



What is the best glenoid configuration in onlay reverse shoulder arthroplasty?

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Abstract

Purpose The purpose of this study was to analyze the effect of different glenoid configurations on arm position and range of motion (ROM) following reverse shoulder arthroplasty (RSA). The hypothesis was that different glenoid configurations would lead to changes in humeral offset, acromio-humeral distance (AHD), ROM, and rotator cuff muscle length.

Methods Using a three-dimensional (3D) computer model, implantation of an RSA was simulated with a 145° onlay humeral stem combined with five different glenoid configurations which varied in diameter and centre of rotation. Glenoid offset, the AHD, ROM, and muscle length were evaluated for each configuration.

Results Changing glenoid design led to up to a 10 mm change in offset and a 3 mm change in the AHD. There was 7° of improvement in abduction and flexion between the different glenoid designs. Two of the configurations, the 36 mm centered and the BIO-RSA, had an adduction deficit. In extension and external rotation arm with the arm at side, the eccentric 36 mm glenosphere was the best configuration while the centered 36 mm glenosphere was the worst configuration. The 42 mm glenosphere limited external rotation at 90° of abduction.

Conclusions Varying the glenosphere configurations leads to ROM and muscle length changes following RSA. With a 145° onlay humeral stem, a 36 eccentric glenosphere theoretically optimizes ROM while limiting scapular notching.

Keywords Reverse total shoulder arthroplasty · Onlay design · Glenoid offset · Arm position · Complications · Range of motion · Muscle tension

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Introduction

The initial Grammont-style reverse shoulder arthroplasty (RSA) utilized a glenosphere with a medialized centre of rotation combined with a straight humeral stem with 155° humeral inclination. While this design reliably improved forward elevation, the high rate of scapular notching and internal and external rotation deficit observed with this design have been attributed to the medialized glenoid design [1]. To address these problems, lateralized or eccentric glenospheres have been proposed [2, 3]. Both glenosphere types may decrease notching by limiting bony abutment with the scapula, while the lateralized glenosphere in particular may improve external rotation by not only decreasing bony abutment but also providing more recruitment of the remaining rotator cuff muscles via a more anatomic centre of rotation [4].

The effect of glenoid variations on range of motion (ROM) [5, 6] and scapular notching [7–9] has been well-reported with a 155° RSA. However, there are now multiple RSAs which offer more vertical inclination of the humeral osteotomy (i.e.,

145° and 135°), situation that then decreases the neck–shaft angle. In addition to variation in inclination, some of these prosthesis have an inlay design whereas others have an onlay design which impacts humeral offset or deltoid wrapping. With an inlay design, the humeral cup or tray lies below the level of the humeral cut, whereas with an onlay design, the humeral cup or tray rests on top of the humeral cup. The latter leads to increased humeral-sided lateralization.

Computer modeling with virtual implantation can be used to compare range of motion (ROM) and bony impingement with different designs. A recent study used this technique to examine the effect of humeral variations and concluded that ROM was improved with a 145° or 135° prosthesis compared to a 155° prosthesis [10]. However, the impact of glenoid variation was not examined in that study.

The purpose of the current study was to examine the effect of glenoid variations on offset, acromiohumeral distance (AHD), ROM, and rotator cuff muscle length observed with 145° onlay humeral stem in a virtual model. The hypothesis was that different glenoid configurations would lead to changes in humeral offset, AHD, ROM, and rotator cuff muscle length.

Materials and method

Computer model and prosthetic scenarios

A three-dimensional (3D) computer model was developed from computer tomography (CT) images of a cadaveric shoulder without any sign of pathology (www.virtualskeleton.ch). The CT included the entire scapula and humerus. The scapula and humerus bones were segmented using Amira (Visage Imaging GmbH, Berlin, Germany). A reconstruction of the bone surface was obtained with Geomagic Studio (Geomagic Inc., Morrisville, NC, USA). The reconstructed bone surface was superimposed to the CT slices to confirm the precision of the reconstruction.

The reconstructed scapula and humerus were then imported into a computer-aided design software program (SolidWorks; Dassault Systèmes SolidWorks Corp., Concord, MA, USA) to virtually perform a RSA. Virtual reaming of the scapula and humerus was done according to the recommended surgical technique under the supervision of two shoulder surgeons (AL, GW).

