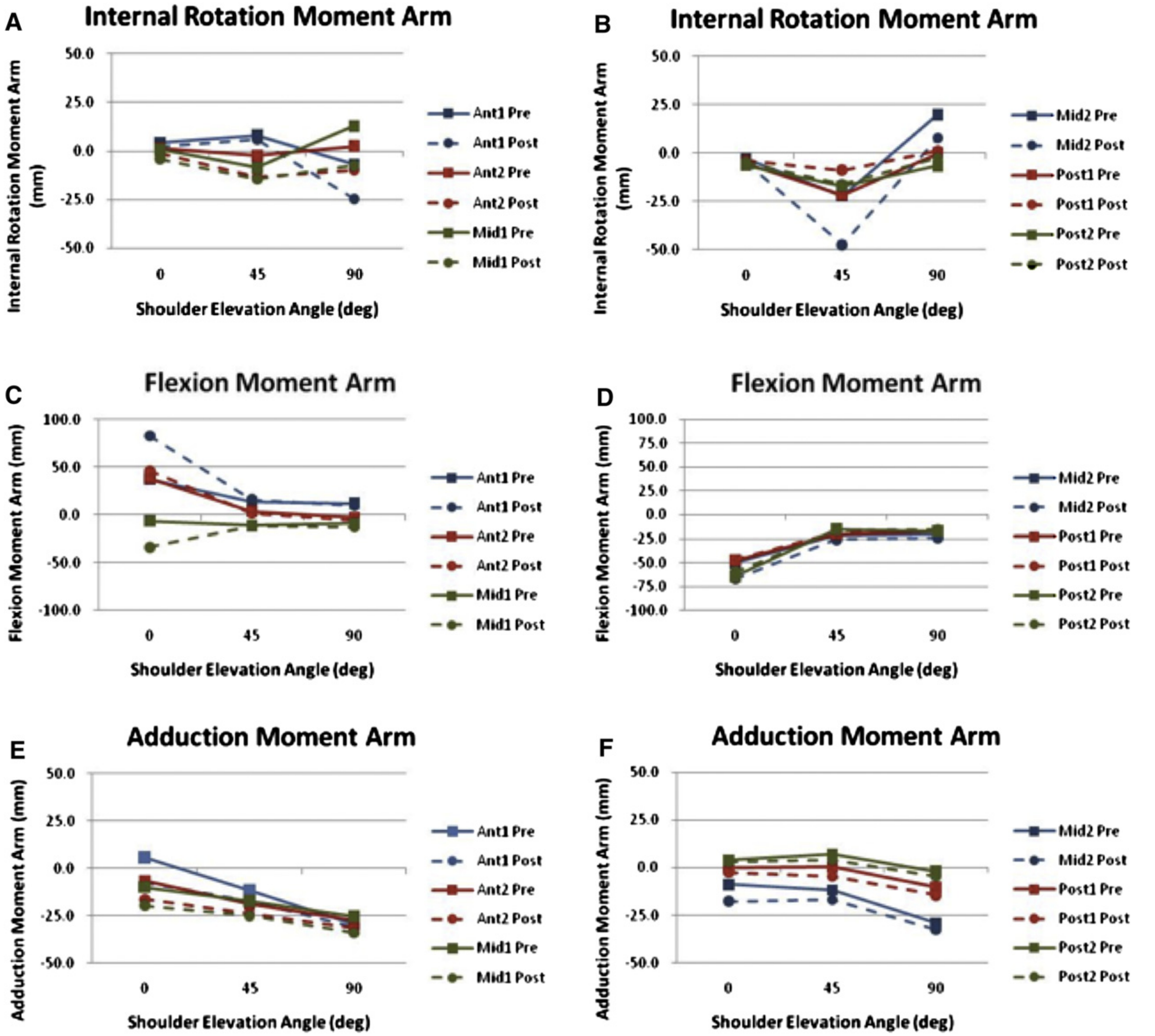

Figure 3 (**A**)-(**F**) represent the changes in moment arms of the 6 deltoid portions in the native specimens (pre) and specimens implanted with the prosthesis (post). (**A**) and (**B**) are the changes in the rotational moment arms. (**C**) and (**D**) are the changes in the flexion/extension moment arms. (**E**) and (**F**) are the changes in the abduction/adduction moment arms.

