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The effect of reverse shoulder arthroplasty design and surgical indications on deltoid and rotator cuff muscle length

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Background: Advancements in surgical planning, technique, and prosthesis design have improved adaptation to patient anatomy in reverse total shoulder arthroplasty (rTSA). Postoperative changes in deltoid and rotator cuff muscle length are important and may vary based on preoperative indications and prosthesis selection. The purpose of this study is to demonstrate the changes in deltoid and rotator cuff muscle length for planned rTSA using the spectrum of prosthesis configurations in both glenohumeral arthritis (GHOA) and rotator cuff tear arthropathy (RCA).

Methods: Ten shoulder arthroplasty surgeons used preoperative planning software to plan rTSA cases for 20 subjects (10 GHOA, 10 RCA) following surgical guidelines. Each surgeon planned each case using 3 prosthesis configurations: (1) 8-mm lateralized glenosphere and 135° neck-shaft angle (135 + 8), (2) 4-mm lateralized glenosphere and 145° neck-shaft angle (145 + 4), and (3) 0-mm

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lateralized glenosphere and 155° neck-shaft angle (155 + 0). Pre- and postoperative deltoid and rotator cuff muscle lengths and percentage-change were calculated and compared between prosthesis configurations within each indication. Different muscle lines of action were included representing the deltoid, subscapularis, infraspinatus, and teres minor.

Results: Preoperatively, the RCA cohort had significantly shorter muscle lines of action in the posterior, lateral, and anterior deltoid ($P < .001$), a longer inferior subscapularis ($P = .022$), and a longer teres minor ($P = .001$) than the GHOA cohort. ANOVA and post-hoc analysis showed that postplanning lengths of each deltoid action line were greater in the 155 + 0 configuration compared to the 135 + 8 configuration in the RCA cohort ($P < .001$, $P = .003$, $P = .032$, respectively), and postplanning lengths of the anterior and middle deltoid action lines were also greater for the same comparison in the GHOA cohort ($P = .004$ and $P = .017$, respectively). There were no significant differences in postplanning deltoid lengths between the 135 + 8 and 145 + 4 configurations in either diagnosis cohort ($P > .05$). All postplanning rotator cuff muscle lengths (subscapularis, infraspinatus, and teres minor) differed significantly ($P < .001$) between all prosthesis configurations in both diagnosis cohorts, with the 135 + 8 configuration resulting in the longest lengths and the 155 + 0 configuration resulting in the shortest lengths.

Conclusion: Automated preoperative planning software calculates the lengths of muscle action lines, which vary between GHOA and RCA diagnoses. Varying rTSA implant geometries result in predictable differences in deltoid lengthening and rotator cuff shortening. Shoulder prostheses with a more lateralized center of rotation show greater rotator cuff muscle length and similar deltoid muscle length when compared to medialized designs with similar deltoid lengthening. Surgeons can use this software to understand the impact of implant geometry on muscle length.

Level of evidence: Basic Science Study; Computer Modeling

Keywords: Reverse total shoulder arthroplasty; glenohumeral osteoarthritis; rotator cuff arthropathy; deltoid length; rotator cuff; prosthesis design; surgical planning

Changes to reverse total shoulder arthroplasty (rTSA) prosthesis design have coincided with expansion of the indications for rTSA. Much evidence has been gathered regarding rTSA in the setting of primary glenohumeral arthritis (GHOA) with and without severe glenoid deformity with excellent outcomes.[3,6,12,13,15,17] Range of motion analysis and clinical outcomes in these patients have been found to range from similar-to-superior to rotator cuff tear arthropathy (RCA) with intact rotator cuff function considered the likely reason for improved motion.[14,19,21] Use of three-dimensional computed tomography has benefited surgeons to better understand glenohumeral deformity and studies have demonstrated increased precision with use of preoperative planning and patient-specific instrumentation.[7,10,11,18,20] These benefits have not yet translated to improved clinical outcomes; however, technological advancements show promise in providing additional information to surgeons preparing for shoulder arthroplasty.

Recent computer modeling has demonstrated increased deltoid length and moment arm in all prosthesis designs with decreased supraspinatus length and moment arm seen in all designs as well. The authors demonstrated shortening of the supraspinatus and lengthening of the deltoid across the major prosthesis designs and neck-shaft-angles.[9] It did not address the remaining rotator cuff tendons or factor in variability amongst surgeons when planning, preoperatively. It has been theorized that replicating native length-tension relationships in rTSA is optimal for function and range of motion.[5] Lädermann et al utilized another platform to determine optimal onlay component size and placement to achieve desirable length-tension of the deltoid and rotator cuff musculature.[8] To date, no study has followed the length changes for the deltoid and rotator cuff muscles between GHOA and RCA from the preoperative to planned-postoperative state.

The automated muscle elongation measurement within the Materialise planning software was recently validated to inform surgeons of these changes and allow them to plan accordingly.[16] The purpose of this study is to demonstrate the changes in deltoid and rotator cuff muscle length for planned rTSA using the spectrum of prosthesis configurations in both GHOA and RCA.