The scapula was prepared to obtain neutral inclination and version. A 29 mm circular baseplate (Aequalis Reversed II, Wright Medical, Montbonnot, France) was implanted at the inferior edge of the glenoid surface. Five different glenoid configurations were tested (Fig. 1): (1) a neutral 36 mm with a medialized centre of rotation; (2) a neutral 42 mm glenosphere; (3) a 36 mm 10° tilted glenosphere with 3.7 mm of lateral offset; (4) a neutral 36 mm glenosphere with

a baseplate lateralized by 10 mm of bone graft (bony increased offset (BIO-RSA)) [2]; and (5) an eccentric 36 mm glenosphere which offsets the centre of rotation 2 mm inferiorly.

Each glenoid configuration was associated with an onlay short curved anatomical stem (Aequalis Ascend Flex; Wright Medical, Montbonnot, France) placed in 20° of retroversion. The humeral cut was performed at 132.5° close to the anatomic humeral neck, and a concentric humeral tray was placed. Then, a 12.5° standard 6 mm polyethylene was placed on the humeral tray to obtain a humeral inclination of 145° (Fig. 2) [10].

Measurement of implant placement and arm position

The scapula and humerus were positioned to a rest position, according to van Andel et al. [11] and using the recommended joint coordinate system [12]. For each of the five configurations, glenoid offset, humeral offset, and AHD were measured in the frontal plane based on 2D representations. As previously described [10], although the model allowed 3D assessment, measurements were made in 2D so that they would be clinically applicable to plain radiographs. Glenoid offset was calculated by measuring the horizontal distance from the face of the native glenoid to the centre of rotation of the glenosphere. Humeral offset was calculated by measuring the distance from the centre of rotation of the glenosphere to the most lateral aspect of the greater tuberosity. AHD was calculated by measuring vertically the distance from the infero-lateral aspect of the acromion to the most supero-lateral aspect of the greater tuberosity (Fig. 3).

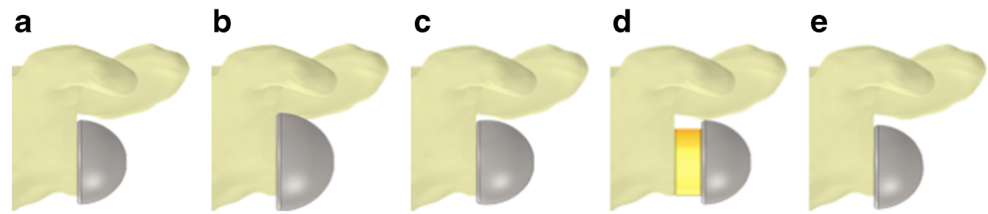
Kinematic simulation

Glenohumeral ROM was assessed in the native shoulder and for each of the five glenoid configurations using the 3D model as previously described [10]. Simulation was executed with software that allows testing of the prosthetic shoulder model with real-time evaluation of bony impingement. Abduction–adduction and forward flexion–extension were assessed with the arm in neutral rotation. External–internal rotation was assessed both with the humerus in 10° of abduction and with the humerus in 90° of abduction. Then, a collision detection algorithm [13] was used to virtually locate any prosthetic or bony impingements. Soft tissue tension was not accounted for in this model.

Rotator cuff muscle length

Rotator cuff muscle length in each state was estimated as the change of length of a linear segment representing the muscles (Fig. 4). The supraspinatus pseudo-origin was defined as the supraglenoid tubercle, and the insertion was defined as the

Fig. 1 Different glenoid configurations: **a** 36 mm, **b** 42 mm, **c** 36 mm 10° with 3.7 mm of lateral offset, **d** 36 mm BIO-RSA with 10 mm of lateral offset, and **e** 36 mm with 2 mm of inferiorly offset glenospheres



superior edge of the greater tuberosity. The origins of the infraspinatus and subscapularis were set at their most lateral bone attachment on the scapula. Their insertions were set at three points evenly distributed on the greater tuberosity and lesser tuberosity, respectively, in order to simulate their broad attachments. Muscle length was measured in neutral rotation with the humerus at the side.

Statistical analysis

Linear regression analysis was conducted between the different measurements and ROMs. If no linear regression was established, correlation analysis was conducted. A coefficient higher than 0.9 in absolute value was considered as a high correlation and a coefficient above 0.8 in absolute value as a good correlation.