Discussion

The reverse shoulder prosthesis has revolutionized the way we treat cuff tear arthropathy, failed shoulder arthroplasty, and fractures in cuff deficient shoulders. This prosthesis functions by recruiting deltoid muscle fibers to initiate glenohumeral abduction and rotation. Unfortunately, many patients who have these problems have had prior surgery that may compromise the integrity of the anterior deltoid muscle. Thus it is important to not only understand how reverse shoulder arthroplasty changes the moment arms of the various segments of the deltoid but to also determine if the anterior segments of the deltoid must be functional for successful reverse shoulder arthroplasty.

Ackland et al have reported previously on the increased moment arm of anterior and middle deltoid moment arms after placement of a reverse shoulder prosthesis.[1] These authors utilized a Grammont-style reverse prosthesis that medializes and lowers the glenohumeral center of rotation. Our study differs from theirs in that we utilized a prosthetic design with a more lateralized center of rotation (by 6 mm). Like Ackland et al, we found that the anterior deltoid functions as an abductor and flexor of the glenohumeral joint after implantation of a reverse shoulder prosthesis. Thus it appears that these biomechanical advantages can be obtained with either a medial or lateral offset reverse shoulder design.

Reverse shoulder prosthesis designs with a more lateralized glenosphere have been introduced in an effort to obtain a more anatomic offset of the center of rotation and to reduce scapular notching.[3,5,7,14,22] While our study did not directly compare a Grammont style prosthesis to

Table II Moment arm changes (mm)

Shoulder angle (deg)	Portion of Deltoid	Ru (int/ext rotation)		Rv (flexion/extension)		Rw (adduction/abduction)	
		(Preoperative)	(Postoperative)	(Preoperative)	(Postoperative)	(Preoperative)	(Postoperative)
0	ant 1	4.4 (5.4)	2.4 (2.4)	37.3 (21.8)	82.7 (74.9)	**5.9 (13.9)****	**−7.5 (11.6)****
	ant 2	1.5 (4.6)	−1.4 (5.5)	37.9 (35.4)	45.7 (45.4)	−6.6 (13.3)	−16.3 (18.1)
	mid 1	1.0 (8.9)	−4.2 (4.0)	−6.4 (54.8)	−33.6 (29.9)	−9.9 (20.3)	−19.6 (12.6)
	mid 2	−3.1 (7.6)	−4.9 (4.9)	−50.3 (34.2)	−66.9 (44.4)	−8.8 (19.2)	−17.7 (11.4)
	post 1	−5.7 (7.1)	−3.8 (4.9)	−47.5 (27.4)	−47.1 (32.4)	−0.1 (8.7)	−2.5 (4.3)
	post 2	−6.3 (5.3)	−4.8 (5.1)	−64.6 (73.1)	−59.8 (72.8)	3.8 (10.6)	3.0 (7.5)
45	ant 1	8.1 (11.0)	6.0 (16.6)	13.1 (8.8)	15.9 (5.8)	**−11.5 (6.6)***	**−17.1 (10.2)***
	ant 2	**−2.4 (16.8)***	**−13.5 (32.8)***	3.8 (6.7)	1.7 (7.4)	**−18.9 (7.7)***	**−24.0 (13.5)***
	mid 1	−8.6 (26.4)	−14.5 (33.3)	−11.4 (16.0)	−11.9 (15.8)	**−17.2 (7.0)****	**−25.0 (7.2)****
	mid 2	−22.2 (47.9)	−47.4 (52.7)	−21.4 (18.2)	−25.8 (8.6)	−11.6 (10.8)	−16.8 (6.9)
	post 1	−21.6 (30.1)	−8.9 (15.5)	−20.3 (8.5)	−18.5 (3.9)	0.3 (10.2)	−4.5 (5.8)
	post 2	−17.1 (16.7)	−16.2 (20.4)	−15.0 (8.1)	−16.2 (9.5)	6.9 (5.4)	4.2 (4.4)
90	ant 1	**−7.0 (19.7)***	**−24.7 (23.2)***	11.9 (10.3)	9.9 (4.7)	−29.4 (9.9)	−30.9 (8.1)
	ant 2	2.5 (22.7)	−9.7 (21.8)	−2.8 (6.1)	−5.8 (5.4)	−27.4 (9.1)	−31.3 (9.1)
	mid 1	**12.8 (29.4)***	**−7.6 (21.5)***	−9.1 (10.9)	−12.7 (10.8)	−25.5 (7.3)	−34.0 (7.6)
	mid 2	19.8 (34.8)	7.7 (23.2)	**−20.0 (15.0)***	**−24.5 (14.9)***	−29.0 (12.7)	−32.6 (8.6)
	post 1	−0.2 (20.1)	0.9 (14.2)	−17.4 (11.1)	−16.9 (10.0)	−10.4 (10.7)	−14.4 (5.0)
	post 2	−6.7 (5.8)	−2.4 (6.6)	−16.9 (9.6)	−15.3 (9.6)	−1.8 (8.2)	−4.6 (5.6)

Bold text indicates significant results.
* denotes $P < .05$; ** denotes $P < .01$ (paired t test).