Methods

Patient selection

This retrospective cohort study was conducted on patients indicated for primary rTSA and with preoperative computed tomography (CT) imaging. Ten consecutive patients with GHOA and 10 consecutive patients with RCA (n = 20 total) were identified from the 2023 surgical schedule of the senior author (A.J.) and included in this study. Primary diagnosis was found through chart review and was retrospectively confirmed by the senior author through a review of the preoperative imaging. Patients were not excluded based on any demographic factors (ie, age, sex, insurance, etc.) or medical conditions. The GHOA and RCA cohorts were each composed of 7 females and 3 males.

Delphi process

Each aspect of the study design was determined through a Delphi process amongst 11 fellowship-trained shoulder surgeons.

Through an iterative survey process, the group members determined the method for patient selection, implant specifics, and surgical planning requirements. Each question required 80% agreement to reach consensus and be regarded as finalized. Follow-up surveys were sent to each group member in a recurring manner each week until consensus on each aspect of the study design was achieved. Each survey yielded a 100% response rate. Anonymity was maintained throughout the Delphi process.

Glenoid parameters

Preoperative CT imaging was used to calculate the following measurements of the included glenoids: degree of inclination, degree of retroversion, and percent posterior subluxation. Materialise 3D planning software calculated inclination by measuring the angle between the glenoid plane and the axis of the scapula in the coronal plane. Degree of retroversion was determined by assessing the angle of the glenoid face in relation to the scapular axis in the axial plane. Percent posterior subluxation was calculated by evaluating the degree of posterior displacement of the humeral head in relation to the scapular place expressed as a percentage.

Surgical case planning

Preoperative CT imaging was uploaded to and segmented by Mimics image processing software (version 25, Materialise NV, Leuven, Belgium) to produce 3D scapula and humerus models. They were then anonymized and shared with the participating surgeons to perform preoperative surgical planning for rTSA implantation using 3 different implant configurations on each subject with specific requirements as defined through the Delphi process:

(1) the INHANCE Shoulder System (DePuy Synthes, Raynham, MA, USA) with an 8-mm lateralized glenosphere and a 135° neck-shaft angle (referred to as 135 + 8 throughout this article),
(2) the DELTA XTEND Reverse Shoulder System (DePuy Synthes, Raynham, MA, USA) with a 4-mm lateralized glenosphere and a 145° neck-shaft angle (referred to as 145 + 4 throughout this article), and
(3) the DELTA XTEND Reverse Shoulder System with a medialized (0-mm lateralized) glenosphere and a 155° neck-shaft angle (referred to as 155 + 0 throughout this article).

Only nonaugmented baseplates were used and all cases planned were also required to adhere to the following additional guidelines:

(A) glenospheres selected may be of any diameter, but must have the correct magnitude of lateralization of the center-of-rotation (COR),
(B) glenoid retroversion must be corrected to 15° or less,
(C) superior inclination must be corrected to 0° or less with relative inferior tilt, and
(D) baseplate coverage of the glenoid must be at least 70%.

Glenoid version and inclination were measured using a technique similar to that implemented by Frankle et al.[4] However, instead of connecting the anterior and posterior glenoid rims for version, and connecting the superior and inferior rims for inclination, a plane was first fit through the glenoid face. The normal of this plane was then projected to the correct scapular plane, which allowed us to measure the corresponding angles for version and inclination.

With each surgeon (n = 10) completing the surgical planning for each patient (n = 20) using 3 distinct implant configurations (135 + 8, 145 + 4, and 155 + 0), there were 600 total cases planned.

Muscle elongation measurement

To quantify muscle lengths, this study used methods that were reported previously,[16] with some changes to the muscle trajectories as described below. The algorithms implementing these methods were created with custom scripts in Python (version 3.8; Python Software Foundation, Wilmington, DE, USA).

The muscle lines investigated in this study included the following: the anterior, middle, and posterior deltoids; the superior borders, mid-lines, and inferior borders of the infraspinatus and subscapularis; and the teres minor. Starting from the previously reported work,[16] several muscles were split into different parts, each represented by a different line trajectory. This technique is commonly used for musculoskeletal models to better approximate muscles with wide attachment sites.[2] Specifically, the anterior part of the deltoid muscle was added (the posterior and middle parts were already present), and the infraspinatus and subscapularis muscles were each split into 3 parts. To this end, the following changes were applied to the muscle origin points and the fixed wrapping directions:

- A point on the clavicle was added to represent the origin of the anterior part of the deltoid muscle, with the anterolateral direction used as the fixed wrapping direction for this part;
- The point representing the infraspinatus muscle origin on the scapula was replaced by 3 points to split this muscle into a superior, middle, and inferior part, with all parts using the posterior wrapping direction;
- The point representing the subscapularis muscle origin on the scapula was replaced by 3 points to split this muscle into a superior, middle, and inferior part, with all parts using the anterior wrapping direction.

The muscle origin points on the scapula and humerus were located as before,[16] by manually indicating them once on the statistical shape model mean shape (Fig. 1), using the statistical shape model fitting procedure to move them near the target scapulae and humeri, and projecting them onto the patients' bone models. To locate the anterior deltoid origin on the patients' clavicles, a 3D model of each patient's clavicle was constructed using the CT Bone segmentation algorithm in Mimics version 25 (Materialise NV, Leuven, Belgium). As only a single attachment point was needed for this bone, we manually indicated this point for each patient separately (Fig. 2). All manual point indications were performed by 2 experts (S.V. and A.J.) working in consensus. For each muscle that was split, the different origin points were connected to the same insertion point, resulting in a set of different trajectories (Fig. 3).

