Posterior and inferior glenosphere position in reverse total shoulder arthroplasty supports deltoid efficiency for shoulder flexion and elevation

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Background: For humeral flexion and elevation, most relevant for daily activities with reverse total shoulder arthroplasty, the anterior and lateral deltoid muscles are most important. However, how this direction of movement is best supported with the glenosphere position is not fully understood. We hypothesized that both inferior positioning and posterior positioning of the glenosphere may best support this direction of movement.
Methods: A validated, anatomic biomechanical shoulder model was modified to host a reverse shoulder prosthesis. The glenoid baseplate was altered to allow inferior, lateral, and posterior center-of-rotation (COR) offsets. An optical tracking system was used to track the excursion of ropes simulating portions of various shoulder muscles during humeral abduction, elevation, and flexion.
Results: The inferior COR offset resulted in a significant increase in the deltoid moment arm in all 3 planes of motion. The lateral COR offset showed a significantly lower posterior deltoid moment arm during humeral abduction and a significantly lower lateral deltoid moment arm during humeral elevation. The posterior offset showed significantly larger anterior and lateral deltoid moment arms during humeral flexion.
Discussion and conclusion: Owing to the oblique direction of the deltoid muscle across the shoulder joint, an inferior offset of the COR in reverse total shoulder arthroplasty increases the deltoid moment arm during abduction, elevation, and flexion, whereas it mainly supports humeral flexion at a posterior offset. For humeral elevation and flexion, favorable positioning of the glenosphere may, therefore, be defined by a more inferior and posterior placement compared with the non-offset position.
Level of evidence: Basic Science Study; Biomechanics
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Keywords: Reverse total shoulder arthroplasty; deltoid muscle; muscle moment arm; joint center of rotation; glenosphere position; glenoid offset

Despite the undisputed success and benefit of reverse shoulder arthroplasty, complications remain, such as acromial fracture, implant loosening, scapular notching, and dislocation.[4,5,11,20,24,27,31] Such unwanted events and the fact

that there is still considerable variability in the active movement of patients suggest that not all aspects of the biomechanics of reverse shoulder prostheses are fully understood.

Comparisons between the anatomic shoulder and reverse total shoulder arthroplasty (RTSA) regarding muscle moment arms, muscle forces, and range of motion (ROM) have been reported in a variety of biomechanical, cadaveric, and computational studies. These concluded on an inferior-medialized center of rotation (COR) compared with the anatomic shoulder, leading to an increased deltoid moment arm and reduced ROM.[1,3,14,15,21,30] An increased deltoid moment arm improves deltoid efficiency to achieve humeral elevation.[13] In RTSA, the anterolateral deltoid muscle is the most important abductor in the case of a rotator cuff tear.[1] Therefore, the influence of RTSA design parameters on the moment arm of this portion of the deltoid muscle appears to be particularly important.

There have been studies that analyzed lateralization of the COR[14] and superior and lateral COR displacement,[15] as well as humeral lateralization, concluding that humeral lateralization counters some of the negative effects of COR lateralization.[10] Other studies have evaluated the effect of a posterior humeral offset in terms of ROM[6] and moment arm analysis.[22] Reduced ROM and better teres minor tensioning could be recorded, but no moment arm analysis of the deltoid was stated.[22] Humeral offset mechanically has the same effect on shoulder muscle moment arms as offset of the glenosphere owing to a relative change in COR in both situations. However, no work has taken into consideration isolated displacement of the glenosphere and the COR particularly in the posterior or inferior direction in relation to the deltoid moment arm.

The purpose of this study was to analyze the influence of changing the COR by offsetting the glenosphere 11 mm inferiorly, 5 mm laterally, or 5 mm posteriorly on the deltoid moment arm as represented by ropes in an in vitro validated model. We hypothesized that (1) an inferior offset of the COR in RTSA would result in a larger deltoid moment arm during arm movement in different planes, (2) a posterior offset of the COR in RTSA would result in a larger anterior deltoid moment arm during humeral flexion and consequently reduce the required deltoid muscle forces to elevate the arm, and (3) lateralization of the COR in RTSA would decrease the deltoid moment arm during arm movement in different planes.

Materials and methods

Adjustable RTSA implant

In this vitro biomechanical study, it was possible to measure moment arms of shoulder muscles and to investigate the effect of COR offsets in different directions on the moment arms. To test the hypotheses independently of the limited implant configurations commercially available, a customized glenoid component was designed (Fig. 1).[19]