Results

Glenoid offset

Glenoid offset varied by 10 mm with the smallest offset occurring with the centered glenoid glenosphere independently

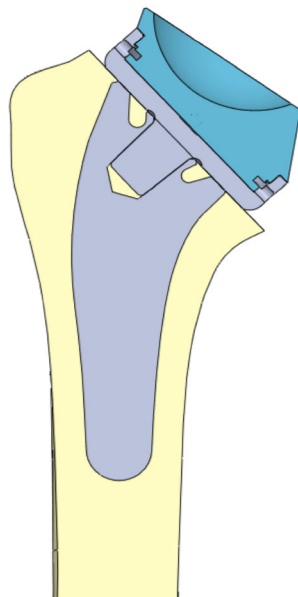


Fig. 2 Onlay short curved anatomical 145° stem with concentric humeral tray

of the diameter (0.9 mm) and largest occurring with the BIO-RSA (10.9 mm) configuration (Table 1).

Humeral offset

Humeral offset varied by 2.8 mm between the 36 and 42 mm configurations (Table 1).

AHD

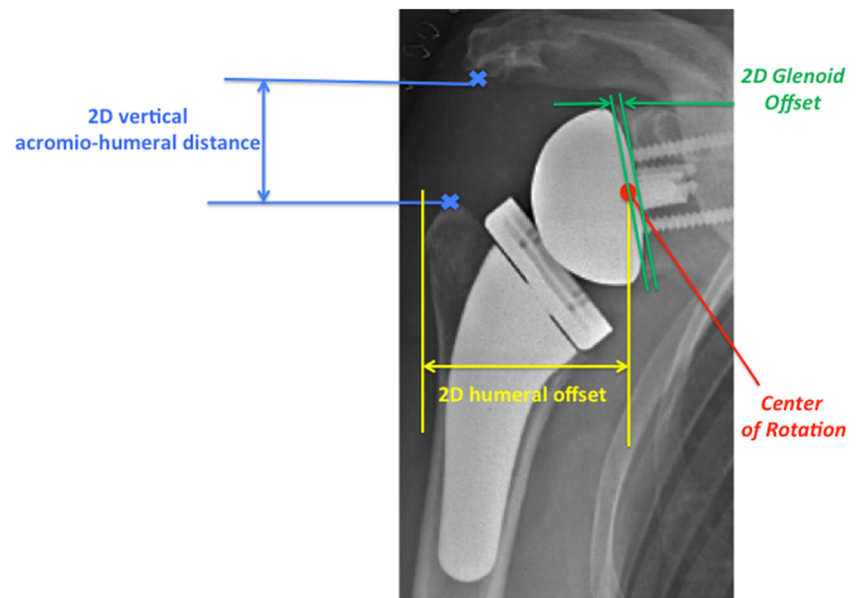
The AHD varied by 3 mm with the smallest occurring with the 42 mm neutral glenosphere (21.6 mm) and the largest occurring with the 36 mm eccentric glenosphere (24.5 mm) (Table 1). Neither linear regression nor correlation between AHD and glenoid offset has been found, while some correlation between AHD and humeral offset has been noted (-0.79).

ROM and impingement

ROM results are summarized in Table 2. Abduction ranged from 61.9 to 68.8° among the configurations and was decreased compared to the native shoulder (106.6°). Only the 36 mm neutral glenosphere and the BIO-RSA configuration did not achieve native adduction. The adduction deficit of the 36 mm neutral glenosphere was 6°, and the BIO-RSA deficit was 13°. Flexion was similar among all the configurations ranging from 107.9 to 114.3° with the optimal configuration being the 3.7 mm lateralized glenosphere. However, no configuration restored native flexion (129.2°). Similarly, native extension (-46°) was never achieved. The greatest extension was obtained with the eccentric glenosphere (-27°) and the lowest with the 36 mm neutral glenosphere (-19°).

Native internal rotation with the humerus in 10 and 90° of abduction reached the native value for all glenoid configurations. Conversely, native external rotation with the humerus in 10° of abduction was never obtained. Similar to extension, the greatest external rotation with arm at the side was obtained with the eccentric glenosphere (-38°) and lowest with the 36 mm neutral glenosphere (-28°). Native external rotation at 90° of abduction was observed in all designs except for the 42 mm glenosphere which had a 7° deficit.