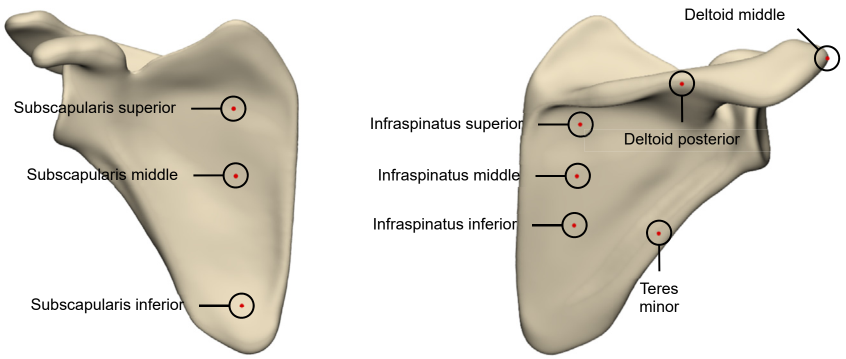

Figure 1 Anterior (*left*) and posterior (*right*) view of the scapula SSM mean shape, with the manually indicated muscle trajectory origin points highlighted. *SSM*, statistical shape model.

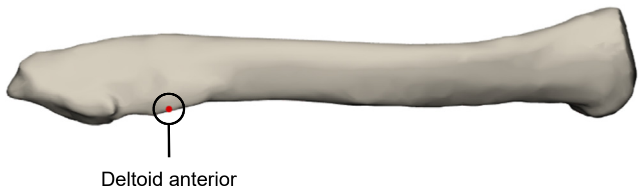

Figure 2 Representative views of the 3D model representing the right clavicle of one patient, with the manually indicated anterior deltoid origin for that patient highlighted.

Statistical analysis

Univariate analysis using the unpaired two-sample *t*-test was conducted to identify statistically significant differences between the GHOA and RCA cohorts in patient characteristics and glenoid parameters, including age, sex, body mass index, degrees of inclination, degrees of retroversion, and percent posterior subluxation. Following the muscle elongation measurement of each patient, a dataset was created containing the preoperative and resultant "postoperative" (postsurgical planning) muscle lengths, as well as the percentage-change-in muscle length for each muscle investigated. Preoperative muscle lengths were first pooled by diagnosis (GHOA and RCA) and descriptive statistics (group means and standard deviations) were calculated for each muscle. Univariate testing using the unpaired two-sample *t*-test was then performed to identify statistically significant differences in preoperative muscle lengths between the GHOA and RCA cohorts.

The study population was then stratified in a two-fold manner within the dataset, first by diagnosis (GHOA and RCA) and then by implant configuration (135 + 8, 145 + 4, and 155 + 0). This created 3 discrete sub-cohorts of planned surgical cases within each of the 2 diagnosis cohorts. The values representing postoperative length and percentage-change-in muscle length were isolated for each sub-cohort and descriptive statistics were performed to calculate the means and standard deviations for each muscle. ANOVA testing was then performed to identify statistically significant differences in the average postoperative length and percentage-change-in muscle lengths, first between each of the GHOA sub-cohorts (GHOA [135 + 8], GHOA [145 + 4], and GHOA [155 + 0]) and then between each of the RCA sub-cohorts (RCA [135 + 8], RCA [145 + 4], and RCA [155 + 0]). If a statistically significant difference was found between sub-cohorts, posthoc pairwise comparison testing was performed to compare sub-cohort averages in a head-to-head fashion.

Bonferroni corrections were performed in each statistical comparison to mitigate the risk of type I errors. All statistical analyses were performed using R statistical software (R Foundation for Statistical Computing, Vienna, Austria).

Results

Patient and glenoid characteristics by diagnosis

Both the GHOA and RCA cohorts consisted of 70% females (n = 7). The average body mass index was 29.2 ± 3.8 and 29.7 ± 6.8 kg/m^2 ($P = .833$) and the average age was 69.6 ± 5.8 and 73.5 ± 8.4 ($P = .245$) in the GHOA and RCA cohorts, respectively. The RCA cohort had a significantly greater degree of inclination of the glenoid compared to the GHOA cohort (11.1° ± 6.0° vs. 4.0° ± 5.7°; $P = .014$). There was no significant difference between the degrees of retroversion (9.8° ± 5.2° vs. 15.4° ± 11.5°; $P = .185$) and percent posterior subluxation (54.3% ± 6.8% vs. 65.8% ± 18.1%; $P = .086$) in the RCA and GHOA cohorts respectively (Table I). The Walch and Favard classifications for the GHOA and RCA cohorts respectively, are displayed in Table I.

Preoperative differences by diagnosis

Significant differences in muscle lengths of both deltoid and rotator cuff were seen when comparing preoperative diagnoses of GHOA and RCA. The preoperative deltoid length was significantly shorter in all action lines (anterior, middle, posterior) in RCA ($P < .001$). This is in keeping with superior migration of the humerus seen with cuff arthropathy. This superior position also caused an increased preoperative length in the teres minor (106.1 ± 6.7 mm vs.