As described by Meisterhans,[19] the baseplate from the Anatomical Shoulder Replacement System (Zimmer, Warsaw, IN, USA) was replaced by a custom baseplate that allowed offset of the COR into superior-inferior, anterior-posterior, and lateral directions (Fig. 1, C). A 5-mm-thick aluminum baseplate with a 29-mm diameter, equipped with a 4-mm screw on the back to allow fixation to the glenoid of the scapula, was designed. The glenoid was reamed to the extent that the distal face of the baseplate was on the same level as the Zimmer baseplate of the Anatomical Shoulder Replacement System. A 40-mm trial glenosphere from the Anatomical Shoulder Replacement System was modified with a centered 4-mm pin instead of the original oval peg to allow a push-fit connection with the custom baseplate (Fig. 1, A). With the help of this centered pin, the glenosphere can be inserted into designated holes at the front of the baseplate, allowing a neutral position or a displacement of either 5, 7, 9, or 11 mm into inferior-superior and anterior-posterior directions. For the lateral offset of the COR, 5- and 10-mm spacers can be used (Fig. 1, B).[19] In this study, only a neutral position of the glenosphere and 11-mm inferior, 5-mm lateral, and 5-mm posterior offsets were analyzed to assess the stated hypotheses.
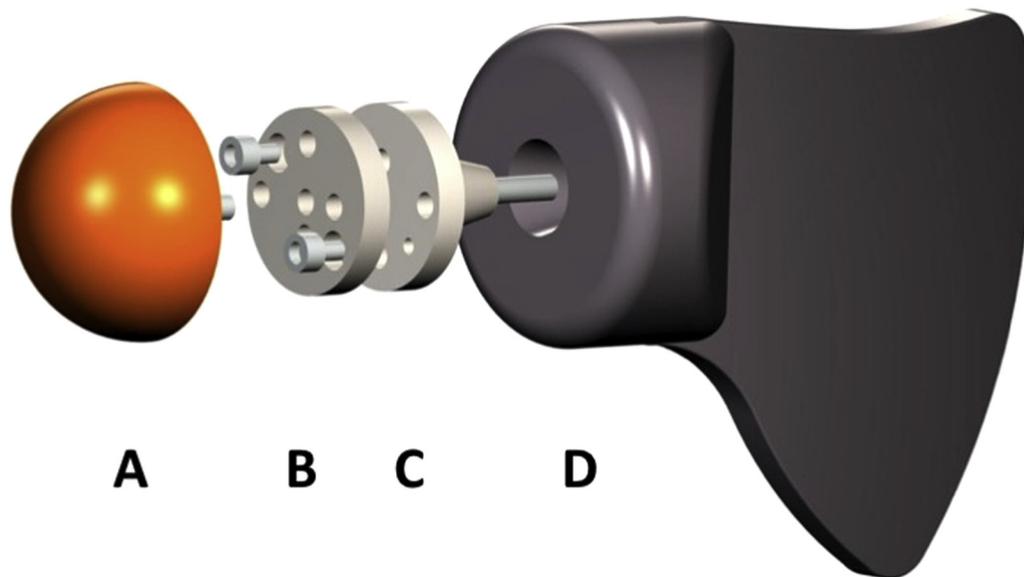
A size 9 stem from the Anatomical Shoulder Replacement System was implanted in 20° of humeral retroversion, and a 6-mm off-center humeral trial cup was used.[7] The glenoid component was implanted in neutral version, with the border of the custom baseplate placed flush with the inferior border of the glenoid rim to achieve optimal glenoid component positioning.[7,21]
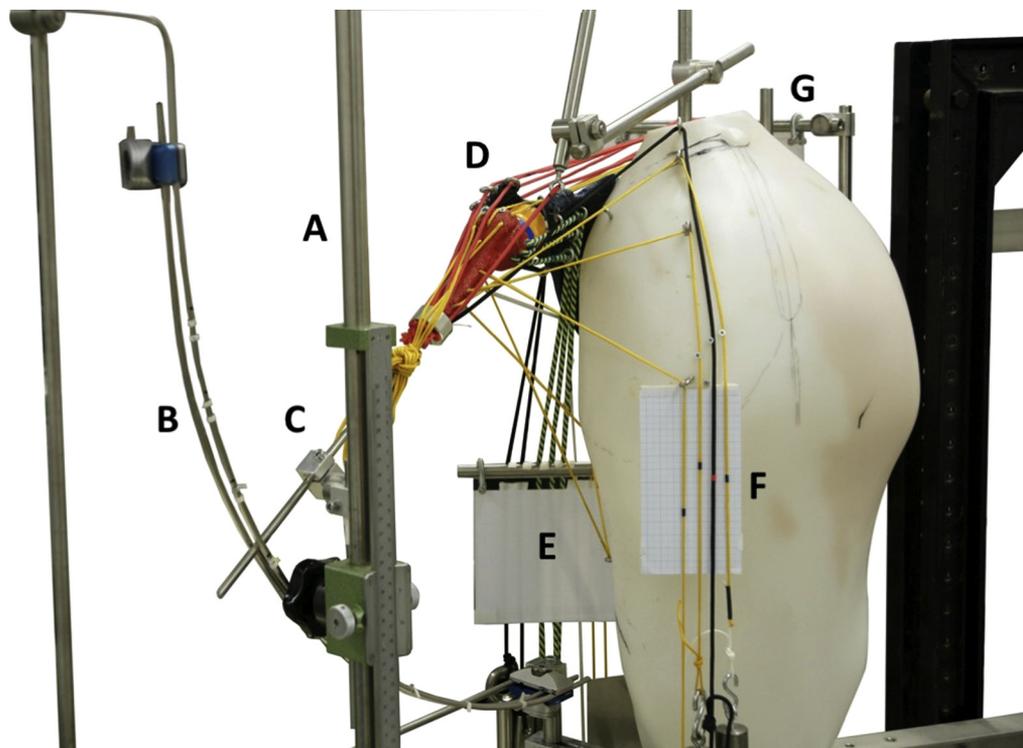
Biomechanical shoulder model

A validated and previously described biomechanical shoulder model was used to host the custom adjustable RTSA implant described earlier.[7-9] A fresh, adult cadaveric specimen with no pathology was used as a basis to create a realistic 3-dimensional model of the thorax, scapula, and proximal humerus (Fig. 2).[7,8] Braided cords were used to simulate the tendons. Broad muscles were divided into multiple segments because the moment arm length and direction of tendon action can vary considerably within muscles with broad insertions. The biomechanical model allows investigation of the moment arms of the following muscles: deltoid, supraspinatus, infraspinatus, latissimus dorsi, teres major, teres minor, subscapularis, pectoralis major, and coracobrachialis. However, for this study, only the moment arms of the deltoid muscles were investigated. For the deltoid muscles, subregion 1 corresponds to the anterior deltoid; subregions 2, 3, and 4 correspond to the lateral deltoid; and subregions 5 and 6 correspond to the posterior deltoid.[8] To derive moment arm values for the anterior, lateral, and posterior deltoid regions, the median of the defined subregion groups was taken at each arm angulation.