Fig. 3 Representation of the different measures. The centre of rotation of the glenosphere (red point). The glenoid offset corresponds to the horizontal distance from the face of the native glenoid to the centre of rotation of the glenosphere (in green). The humeral offset is the distance from the centre of rotation of glenoid to the most lateral aspect of the greater tuberosity (in yellow). The AHD is determined by the vertical distance from the infero-lateral aspect of the acromion to the most supero-lateral aspect of the greater tuberosity (in blue)



Correlations with ROM

No ROM had a linear regression or even a correlation with glenoid offset. Conversely, AHD had a strong linear regression with abduction ($R^2 = 0.946$) (Fig. 5). We found also a good inverse correlation with the AHD and external rotation at 90° of abduction ($R^2 = -0.86$). Similarly, humeral offset had a strong inverse linear regression with the external rotation at 90° of abduction ($R^2 = 0.986$), a good inverse linear regression with the flexion ($R^2 = 0.838$), and a good inverse correlation with abduction ($R^2 = -0.837$) (Fig. 5).

Muscle length

Increase in supraspinatus length was observed for all constructs (Table 3). Supraspinatus lengthening was highest with the BIO-RSA construct (18.6 mm) and lowest with the 36 mm

neutral glenosphere (10.5 mm). The infraspinatus was also lengthened for each construct. The superior part of the subscapularis was lengthened by 0 to 5 mm for most configurations and was > 10 mm for the BIO-RSA configuration. Conversely, the inferior part of the subscapularis was not lengthened in any configuration.

Discussion

The findings of this study confirm our hypothesis that glenoid configuration has an effect on offset, AHD, ROM, and rotator cuff muscle length. Glenoid offset was as expected minimum with the neutral 36 and 42 mm glenospheres and maximum with the BIO-RSA configuration. Conversely, humeral offset varied by about 3 mm between the 36 mm configurations (including the BIO-RSA) and the 42 mm configuration.

Fig. 4 Illustration of measurement of preoperative (a) and post-operative (b) muscle length

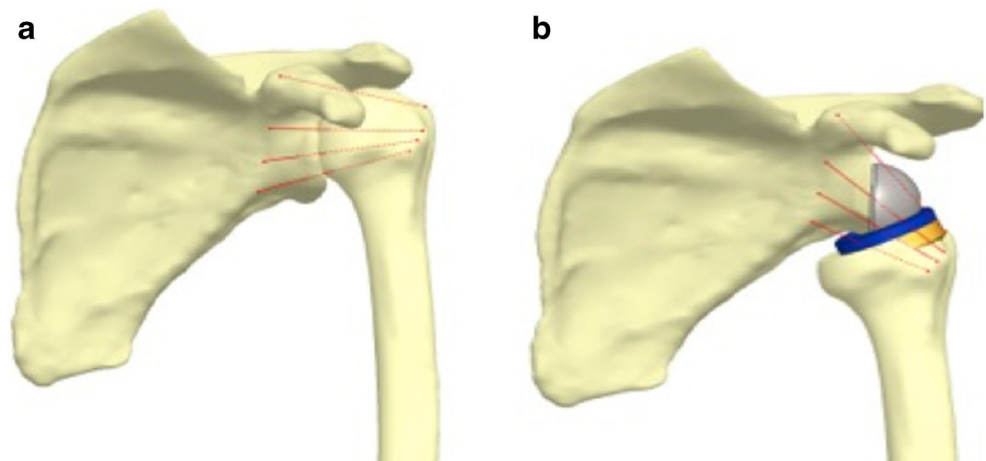


Table 1 Glenoid offset and humeral position in relation to the five different glenoid configurations in millimeter

Glenoid configuration	Articular diameter	2D glenoid offset	2D humeral offset	ADH
36 mm glenosphere neutral	36	0.9	34.2	23.1
42 mm glenosphere neutral	42	0.9	37.0	21.6
36 mm glenosphere lateralized 4 mm	36	4.1	34.2	23.1
36 mm glenosphere BIO-RSA	36	10.9	34.2	23.1
36 mm glenosphere inferior eccentric 2 mm	36	0.9	34.	24.5

ADH, acromio-humeral distance; 2D, two-dimensional

ROM was greatest with the eccentric glenosphere. Finally, the rotator cuff was lengthened inferiorly in all cases. These findings have several implications important to RSA.

Arm lengthening has been reported to be a critical factor in maximizing ROM following RSA [14–17]. The type of glenospheres used in the present study provided arm lengthening of only about 3 mm thus or 1% of arm length. This is less than can be obtained via adjustment on the humeral side. In a previous study, 6 mm of arm lengthening was obtained with a change in humeral inclination which could be further modified by eccentric positioning of a humeral tray [10]. Consequently, the determining factor for arm length is not the glenoid but the humerus which is affected by the height and type of stem, polyethylene thickness, and use of an augment or spacer. Collectively, these factors allow arm lengthening by up to several centimeters (about 10% of arm length) [14].