Table III Moment change (Nm)

Shoulder angle (deg)		Flexion moment change		Adduction moment change	
		Preoperative	Postoperative	Preoperative	Postoperative
0	ant 1 unloaded	**−0.47 (0.18)****	**−0.34 (0.25)****	0.09 (0.23)	**0.64 (0.40)****
	ant 1&2 unloaded	**−0.71 (0.21)****	**−0.52 (0.31)****	**0.39 (0.24)***	**1.18 (0.60)***
	ant 1&2 and mid 1 unloaded	**−0.43 (0.54)***	−0.17 (0.52)	0.93 (0.32)	**1.85 (0.70)****
45	ant 1 unloaded	**−0.44 (0.36)***	**−0.68 (0.43)****	−0.05 (0.39)	0.11 (0.26)
	ant 1&2 unloaded	**−0.55 (0.53)***	**−0.74 (0.37)****	0.46 (0.51)	**0.76 (0.49)****
	ant 1&2 and mid 1 unloaded	−0.20 (0.86)	**−0.38 (0.41)***	**1.05 (0.65)****	**1.62 (0.65)****
90	ant 1 unloaded	−0.35 (0.39)	−0.31 (0.49)	−0.78 (1.20)	**−0.62 (0.70)***
	ant 1&2 unloaded	−0.29 (0.50)	−0.17 (0.41)	0.09 (1.42)	0.35 (0.80)
	ant 1&2 and mid 1 unloaded	0.00 (0.58)	0.28 (0.27)	0.93 (1.52)	**1.49 (0.89)****

Bold text indicates significant results.
* denotes $P < .05$; ** denotes $P < .01$ (independent t test).

a lateralized offset prosthesis, the center of rotation with lateral offset designs has been shown in the literature to be significantly different from Grammont style prostheses.[25] This change in center of rotation affects the tension on the deltoid as well as any remaining rotator cuff musculature. Our data confirm that the anterior and middle deltoid moment arms are increased with a lateral offset design reverse prosthesis.

Active rotation of the glenohumeral joint is difficult to consistently improve following reverse shoulder arthroplasty.[4,7,11,27] While limited to the design of a cadaveric study, to our knowledge, the present study is the only work to study all 3 degrees of freedom (flexion-extension, abduction-adduction, and internal-external rotation) following reverse shoulder arthroplasty. This information is potentially useful as physiologic motion occurs in the 3D plane.

Whatley et al[28] reported on a series of patients that experienced anterior deltoid rupture following reverse total shoulder arthroplasty with resultant poor functional outcomes. In our model, when the anterior deltoid was isolated and unloaded, significant decreases in flexion and abduction were demonstrated. Thus our biomechanical data support the clinical findings of Whatley et al, namely that the anterior deltoid is indeed a vital structure to a functional reverse total shoulder arthroplasty.

There are implicit limitations to our data. This is a cadaveric model that clamped the scapula to our experimental apparatus in one plane with the glenoid vertical and in line with biomechanical sensor. This setup does not account for the scapula's normal 3D rotation during shoulder movement.[17] Additionally, we performed our experiment in 0, 45, and 90° of abduction. Thus our findings may not truly reflect what occurs during physiologic motion that occurs in a continuous plane, and may not be accurate physiologic expectations in a clinical setting when the extremes of abduction may not be obtainable. While flexion and abduction moments decreased significantly when the deltoid was unloaded, further study is needed to investigate the relationship between this biomechanical change and the clinical significance. Despite these limitations, our biomechanical data suggest that the anterior deltoid is crucial to good function following reverse shoulder arthroplasty.

Conclusion

Three-dimensional moment arms (internal-external rotation, flexion-extension, and adduction-abduction) of 6 portions of deltoid before and after reverse total arthroplasty were evaluated. After arthroplasty, abduction and flexion moment arms were both increased. By sequentially unloading the anterior deltoid and recording the changes in moment arms, it was confirmed that the anterior deltoid is vital to flexion and abduction following reverse total shoulder arthroplasty. This study lends support to warnings that surgeons should cautiously use reverse total shoulder arthroplasty in patients with anterior deltoid insufficiency.

Disclaimer

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