The scapula was fixed to the thorax with a 30° angulation from the coronal plane in the anterior direction (Fig. 2, D).[7,8] The humeral shaft, simulated by a steel rod, was led by a guiding arc, allowing the humerus to be moved in the predefined plane of elevation (Fig. 2, A and B). The humerus was additionally fixed to a linear rail that constrained axial rotation of the humerus and furthermore defined the arm elevation in degrees (Fig. 2, C).[19]

The tendon excursion method, widely accepted in biomechanical shoulder studies,[1,2,23] was used to determine the moment arm length of the shoulder muscles. The cords, simulating the muscle tendons, were bundled in 3 groups and directed over a scaled background. In front of the scaled background, digital

Figure 1 (**A**) A 40-mm trial glenosphere from the Anatomical Shoulder Replacement System was modified with a centered 4-mm pin, which allows a push-fit connection to the predrilled holes in the baseplate. (**B**) A 5-mm spacer allows a 5-mm lateral offset of the glenosphere with predrilled holes in a similar configuration to the baseplate. Two 3-mm metric threaded screws fix the spacer to the baseplate. (**C**) Baseplate with predrilled holes for neutral position and 5-, 7-, 9-, 11-mm offsets in anterior-posterior and inferior-superior directions depending on rotation of baseplate. A 4-mm metric threaded rod fixes the baseplate to the scapula. (**D**) Scapula with reamed cone and threaded insert in glenoid.

Figure 2 (**A**) Biomechanical shoulder model with arm elevation guide. (**B**) The 2 curved metal rods allow guidance of the humerus. (**C**) A vertical linear rail is fixed to the humerus via a pivotable joint to adjust the arm elevation and rotation. (**D**) The epoxy scapula is fixed to the plastic thorax. The cords, which are simulating the tendons, are running over the reverse shoulder prosthesis and are loaded with a weight of 2 N. (**E-G**) A scaled background is provided, in front of which digital reflex cameras mounted on tripods detect the excursion of the cords for every increment of arm elevation conducted.

reflex cameras (Alpha 550; Sony, Tokyo, Japan), with 1 camera for each of the 3 groups, were mounted on tripods. They detected the excursion of the cords for every increment of arm elevation conducted (Fig. 2, E-G). The image processing tool ImageJ (National Institutes of Health, Bethesda, MD, USA; http://imagej.net/) was used to derive the tendon excursion from the collected pictures with the help of a semiautomated algorithm, which selected the marked cords with a cursor in front of the scaled background and exported their coordinates. The derived tendon excursion allowed calculation of the moment arm for every increment of arm elevation.[19]

Testing protocol

Four custom RTSA configurations with a neutral glenosphere position and 5-mm posterior, 11-mm inferior, and 5-mm lateral offsets of the glenosphere were tested, in this order. For each configuration, glenohumeral abduction in the coronal plane, glenohumeral elevation in the scapular plane, and glenohumeral flexion in a plane rotated 60° from the coronal plane were conducted with 10° increments from 10° to 70° of glenohumeral elevation—a range that all configurations achieved, except for the 5-mm posterior glenosphere offset during glenohumeral abduction in the coronal plane, which was limited to 60° of abduction because of acromiohumeral impingement. This allowed a moment arm derivation for every 10° increment from 20° to 60° of arm elevation using the tendon excursion method.[19] To verify reproducibility of the measurements, the measurements were repeated 3 consecutive times for all given arm angulations. This resulted in 10,200 measurement points in total.

Outcome variables and statistical analyses

A 2-way analysis of variance was conducted to compare mean moment arms of each muscle subregion through the range of arm elevation in 3 planes in different COR offset positions. The moment arm was the dependent variable, with arm angulation and glenosphere position as independent variables. The level of significance was defined as $P < .05$, and a 95% confidence interval was used. The Tukey honestly significant difference was used to perform pair-wise post hoc comparisons between mean moment arm lengths in different COR positions. SPSS software (version 24; IBM, Armonk, NY, USA) and Microsoft Excel (Microsoft, Redmond, WA, USA) were used to conduct the analysis. This statistical analysis approach was chosen based on published studies.[1,30]

Results

Abduction

The lateral deltoid segment registered the highest moment arms of all the deltoid segments for all the different glenosphere offsets. The inferior offset of the glenosphere by 11 mm (P11inf) showed significantly larger moment arms in all 3 deltoid regions compared with the baseline position (P0) for the mean values, as well as for the individual moment arms over the abduction range of 20° to 60° (22 ± 6 mm for anterior deltoid, $P = .02$; 46 ± 4 mm for lateral
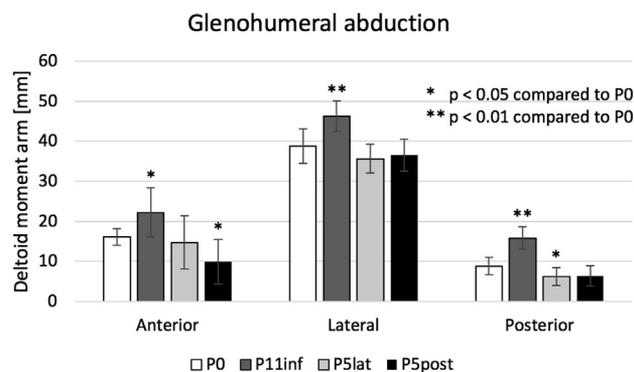
Figure 3 Deltoid moment arm lengths of anterior, lateral, and posterior deltoid subregions averaged over entire shoulder abduction range from 20° to 60° during glenohumeral abduction in coronal plane. Mean data are shown with standard deviations (*error bars*). Significantly different results compared with reverse total shoulder arthroplasty in the baseline position (*P0*) are marked: $P < .05$ (*) or $P < .001$ (**). *P11inf*, 11-mm inferior offset; *P5lat*, 5-mm lateral offset; *P5post*, 5-mm posterior offset.