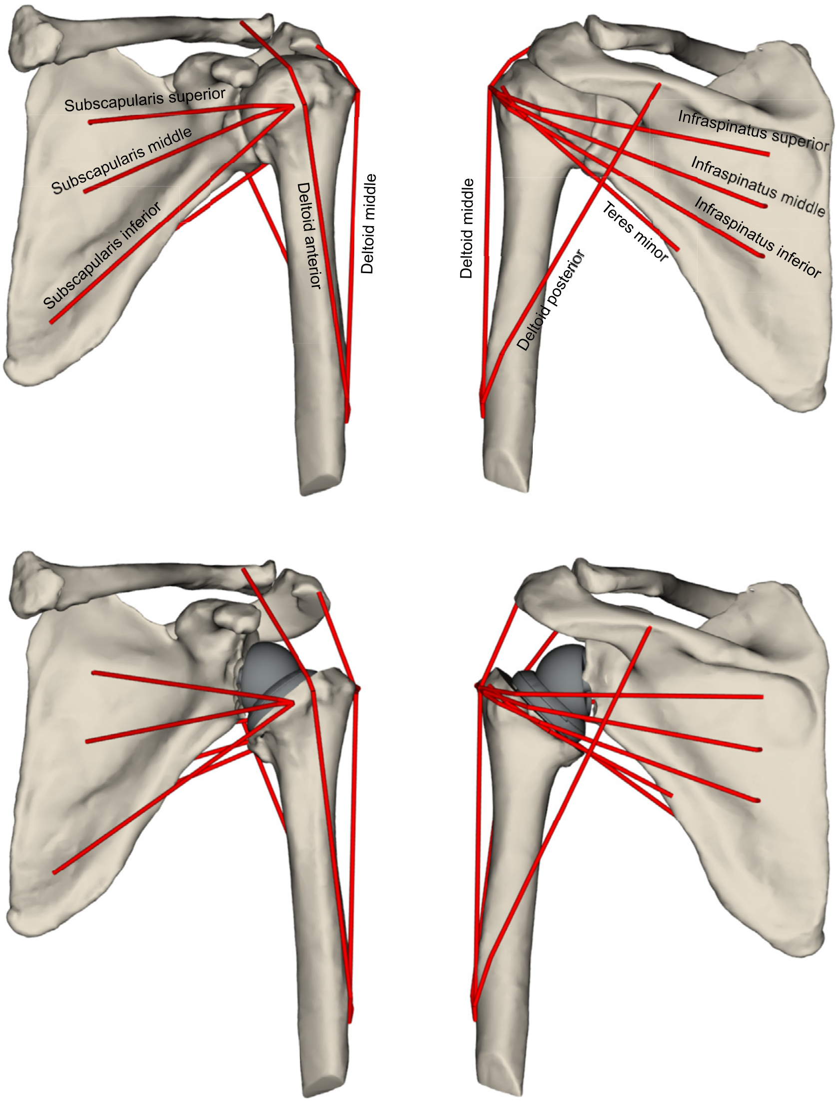

Figure 3 Anterior (*left*) and posterior (*right*) view of the bones (*beige*), implant components (*gray*) and muscle trajectories (*red*) for one patient, showing the planned preoperative (*top*) and postoperative (*bottom*) configurations. For this example, the planning for the Inhance (135 + 8) implant is shown.

102.4 ± 8.4 mm, $P = .001$) and the subscapularis inferior (149.8 ± 16.7 mm vs. 145.1 ± 10.2 mm, $P = .022$). The remaining subscapularis and all infraspinatus action lines did not demonstrate significant differences between preoperative diagnosis groups (Table II).

Deltoid lengthening

In the cases planned for GHOA, significant differences in deltoid length were seen for the anterior ($P < .001$), middle ($P < .001$), and posterior deltoid ($P = .007$). Posthoc, pairwise analysis revealed significant differences in anterior, middle, and posterior deltoid action lines between the 135 + 8 and 155 + 0 designs, while a significant difference in the posterior deltoid action line was only seen when comparing the 155 + 0 and 145 + 4 implants. No significant differences in any deltoid muscle line of action were seen when comparing the 135 + 8 and 145 + 4 designs. Overall, the 135 + 8 design resulted in the least amount of lengthening of the deltoid muscle action lines (10%-12% for all lines of action of the deltoid) compared to the 145 + 4 design (11%-13%) and the 155 + 0 design (13%-15%) (Table III).