Clinically, the literature is controversial with regard to ROM following RSA. A recent study by Collin et al. reported statistically significant (but not clinically) higher forward flexion following a BIO-RSA compared to a 36 mm neutral glenosphere ($145 \pm 21^\circ$ vs. $138 \pm 20^\circ$ respectively, $p = 0.017$), but there was no difference in external or internal rotation [6]. In a randomized controlled trial, Greiner et al. compared 17 RSAs with a neutral 36 mm glenosphere to 17 BIO-RSAs and reported no significant difference in ROM between the two groups [18]. Similarly, Athwal et al. did not observe substantial differences in ROM between a 36 and 42 mm neutral glenosphere RSA and BIO-RSAs [19].

However, all three of these studies utilized a humeral prosthesis with a 155° humeral inclination which limit the findings compared to current designs and none evaluated inferiorly eccentric glenospheres. In our evaluation, an onlay prosthesis with a 145° humeral inclination was used. The most favorable glenoid configuration to optimize ROM with the humeral stem in the current study was an eccentric 36 mm glenosphere. Comparatively, the 42 mm glenosphere limited abduction and external rotation at 90° of abduction. The BIO-RSA, lateralized, and neutral glenospheres all had an adduction deficit compared to the eccentric option. While the differences were small, the eccentric glenosphere provided the greatest ability to limit scapular notching while maximizing ROM with an onlay 145° humeral stem.

Mizuno et al. previously reported that an inferiorly eccentric glenosphere reduced the severity of notching with a 155° prosthesis [9]. Our findings furthermore support the use of an eccentric glenosphere in combination with a 145° prosthesis. Scapular notching occurs through a combination of adduction, extension, and rotation [4], and in this study, these were optimized with the inferiorly eccentric 36 mm glenosphere. Another option to decrease the prevalence of scapular notching is to use a 145 or 135° neck–shaft angle [20]. Interestingly, the BIO-RSA did not provide any advantage in these ROMs compared to the other configurations since impingement continued to occur between the prosthesis and the bone graft. Clinical results regarding scapular notching in traditional RSA compared to BIO-RSA have varied. Athwal et al. found a significantly higher rate of notching in 36 and

Table 2 Standardized ROM in degrees for the native shoulder and the five different prosthetic configurations

	Abduction	Adduction	Flexion	Extension	Internal rotation at 0°	External rotation at 0°	Internal rotation at 90°	External rotation at 90°
Native shoulder	106.6	−48.7	129.2	−46.0	99.0	−59.7	116.5	−43.0
Sphere 36 mm centered	65.0	−42.8	112.1	−18.7	99.0	−28.1	116.5	−43.0
Sphere 42 mm centered	61.9	−62.0	107.9	−25.6	99.0	−36.6	116.5	−7.1
Sphere 36 mm tilted	66.1	−53.4	114.3	−25.2	99.0	−36.3	116.5	−43.0
Sphere 36 mm with Bio-RSA	68.8	−35.3	112.2	−20.2	99.0	−30.2	116.5	−43.0
Sphere 36 mm with 2 mm inferior offset	67.8	−62.6	112.1	−26.5	99.0	−37.7	116.5	−43.0

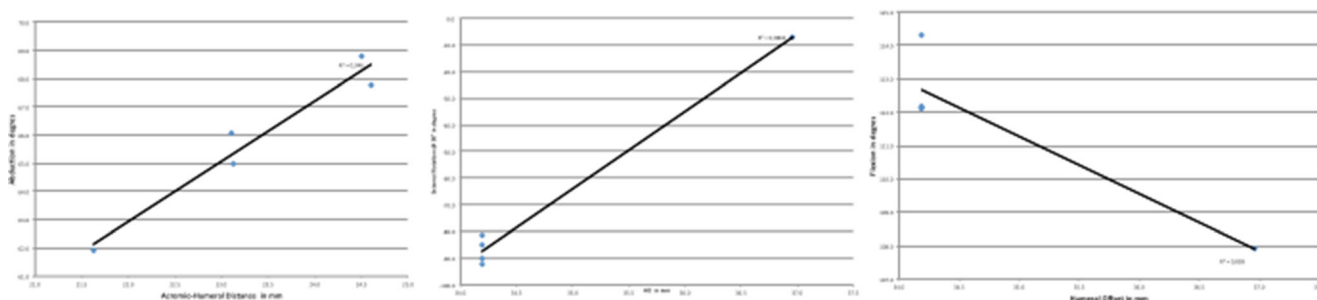


Fig. 5 Linear regression between ROM and AHD and humeral offset

42 mm neutral glenosphere RSAs compared to BIO-RSAs (75% vs 40%, $p = 0.022$). Conversely, Collin et al. reported no difference in notching with the two techniques [6]. One explanation could be that individual bony anatomy that can affect impingement [21]. Another explanation could be that scapular notching is harder to detect radiographically with a BIO-RSA.