deltoid, $P < .001$; and 16 ± 3 mm for posterior deltoid, $P < .001$; Figs. 3 and 4). For the lateral offset of the glenosphere by 5 mm (P5lat), a significantly lower moment arm was registered for the posterior deltoid region compared with P0 (6 ± 2 mm for posterior deltoid, $P = .036$; Fig. 3). The moment arm for a 5-mm posterior offset of the glenosphere (P5post) was significantly lower compared with P0 for the anterior deltoid region (10 ± 6 mm for anterior deltoid, $P = .028$; Fig. 3). P5lat and P5post showed lower deltoid moment arms at 20° of abduction for all 3 deltoid regions compared with P0 (Fig. 4). At 60° of abduction, acromiohumeral impingement occurred for P5post owing to contact between the greater tuberosity and the acromion (Fig. 4).

Elevation

The lateral deltoid segment showed the largest moment arm of all the deltoid segments for all the different glenosphere offsets. In comparison with P0, P11inf showed significantly higher moment arms in all 3 deltoid regions for the mean values, as well as for the individual moment arms over the elevation range of 20° to 60° (31 ± 6 mm for anterior deltoid, $P = .021$; 41 ± 4 mm for lateral deltoid, $P < .001$; and 2 ± 7 mm for posterior deltoid, $P = .011$; Figs. 5 and 6). P5lat showed significantly lower moment arms for the lateral deltoid region compared with P0 for the mean value (30 ± 3 mm for lateral deltoid, $P = .006$; Fig. 5). P5lat showed a lower deltoid moment arm at 40° of elevation for all 3 deltoid regions compared with P0 (Fig. 6).

Flexion

The anterior segment showed the largest moment arm of all the deltoid segments for all the different glenosphere offsets. P11inf showed significantly increased moment arms
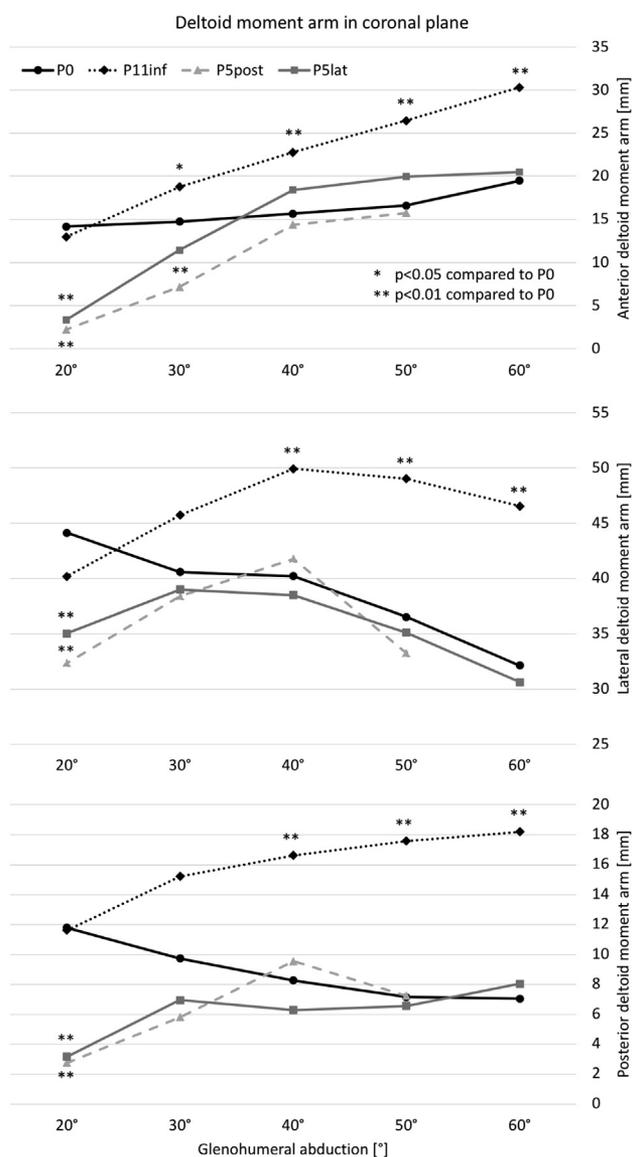
Figure 4 Anterior, lateral, and posterior deltoid moment arms are plotted during a glenohumeral abduction range from 20° to 60° in the coronal plane for the baseline position (*P0*), 11-mm inferior offset (*P11inf*), 5-mm posterior offset (*P5post*), and 5-mm lateral offset (*P5lat*) of the center of rotation in reverse total shoulder arthroplasty. Significant results compared with reverse total shoulder arthroplasty in P0 are marked: $P < .05$ (*) or $P < .001$ (**). For visual simplification, no error bars for standard deviations are included in the graphs.