Similar findings were reflected in the deltoid length changes in the RCA cohort. All deltoid muscle lines of action were considered significantly different on ANOVA analysis. Direct comparison between implant designs for

Table I Comparison of patient and glenoid characteristics by diagnosis

	GHOA n = 10	RCA n = 10	*P* value
Age	69.6 ± 5.8	73.5 ± 8.4	.245
Female sex	7 (70%)	7 (70%)	1.000
BMI	29.2 ± 3.8	29.7 ± 6.8	.833
Walch classification			
A1	2 (20%)	-	
A2	2 (20%)	-	
B1	0 (0%)	-	
B2	4 (40%)	-	
B3	1 (10%)	-	
C	0 (0%)	-	
D	0 (0%)	-	
Favard classification			
E0	-	4 (40%)	
E1	-	1 (10%)	
E2	-	3 (30%)	
E3	-	2 (20%)	
E4	-	0 (0%)	
Glenoid parameters			
Inclination (°)	4.0 ± 5.7	11.2 ± 6.0	.014*
Retroversion (°)	15.4 ± 11.5	9.8 ± 5.2	.185
Posterior subluxation (%)	65.8 ± 18.1	54.3 ± 6.8	.086

GHOA, glenohumeral osteoarthritis; *RCA*, rotator cuff arthropathy; *BMI*, body mass index.
* Denotes statistical significance with alpha risk set to 0.05; x ± s represents mean and standard deviation; n (%) represents count and frequency.

patients with RCA demonstrated fewer significant differences for the 145 + 4/155 + 0 comparison, and no significant differences for the 135 + 8/145 + 4 comparison except for the percentage change in anterior deltoid length ($P = .027$). Significant differences in deltoid length were maintained across all deltoid muscle action lines in pairwise analysis for the 135 + 8/155 + 0 comparison. Because of significant relative preoperative shortening of the deltoid in the RCA group, a higher degree of deltoid lengthening was seen. Again, the 135 + 8 design produced the least amount of lengthening of these muscle lines (15%-17% for all lines of action of the deltoid) compared to the 145 + 4 design (18%-19%) and the 155 + 0 design (19%-20%) (Table IV).

Rotator cuff shortening

Significant differences were found in all lines of action of the infraspinatus, subscapularis, and the teres minor ($P < .001$) muscles across implant designs for both GHOA and RCA. A small degree of subscapularis lengthening was seen in the superior subscapularis lines of action for the 135 + 8 and 145 + 4 designs (∼5%-7%, $P < .001$), while

Table II Comparison of preoperative muscle length by diagnosis

Muscle	GHOA *N = 10*	RCA *N = 10*	*P* value
Deltoid (mm.)			
Posterior	186.1 ± 9.9	170.8 ± 8.7	**<.001***
Middle	177.3 ± 8.6	170.0 ± 7.0	**<.001***
Anterior	201.3 ± 7.2	191.5 ± 6.8	**<.001***
Infraspinatus (mm.)			
Middle	133.7 ± 7.6	136.4 ± 15.2	.137
Superior	135.0 ± 13.7	135.5 ± 9.5	.773
Inferior	145.6 ± 10.7	146.2 ± 11.3	.693
Subscapularis (mm.)			
Middle	111.6 ± 7.5	114.1 ± 14.8	.160
Superior	102.7 ± 7.1	104.9 ± 14.2	.202
Inferior	145.1 ± 10.2	149.8 ± 16.7	**.022***
Teres minor (mm.)	102.4 ± 8.4	106.1 ± 6.7	**.001***

GHOA, glenohumeral osteoarthritis; *RCA*, rotator cuff tear arthropathy.
* Statistical significance with alpha risk of 0.05; x ± s represents mean and standard deviation.

shortening of the rotator cuff was seen in all other lines of action for all rotator cuff muscles studied. Muscle lines of action demonstrated the greatest degree of shortening in the 155 + 0 design ($P < .001$), followed by 145 + 4 ($P < .001$), and the least shortening with 135 + 8 ($P < .001$). The 155 + 0 implant showed shortening of the infraspinatus of ∼12-13% (vs. ∼2-3% with 135 + 8), the subscapularis of ∼4-18% (vs. lengthening up to ∼7% with 135 + 8), and teres minor of ∼23% (vs. ∼7% with 135 + 8) in the GHOA group ($P < .001$). For the 155 + 0 prosthesis in the RCA group, infraspinatus shortening was on the order of ∼11%-16% (vs. 2%-5% with 135 + 8), while the subscapularis shortened ∼7%-22% (vs. lengthening up to ∼5% with 135 + 8), and teres minor shortened ∼28% (vs. ∼12% with 135 + 8, $P < .001$).

Discussion

Through validated preoperative planning software, changes in deltoid and rotator cuff muscle lengths were differentiated across primary GHOA and RCA in preoperative and postoperative planning states using varying offset rTSA implants. Rotator cuff arthropathy showed greater deltoid lengthening and a larger degree of shortening of the inferior subscapularis and teres minor compared to primary GHOA. This was attributed to the superior position of the humeral head relative to the glenoid face and scapular axis in the RCA group, preoperatively. All rTSA designs demonstrated relative deltoid lengthening compared to the preoperative state in both GHOA and RCA and overall shortening of the subscapularis, infraspinatus, and teres minor. Implant designs incorporating increasing glenoid lateral offset resulted

Table III Comparison of final and change in muscle length by prosthesis configuration in the GHOA cohort