Internal and external rotation weakness remains a concern after RSA. This functional deficit may be related to the medialization of the glenohumeral centre of rotation and lowering of the humerus [22], which both modify post-operative rotator cuff muscle length. In this study, the latter increased with all designs, except for the middle and inferior part of the subscapularis. The combination of glenoid and humeral offsets caused by the curved stem may consequently have a post-operative positive effect on active gleno-humeral ROM. Effectively, as the Blix curve describes, maintenance of length is required for a muscle to generate adequate tension [23]. Rotator cuff tear models have shown that muscle retraction leads to loss of force generation [24]. Similarly, an alteration of the function of a part of the rotator cuff in relation to RSA could be attributed to shortening of the muscle–tendon unit and to changes in muscle force vectors. At the other end of the spectrum, an excessive lengthening could be responsible for deleterious changes of the muscular architecture. The more important muscle stretching is seen on the supraspinatus (i.e., 19 mm with BIO-RSA configuration), followed by the upper part of the subscapularis. Acute lengthening might consequently induce muscle rupture or also cause impediment for reinsertion of the subscapularis, particularly with BIO-RSA. It thus seems logical to one of the authors (A.L., who was

blinded for review purposes) to preserve the subscapularis if intact and to detach the supraspinatus in a deltopectoral approach [25, 26].

Limitations

There are several limitations to this study. First, the computer model was developed from one cadaveric shoulder without any sign of pathology. The lack of morphological variation prevented us from analyzing patient-related factors, such as scapular neck morphology, glenoid version, and inclination, or critical shoulder angle [27], which may impact bony impingement and thus post-operative ROM [28]. The analysis was limited to the glenoid, and only an onlay 145° humeral prosthesis was used. While this allowed us to isolate the analysis to the glenoid, we cannot comment on different humeral configurations (e.g., 135° or inlay configuration). Future work should investigate varying both components. Additionally, other glenoid configurations, such as increased metallic offset (i.e., 6 mm lateral offset), were not tested and could affect the results. The analysis was limited to glenohumeral motion and excluded scapulothoracic motion. While we do not believe this would likely influence bony impingement, from a clinical perspective, scapulothoracic motion may increase in patients who have undergone RSA. Our analysis was limited to bony impingement and muscle tension, but quality of the deltoid, rotator cuff, and other shoulder muscles may affect clinical ROM. However, once an optimal prosthetic construct can be achieved based on avoiding bony impingement, further studies can be designed to evaluate the impact of muscle quality and other soft tissue tension.

Table 3 Muscle length elongation in millimeter for the five different glenoid prosthetic configurations in millimeter

	Supraspinatus	Superior infraspinatus	Middle infraspinatus	Inferior infraspinatus	Superior subscapularis	Middle subscapularis	Inferior subscapularis
Sphere 36 mm centered	11.5	10.5	7.6	4.3	2.0	−4.5	−10.9
Sphere 42 mm centered	14.5	13.5	10.8	7.6	5.1	−1.4	−7.7
Sphere 36 mm tilted 10°	13.7	12.6	9.8	6.7	4.6	−1.7	−7.9
Sphere 36 mm with BIO-RSA	18.6	17.2	14.8	11.9	10.3	4.4	−1.4
Sphere 36 mm with 2 mm inferior offset	13.0	12.1	9.1	5.7	3.2	−3.5	−10.2

Conclusions

Varying the glenosphere configurations leads to ROM and muscle length changes following RSA. With a 145° onlay humeral stem, a 36 eccentric glenosphere theoretically optimizes ROM while limiting scapular notching.

Compliance with ethical standards

Conflicts of interest Two authors (G.W., P.B.) of this study received royalties from the Wright Medical Group NV. One author (P.J.D.) is a paid consultant for Arthrex. One author (P.D.) of this study held stock from the Wright Medical Group NV.

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