compared with P0 for the anterior and lateral deltoid segments (41 ± 6 mm for anterior deltoid, $P = .001$, and 33 ± 6 mm for lateral deltoid, $P < .001$; Fig. 7). The deltoid moment arms over the glenohumeral flexion range of 20° to 60° were significantly higher for P11inf than for P0 in every deltoid segment (Fig. 8). P5lat showed a lower posterior deltoid moment arm at 60° of flexion compared with P0 (Fig. 8). P5post showed significantly larger moment arms than P0 for the anterior and lateral deltoid segments (39 ± 3 mm for anterior deltoid, $P = .021$, and 31 ± 3 mm
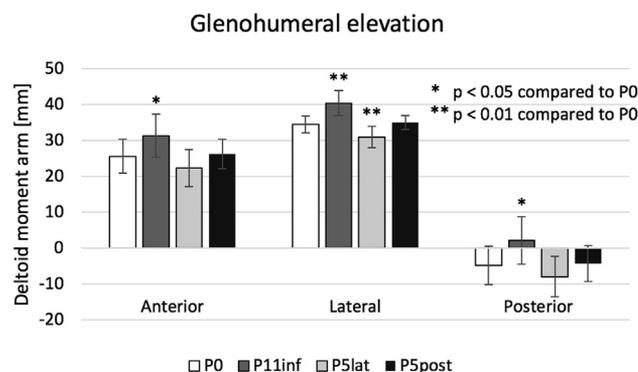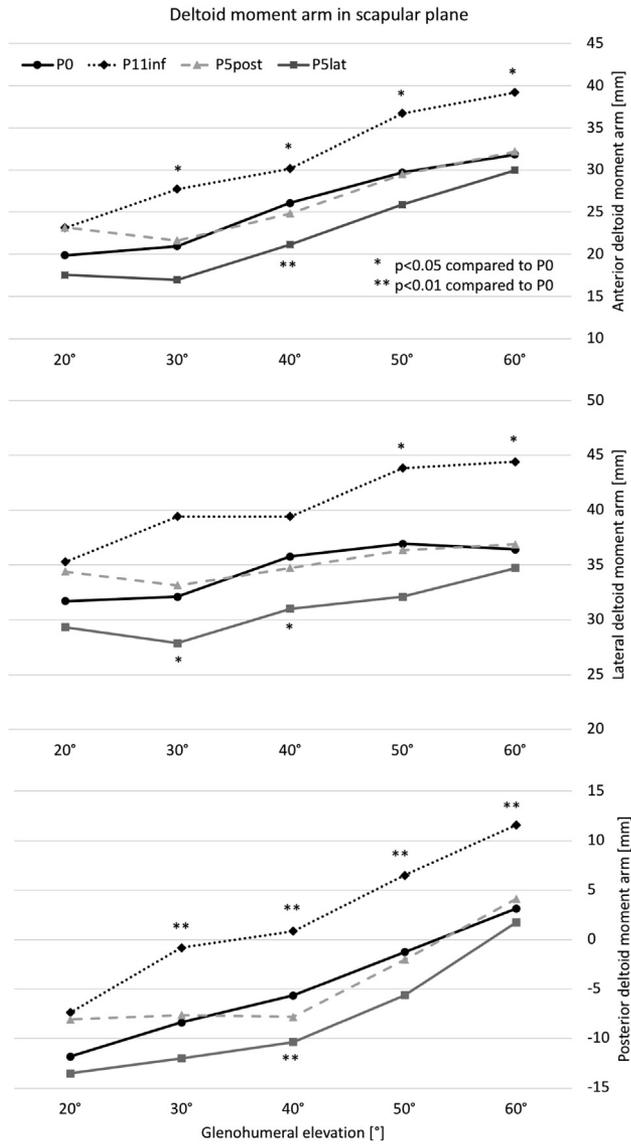

Figure 5 Deltoid moment arm lengths of anterior, lateral, and posterior deltoid subregions averaged over entire shoulder elevation range from 20° to 60° during glenohumeral elevation in scapular plane. Mean data are shown with standard deviations (*error bars*). Significantly different results compared with reverse total shoulder arthroplasty in the baseline position (*P0*) are marked: $P < .05$ (*) or $P < .001$ (**). *P11inf*, 11-mm inferior offset; *P5lat*, 5-mm lateral offset; *P5post*, 5-mm posterior offset.

for lateral deltoid, $P = .015$; Fig. 7). During assessment of glenohumeral flexion from 20° to 60°, P5lat showed a higher lateral deltoid moment arm compared with P0 at 30° and 50° of flexion (Fig. 8).
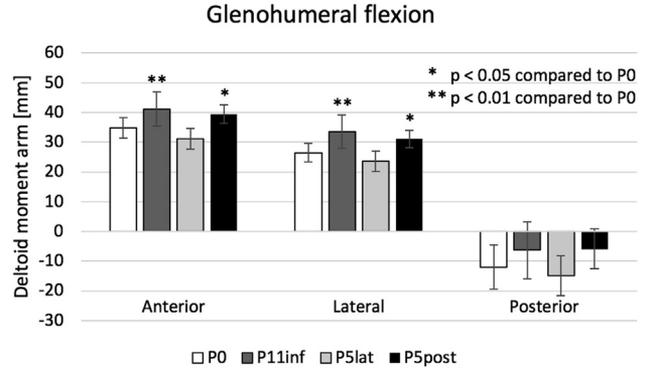
Discussion

Even though the position of the COR is a decisive factor for the success of RTSA, the effects of altering its position have not been investigated systematically beyond the configurations available in commercial implants. The major findings of this study were as follows: First, an inferior offset of the COR by 11 mm led to a significant increase in the anterior and lateral deltoid moment arms during humeral abduction, elevation, and flexion (Figs. 3-8). This finding is explained by the mostly oblique direction of the deltoid muscle across the shoulder joint. Second, a 5-mm posterior offset of the COR also increased the moment arms of the anterior and lateral deltoid subregions significantly during humeral flexion (Figs. 7 and 8), supporting the muscle area that is most used in activities of daily living. To our knowledge, this finding has not been previously reported. Third, lateralization of the COR by 5 mm had a significantly decreasing effect on the moment arms for humeral elevation and abduction (Figs. 3, 4, 5, and 6). The last finding is supported by reports that have shown detrimental effects on the deltoid moment arm due to glenohumeral lateralization.[14,15] Henninger et al[14] mentioned a significant cumulative deltoid force increase during elevation in the scapular plane for every increment of COR lateral offset from 5 to 15 mm compared with the RTSA baseline. Hoenecke et al[15] found similar results, with 6- and 13-mm lateral COR offsets leading to a decrease in the