Muscle	Prosthesis configurations			ANOVA	Posthoc pairwise comparison*		
	135 + 8†	145 + 4‡	155 + 0§		*P* values		
	N = 100	*N = 100*	*N = 100*	*P* value	135 + 8/ 145 + 4	135 + 8/ 155 + 0	145 + 4/ 155 + 0
Deltoid							
Anterior, final (mm)	222.6 ± 10.9	223.9 ± 10.7	227.6 ± 11.1	**.004**‖	>.999	**.004**‖	.051
Anterior,¶ (%)	10.6 ± 2.4	11.2 ± 2.8	13.1 ± 3.9	#	.460	#	#
Middle, final (mm)	199.1 ± 13.1	200.4 ± 14.2	204.7 ± 14.8	**.016**‖	>.999	**.017**‖	.105
Middle,¶ (%)	12.2 ± 3.4	13.0 ± 3.8	15.4 ± 4.0	#	.430	#	#
Posterior, final (mm)	207.9 ± 11.5	208.1 ± 11.1	210.6 ± 11.5	.182	-	-	-
Posterior,¶ (%)	11.8 ± 3.3	11.8 ± 3.6	13.2 ± 3.8	**.007**‖	>.999	**.017**‖	**.024**‖
Infraspinatus							
Middle, final (mm)	131.2 ± 8.4	122.8 ± 7.7	115.4 ± 7.8	#	#	#	#
Middle,¶ (%)	−1.8 ± 5.4	−8.1 ± 5.4	−13.6 ± 5.6	#	#	#	#
Superior, final (mm)	142.4 ± 10.0	133.4 ± 9.6	125.8 ± 10.0	#	#	#	#
Superior,¶ (%)	−2.17 ± 4.8	−8.1 ± 5.4	−13.4 ± 5.8	#	#	#	#
Inferior, final (mm)	131.0 ± 9.4	124.5 ± 8.9	118.4 ± 8.9	#	#	#	#
Inferior,¶ (%)	−2.6 ± 5.1	−7.3 ± 5.1	−12.0 ± 5.3	#	#	#	#
Subscapularis							
Middle, final (mm)	112.4 ± 7.8	104.3 ± 7.3	97.2 ± 7.7	#	#	#	#
Middle,¶ (%)	0.88 ± 4.6	−6.3 ± 4.9	−12.7 ± 5.4	#	#	#	#
Superior, final (mm)	110.25 ± 6.7	103.4 ± 5.9	98.2 ± 6.3	#	#	#	#
Superior,¶ (%)	7.43 ± 4.9	0.899 ± 5.1	−4.17 ± 5.4	#	#	#	#
Inferior, final (mm)	136.9 ± 9.1	127.8 ± 9.0	119.1 ± 9.1	#	#	#	#
Inferior,¶ (%)	−5.5 ± 4.4	−11.7 ± 4.7	−17.8 ± 5.0	#	#	#	#
Teres minor, final (mm)	95.1 ± 7.0	86.6 ± 7.5	79.0 ± 8.1	#	#	#	#
Teres minor,¶ (%)	−6.9 ± 5.2	−15.4 ± 5.5	−22.9 ± 5.7	#	#	#	#

GHOA, glenohumeral osteoarthritis; *ANOVA*, analysis of variance.
x ± s represents mean and standard deviation.
* Pairwise t-test with bonferroni corrections.
† 135 + 8 cases were planned with glenospheres with +8 mm lateralized center of rotation (COR) and 135° neck-shaft angles.
‡ 145 + 4 cases were planned with a glenosphere with a +4 mm lateralized COR and 145° neck-shaft angle.
§ 155 + 0 cases were planned with a glenosphere with a +0 mm lateralized COR and 155° neck-shaft angle.
‖ Statistical significance with alpha risk of .05.
¶ The percentage change in muscle length between pre- and post-surgical planning.
\# Represents $P < .001$.

in less overall deltoid length changes, and less overall rotator cuff shortening. The use of an 8 mm glenoid-lateralized COR and 135-degree neck-shaft angle (NSA) with an inlay-type humeral design resulted in the greatest rotator cuff length for both GHOA and RCA indications, followed by the use of a 4 mm glenoid-lateralized COR and 145-degree NSA with an onlay-type humeral design, and finally the use of a 0 mm glenoid-lateralized COR and 155-degree NSA with an onlay-type humeral design.

This study demonstrates deltoid lengthening across all prosthesis designs, with more modest changes in the 135° NSA and 8 mm lateralized COR design. There were no statistically significant differences between the 135 + 8 and 145 + 4 configurations, though this may have been confounded by the inconsistency in humeral tray design, whereby 135 + 8 utilized an inlay design and 145 + 4 utilized an onlay design. Our results are generally consistent with previous work by Levin et al who demonstrated less overall lengthening in the anterior and middle deltoid muscle lines for Lateralized-Glenoid, Medialized Humerus, 135° NSA designs, but a more natural force-length relationship. Their study demonstrated that this design allowed for operation of the deltoid on the ascending portion of the Blix curve through a greater range of motion. Similarly, the Medialized Glenoid, Medialized Humerus, 155° NSA design in their study demonstrated a much greater increase in moment arm, but relative over-lengthening of muscle fibers beyond the optimal force-length relationship on the Blix curve.[9] Again, this is consistent with our observation that the deltoid is lengthened to a much greater extent in the 155° NSA, 0 mm glenoid-lateralized COR configuration, especially when the preoperative deltoid shortening in the RCA cohort is considered. The optimal degree of deltoid lengthening would

Table IV Comparison of final and change in muscle length by prosthesis configuration in the RCA cohort