Figure 6 Anterior, lateral, and posterior deltoid moment arms are plotted during a glenohumeral elevation range from 20° to 60° in the scapular plane for the baseline position (*P0*), 11-mm inferior offset (*P11inf*), 5-mm posterior offset (*P5post*), and 5-mm lateral offset (*P5lat*) of the center of rotation in reverse total shoulder arthroplasty. Significant results compared with reverse total shoulder arthroplasty in P0 are marked: $P < .05$ (*) or $P < .001$ (**). For visual simplification, no error bars for standard deviations are included in the graphs.
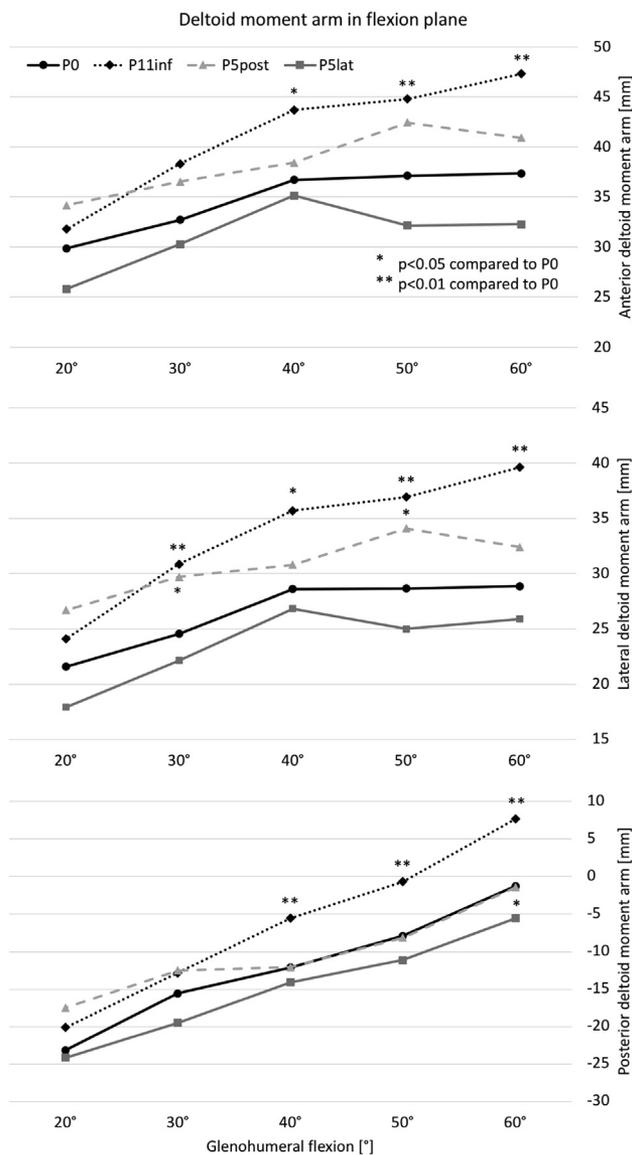

Figure 7 Deltoid moment arm lengths of anterior, lateral, and posterior deltoid subregions averaged over entire shoulder flexion range from 20° to 60° during glenohumeral flexion in plane rotated 60° from coronal plane. Mean data are shown with standard deviations (*error bars*). Significantly different results compared with reverse total shoulder arthroplasty in the baseline position (*P0*) are marked: $P < .05$ (*) or $P < .001$ (**). *P11inf*, 11-mm inferior offset; *P5lat*, 5-mm lateral offset; *P5post*, 5-mm posterior offset.

designs. Furthermore, the influence of other shoulder muscles, such as the pectoralis major, supraspinatus, and coracobrachialis, should be investigated because it has been reported that clavicular fibers of the superior pectoralis major contribute to arm abduction and flexion in RTSA.[1] It has been reported that the subscapularis acts as a partial abductor in RTSA compared with an adductor in the native shoulder.[1] This implies the question of how an inferior COR offset in RTSA influences the moment arm of the subscapularis and the remaining rotator cuff muscles.

As stated by Favre et al,[7] a simplification of the model used is fixation of the scapula in its anatomically neutral position to the thorax. This was considered acceptable because for the deltoid muscle, studied in this article, the directions of action of the muscle do not change based on the scapulothoracic movement because the deltoid links the humerus to the scapula.

Humeral abduction of 90° measured in a thoracic co-ordinate system under consideration of the scapulohumeral rhythm ratio of 1.3:1 for RTSA corresponds to gleno-humeral abduction of 50° relative to the scapula.[18,29] The reduced ROM due to acromiohumeral impingement at 60° of glenohumeral abduction for the 5-mm posterior gleno-sphere offset position supports the findings of Onstot et al,[22] in which acromiohumeral impingement was re-ported for posterior-superior humeral offset in RTSA dur-ing abduction.

As stated by many studies,[1,3,14,15,21,30] RTSA results in medial and inferior positioning of the COR of the gleno-humeral joint relative to the native shoulder; however, no study, to our knowledge, has analyzed the influence of an isolated inferior COR offset in RTSA on deltoid moment arms. In our study, compared with the baseline position in RTSA, an 11-mm inferior COR offset increased the deltoid

deltoid moment arm and increased total muscle force dur-ing abduction, respectively.

A strength of the underlying biomechanical shoulder model is that it has previously been validated in 3 different studies[7-9] but with the limitation that it is based on only 1 specimen.[7] Even though it has been considered acceptable to conclude biomechanical generalities from a single specimen with certain restrictions, as stated by Veeger et al,[26] the results may not be representative of all RTSA

Figure 8 Anterior, lateral, and posterior deltoid moment arms are plotted during a glenohumeral flexion range from 20° to 60° in plane rotated 60° from coronal plane for the baseline position (*P0*), 11-mm inferior offset (*P11inf*), 5-mm posterior offset (*P5post*), and 5-mm lateral offset (*P5lat*) of the center of rotation in reverse total shoulder arthroplasty. Significant results compared with reverse total shoulder arthroplasty in P0 are marked: $P < .05$ (*) or $P < .001$ (**). For visual simplification, no error bars for standard deviations are included in the graphs.

moment arm by 33% during abduction, 33% during elevation, and 39% during flexion and showed the highest moment arms of all configurations in every plane of movement. However, it should also be considered that an 11-mm inferior offset of the COR in RTSA, on the one hand, may reduce inferior notching and, on the other hand, may lead to baseplate overlapping of the outer inferior glenoid rim, creating problems fixing the baseplate to the glenoid. An inferior eccentric glenosphere, as used in this study, could provide sufficient baseplate fixation in the glenoid vault

without sacrificing the positive effects of the inferior offset of the COR. An eccentric glenosphere, however, might experience an increased moment arm acting on the baseplate-bone interface.[12] Furthermore, how muscle lengthening influences the muscle's ability to generate force cannot be predicted in this model. Deltoid lengthening beyond its effective length might lead to a reduced ability to generate force[28] and may counteract the positive effect of the inferior COR offset on the deltoid muscle.

Lädermann et al[16,17] listed excessive humeral lengthening as a possible risk factor for acromial fractures in RTSA but failed to prove this hypothesis. A recent cohort-controlled study showed that lesser distalization of the COR is associated with acromial fractures.[25] Wong et al[32] even reported reduced acromial stress due to inferior positioning of the glenosphere in RTSA. On the basis of these studies, an inferior offset of the COR in RTSA should not negatively affect the occurrence of acromial fractures.

During activities of daily living, however, most of the time, arm elevation is taking place in a plane between the scapular and sagittal planes, corresponding to humeral flexion in this study. During humeral flexion, the lowest deltoid moment arm values have been recorded, with strongly negative antagonistic activity of the posterior deltoid, requiring more anterior deltoid muscle effort to elevate the arm compared with the other planes of motion. Considering our study findings, a promising glenosphere position may therefore be a combination of an inferior position and posterior position. This condition has not yet been mechanically tested in our model as we limited the tests to the basic directions of the coordinate system. However, if such a combination is attempted, anatomic limitations of the glenoid vault regarding fixation of the baseplate should be taken into consideration.

Conclusion

Owing to the mostly oblique direction of the deltoid muscle across the shoulder joint, an inferior position and posterior position of the glenosphere in RTSA both lead to a significant improvement in the deltoid moment arm. This results in an improvement in muscle efficiency for the direction of shoulder motion most relevant for common tasks of daily living. In contrast, however, isolated lateralization of the glenosphere decreases the deltoid moment arm during humeral elevation.

Disclaimer

References

1. Ackland DC, Roshan-Zamir S, Richardson M, Pandy MG. Moment arms of the shoulder musculature after reverse total shoulder arthroplasty. J Bone Joint Surg Am 2010;92:1221-30. https://doi.org/10.2106/jbjs.i.00001

2. An KN, Takahashi K, Harrigan TP, Chao EY. Determination of muscle orientations and moment arms. J Biomech Eng 1984;106:280-2.

3. Boileau P, Watkinson DJ, Hatzidakis AM, Balg F. Grammont reverse prosthesis: design, rationale, and biomechanics. J Shoulder Elbow Surg 2005;14:147S-61S. https://doi.org/10.1016/j.jse.2004.10.006

4. Cheung E, Willis M, Walker M, Clark R, Frankle MA. Complications in reverse total shoulder arthroplasty. J Am Acad Orthop Surg 2011; 19:439-49.

5. Crosby LA, Hamilton A, Twiss T. Scapula fractures after reverse total shoulder arthroplasty: classification and treatment. Clin Orthop Relat Res 2011;469:2544-9. https://doi.org/10.1007/s11999-011-1881-3

6. Dedy NJ, Stangenberg M, Liem D, Hurschler C, Simmen B, Riner M, et al. Effect of posterior offset humeral components on range of motion in reverse shoulder arthroplasty. Int Orthop 2011;35:549-54. https://doi.org/10.1007/s00264-010-1079-4

7. Favre P, Loeb MD, Helmy N, Gerber C. Latissimus dorsi transfer to restore external rotation with reverse shoulder arthroplasty: a biomechanical study. J Shoulder Elbow Surg 2008;17:650-8. https://doi.org/10.1016/j.jse.2007.12.010

8. Favre P, Sheikh R, Fucentese SF, Jacob HAC. An algorithm for estimation of shoulder muscle forces for clinical use. Clin Biomech 2005; 20:822-33. https://doi.org/10.1016/j.clinbiomech.2005.04.007

9. Gatti CJ, Dickerson CR, Chadwick EK, Mell AG, Hughes RE. Comparison of model-predicted and measured moment arms for the rotator cuff muscles. Clin Biomech 2007;22:639-44. https://doi.org/10.1016/j.clinbiomech.2007.02.001

10. Giles JW, Langohr DG, Johnson JA, Athwal GS. Implant design variations in reverse total shoulder arthroplasty influence the required deltoid force and resultant joint load. Clin Orthop Relat Res 2015;473: 3615-26. https://doi.org/10.1007/s11999-015-4526-0

11. Guery J, Favard L, Sirveaux F, Oudet D, Mole D, Walch G. Reverse total shoulder arthroplasty—survivorship analysis of eighty replacements followed for five to ten years. J Bone Joint Surg Am 2006; 88:1742-7. https://doi.org/10.2106/jbjs.e.00851