Muscle	Prosthesis configurations			ANOVA	Posthoc pairwise comparison*		
	135 + 8[†]	145 + 4[‡]	155 + 0[§]		*P* values		
	N = 100	*N* = 100	*N* = 100	*P* value	135 + 8/ 145 + 4	135 + 8/ 155 + 0	145 + 4/ 155 + 0
Deltoid							
Anterior, final (mm)	219.9 ± 10.4	223.4 ± 11.0	227.1 ± 11.5	‖	.113	‖	.069
Anterior,¶ (%)	15.0 ± 4.0	18.6 ± 5.0	18.9 ± 5.0	‖	**.027**#	‖	**.019**#
Middle, final (mm)	198.8 ± 11.9	201.1 ± 12.1	204.7 ± 11.9	**.004**#	.581	**.003**#	.144
Middle,¶ (%)	16.9 ± 3.90	18.3 ± 4.3	20.3 ± 4.5	‖	.094	‖	**.004**#
Posterior, final (mm)	200.1 ± 8.2	201.3 ± 8.6	203.4 ± 8.9	**.036**#	>.999	**.032**#	.318
Posterior,¶ (%)	17.2 ± 4.1	18.0 ± 4.3	19.1 ± 4.5	**.009**#	.775	**.008**#	.176
Infraspinatus							
Middle, final (mm)	131.0 ± 8.4	122.5 ± 8.6	114.8 ± 8.5	‖	‖	‖	‖
Middle,¶ (%)	−3.3 ± 5.9	−9.5 ± 5.8	−15.2 ± 5.9	‖	‖	‖	‖
Superior, final (mm)	138.2 ± 10.1	129.6 ± 9.5	122.5 ± 9.3	‖	‖	‖	‖
Superior,¶ (%)	−5.3 ± 4.6	−11.3 ± 5.1	−16.1 ± 5.9	‖	‖	‖	‖
Inferior, final (mm)	133.6 ± 11.4	126.7 ± 11.2	120.7 ± 10.9	‖	‖	‖	‖
Inferior,¶ (%)	−1.5 ± 3.9	−6.5 ± 4.2	−10.9 ± 4.9	‖	‖	‖	‖
Subscapularis							
Middle, final (mm)	110.8 ± 10.7	102.8 ± 10.1	95.3 ± 10.1	‖	‖	‖	‖
Middle,¶ (%)	−2.4 ± 4.7	−9.6 ± 4.4	−16.2 ± 4.0	‖	‖	‖	‖
Superior, final (mm)	109.5 ± 10.2	102.8 ± 9.7	97.2 ± 9.5	‖	‖	‖	‖
Superior,¶ (%)	5.0 ± 5.5	−1.4 ± 5.4	−6.8 ± 5.2	‖	‖	‖	‖
Inferior, final (mm)	134.7 ± 12.8	125.1 ± 12.3	116.3 ± 12.2	‖	‖	‖	‖
Inferior,¶ (%)	−9.8 ± 4.0	−16.2 ± 4.0	−22.3 ± 3.8	‖	‖	‖	‖
Teres minor, final (mm)	93.1 ± 7.7	84.2 ± 8.1	76.6 ± 8.8	‖	‖	‖	‖
Teres minor,¶ (%)	−12.1 ± 6.2	−20.5 ± 6.8	−27.8 ± 7.5	‖	‖	‖	‖

RCA, rotator cuff tear arthropathy; *ANOVA*, analysis of variance.
x ± s represents mean and standard deviation.
* Pairwise t-test with bonferroni corrections.
† 135 + 8 cases were planned with glenospheres with +8 mm lateralized center of rotation (COR) and 135° neck-shaft angles.
‡ 145 + 4 cases were planned with a glenosphere with a +4 mm lateralized COR and 145° neck-shaft angle.
§ 155 + 0 cases were planned with a glenosphere with a +0 mm lateralized COR and 155° neck-shaft angle.
‖ Represents $P < .001$.
¶ The percentage change in muscle length between pre- and postsurgical planning.
# Statistical significance with alpha risk of .05.

maximally increase the moment arm of the deltoid without exceeding this force-length relationship. Further studies on this topic should continue to incorporate three-dimensional modeling and multiple deltoid action lines to adequately simulate all components of the deltoid. The next step would be incorporation of the force-length relationship with data on impingement-free range-of-motion to determine relative differences in deltoid force production at various degrees of abduction and elevation. Integrating the changes in glenohumeral joint alignment and center-of-rotation with the adjustments in muscle unit lengths is the logical next step in optimizing outcomes for rTSA.