12. Gutiérrez S, Walker M, Willis M, Pupello DR, Frankle MA. Effects of tilt and glenosphere eccentricity on baseplate/bone interface forces in a computational model, validated by a mechanical model, of reverse shoulder arthroplasty. J Shoulder Elbow Surg 2011;20:732-9. https://doi.org/10.1016/j.jse.2010.10.035

13. Hamilton MA, Diep P, Roche C, Flurin PH, Wright TW, Zuckerman JD, et al. Effect of reverse shoulder design philosophy on muscle moment arms. J Orthop Res 2015;33:605-13. https://doi.org/10.1002/jor.22803

14. Henninger HB, Barg A, Anderson AE, Bachus KN, Burks RT, Tashjian RZ. Effect of lateral offset center of rotation in reverse total shoulder arthroplasty: a biomechanical study. J Shoulder Elbow Surg 2012;21:1128-35. https://doi.org/10.1016/j.jse.2011.07.034

15. Hoenecke HR Jr, Flores-Hernandez C, D'Lima DD. Reverse total shoulder arthroplasty component center of rotation affects muscle function. J Shoulder Elbow Surg 2014;23:1128-35. https://doi.org/10.1016/j.jse.2013.11.025

16. Lädermann A, Edwards TB, Walch G. Arm lengthening after reverse shoulder arthroplasty: a review. Int Orthop 2014;38:991-1000. https://doi.org/10.1007/s00264-013-2175-z

17. Lädermann A, Williams MD, Melis B, Hoffmeyer P, Walch G. Objective evaluation of lengthening in reverse shoulder arthroplasty. J Shoulder Elbow Surg 2009;18:588-95. https://doi.org/10.1016/j.jse.2009.03.012

18. Lee KW, Kim YI, Kim HY, Yang DS, Lee GS, Choy WS. Three-dimensional scapular kinematics in patients with reverse total shoulder arthroplasty during arm motion. Clin Orthop Surg 2016;8:316-24. https://doi.org/10.4055/cios.2016.8.3.316

19. Meisterhans M. Development of an experimental setup to measure the moment arms of the shoulder muscles depending on the glenosphere position in a reverse shoulder prosthesis [master thesis]. Zurich. Medicine Library of University of Zurich. University of Zurich; 2017.

20. Nam D, Kepler CK, Neviaser AS, Jones KJ, Wright TM, Craig EV, et al. Reverse total shoulder arthroplasty: current concepts, results, and component wear analysis. J Bone Joint Surg Am 2010;92:23-35. https://doi.org/10.2106/jbjs.j.00769

21. Nyffeler RW, Werner CML, Gerber C. Biomechanical relevance of glenoid component positioning in the reverse Delta III total shoulder prosthesis. J Shoulder Elbow Surg 2005;14:524-8. https://doi.org/10.1016/j.jse.2004.09.010

22. Onstot BR, Jacofsky MC, Hansen ML. Muscle force and excursion requirements and moment arm analysis of a posterior-superior offset reverse total shoulder prosthesis. Bull Hosp Jt Dis (2013) 2013; 71(Suppl 2):S25-30.

23. Otis JC, Jiang CC, Wickiewicz TL, Peterson MGE, Warren RF, Santner TJ. Changes in the moment arms of the rotator cuff and deltoid muscles with abduction and rotation. J Bone Joint Surg Am 1994;76:667-76.

24. Scarlat MM. Complications with reverse total shoulder arthroplasty and recent evolutions. Int Orthop 2013;37:843-51. https://doi.org/10.1007/s00264-013-1832-6

25. Schenk P, Beeler S, Ernstbrunner L, Aichmair A, Meyer D, Gerber C. Acromial fractures following reverse total shoulder arthroplasty—a cohort controlled analysis. Paper presented at: 28th Congress of the European Society for Surgery of the Shoulder and the Elbow. Geneva, Geneva, Switzerland, 19-22. Sept. 2018.

26. Veeger HEJ, Kreulen M, Smeulders MJC. Mechanical evaluation of the pronator teres rerouting tendon transfer. J Hand Surg Br 2004;29: 259-64. https://doi.org/10.1016/j.jhsb.2004.01.004

27. Walch G, Mottier F, Wall B, Boileau P, Molé D, Favard L. Acromial insufficiency in reverse shoulder arthroplasties. J Shoulder Elbow Surg 2009;18:495-502. https://doi.org/10.1016/j.jse.2008.12.002

28. Walker D, Matsuki K, Struk AM, Wright TW, Banks SA. Scapulohumeral rhythm in shoulders with reverse shoulder arthroplasty. J Shoulder Elbow Surg 2015;24:1129-34. https://doi.org/10.1016/j.jse.2014.11.043

29. Walker DR, Kinney AL, Wright TW, Banks SA. How sensitive is the deltoid moment arm to humeral offset changes with reverse total shoulder arthroplasty? J Shoulder Elbow Surg 2016;25:998-1004. https://doi.org/10.1016/j.jse.2015.10.028

30. Walker DR, Struk AM, Matsuki K, Wright TW, Banks SA. How do deltoid muscle moment arms change after reverse total shoulder arthroplasty? J Shoulder Elbow Surg 2016;25:581-8. https://doi.org/10.1016/j.jse.2015.09.015

31. Wierks C, Skolasky RL, Ji JH, McFarland EG. Reverse total shoulder replacement: intraoperative and early postoperative complications. Clin Orthop Relat Res 2009;467:225-34. https://doi.org/10.1007/s11999-008-0406-1

32. Wong MT, Langohr GDG, Athwal GS, Johnson JA. Implant positioning in reverse shoulder arthroplasty has an impact on acromial stresses. J Shoulder Elbow Surg 2016;25:1889-95. https://doi.org/10.1016/j.jse.2016.04.011