The infraspinatus and teres minor shorten significantly in all rTSA configurations studied here. The middle and superior subscapularis lengthens marginally in the most lateralized designs for GHOA; however, the subscapularis is generally shorter postoperatively in RCA. This is clearly relevant for achieving optimal soft-tissue tension in rTSA for ideal function, but also to reduce the risk of dislocation. These findings do not align with that reported by Lädermann et al who demonstrated elongation of the infraspinatus and superior subscapularis in their computer modeling study of a single 145° NSA onlay prosthesis.[8] Their study also approximated changes in length for the supraspinatus, finding lengthening for the supraspinatus, infraspinatus, and upper muscle line of the subscapularis in all constructs. Besides the variation in implant design from this study, these authors also manually measured the infraspinatus and subscapularis from their most lateral attachment on the scapula, linearly, to several points on the tuberosities, and was built off a single cadaveric shoulder. In this study, a statistical shape model approach was used to obtain insertion and attachment on scapula and humerus to avoid case-by-case bias. Moreover, wrapping of the muscle lines around bony structures was assured, as explained in Pitocchi et al. Additionally, the Lädermann model utilized a +6 mm polyethylene insert as standard for all models as this is the method by which their implant achieved an additional 12.5 degrees of valgus neck-shaft-angle to reach 145. Levin et al demonstrated supraspinatus lengthening in the lateralized glenoid and medialized humeral design condition in their study, but found this muscle to shorten in both configurations of a medialized glenoid, also differing from the work by Lädermann et al. Elongation of the supraspinatus was not included in the present analysis, since the relevance is limited within the context of our RCA cohort. Nevertheless, the supraspinatus elongations could be included in future studies.

Individualized examination of changes in the infraspinatus and teres minor is warranted, as many patients are indicated for rTSA for RCA or for massive rotator cuff tear. As Berton et al pointed out, a functional teres minor is often present in these individuals and may be vital for acceptable external rotation after rTSA.[1] Not only did our study demonstrate significant preoperative lengthening in the teres minor in the RCA group relative to that of the GHOA group, we found that the 155 + 0 configuration shortened this muscle on average 27.8% in the RCA group and 22.9% in the GHOA group. By using a relatively lateralized glenosphere and neutral humeral component (135 + 8 configuration), the teres minor shortened 12.1% and 6.9%, respectively. The infraspinatus shortened approximately 2%-5% across both groups with the 135 + 8 configuration compared to ∼11%-16% across both groups with the 155 + 0 configuration. According to Berton et al, rTSA results in shortening of the teres minor of up to 20%, although the change in center-of-rotation results in an improved moment arm of the muscle. We postulate that the relative distalization of the humerus produces a more horizontal line of action for the teres minor, further improving its function as an external rotator. Berton et al also used a computer model to demonstrate teres minor length and function through a variety of activities of daily living and determined that a humeral version between 0° and 20° was the best compromise to achieve optimal teres minor length and moment arm with minimal impingement.[1] Our study builds on this by examining which design may reproduce the most natural length of these external rotators, although humeral stem version was not controlled in our study.

Several limitations to this study are presented. Firstly, although based on the three-dimensional reconstructions of 20 individual shoulders, there are always inherent limitations to utilization of a computer model in predicting in-vivo success. We recognize that selecting points of reference for origin and insertion may be initially arbitrary, however, the use of a statistical shape model and previously validated method[16] for applying the model to these individual cases helped remove the bias of hand-picking every origin and insertion point for each case. Surgeons are likely to plan each case to achieve a maximum allowable impingement-free range-of-motion, but various factors may change that plan intra-operatively. We did not provide clinical correlation of outcomes relative to our planning and cannot comment on how relative deltoid or rotator cuff length changes across disease states for various implant geometries affects strength, function, and overall outcomes. The authors acknowledge that the study is limited to 3 prostheses from a single company, however, each have dramatically different features and design philosophies. These differing features allow us to compare the various designs within the same software model—an actual planning software that is used commercially as opposed to one created for the purpose of this study. We also acknowledge that this results in slightly different stem geometries and different dwell points of articulation. The Inhance stem is lateralized relative to the Delta Xtend due to its lower NSA and its flush-lay design. This adds a layer of confounding relative to comparing the Xtend with another inlay stem with a 135° NSA. Because of the difference in implant geometries including COR, humeral design, and overall offset, our data may not be generalizable or applicable to other implant systems not included in the study. Future investigations should focus on glenoid erosion patterns in GHOA and RCA, using the Walch classification system for GHOA and the Favard classification system for RCA. Our planning incorporated, to the best of our abilities, a standardized approach to glenoid sided planning, which was agreed on by 11 shoulder arthroplasty surgeons in unanimity through a multi-step Delphi process. Glenoid planning accounted for relatively neutral version and slight inferior tilt relative to the anatomic axis of the scapula, while humeral implantation guidelines were not accounted for. It may be that humeral version changes relative to varying implant NSA and inlay/onlay designs may change muscle lines of action. Further studies looking at changes in humeral orientation and overall implant factors are warranted. Other implant orientations including relative retroversion, alternative center line, or higher "more anatomic" baseplate placement have shown clinical successes and would theoretically affect muscle lines of action but were not studied. Despite these limitations, understanding relevant muscle length relationships by surgical indication and implant design is potentially important for surgeon understanding and implant design optimization.

Conclusion

Automated preoperative planning software allows for determination of muscle length. Deltoid and rotator cuff muscle length vary by preoperative diagnosis of glenohumeral arthritis and rotator cuff arthropathy. Shoulder prostheses with a more lateralized center of rotation show greater rotator cuff muscle length and similar deltoid muscle length when compared to medialized designs with similar deltoid lengthening. Further studies are needed to determine if prosthesis design approximates premorbid muscle length, and if this can predict improved patient outcomes. Additionally, research should explore whether restoring normal anatomy or adhering to Grammont principles, which rely primarily on the deltoid, better restores function.

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