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Anatomic factors influencing the anterior stability of reverse total shoulder arthroplasty

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Background: Several factors affect the stability of the reverse shoulder arthroplasty. The influence of bony anatomy on anterior stability remains unclear. This study aimed to identify the correlations between bony anatomy and anterior dislocation forces.
Methods: The differences in anterior dislocation force in reverse total shoulder arthroplasty reported in a previous biomechanical study were used to analyze the anatomic factors influencing anterior stability. The critical shoulder angle, glenocoracoid distance in 2 planes, and glenoid inclination were measured in the tested specimens using 3-dimensional computed tomographic scans and radiographs. Anatomic parameters were then correlated with the anterior dislocation forces.
Results: The critical shoulder angle had no correlation with anterior stability. The glenocoracoid distance in anteroposterior direction showed a negative correlation with the stability of a reverse shoulder arthroplasty with a 9-mm lateralized glenosphere and 155° humeral inclination in 30° and 60° glenohumeral abduction with the arm in 30° external rotation ($r = -0.662$, $P = .004$; $r = -0.794$, $P = .011$) and 30° glenohumeral abduction with neutral rotation ($r = -0.614$, $P = .009$). Using the same hardware configuration, the anterior stability had a negative correlation with the glenocoracoid distance in the mediolateral direction in 30° of glenohumeral abduction with the arm in 0° and 30° of external rotation ($r = -0.542$, $P = .025$; $r = -0.497$, $P = .042$).
Conclusion: The distance between the coracoid tip and glenoid in 2 planes had a significant negative correlation with the anterior stability of the reverse shoulder arthroplasty with a lateralized glenosphere and 155° humeral inclination. The findings suggest that only glenoid lateralization is influenced by the bony anatomy.
Level of evidence: Basic Science Study; Biomechanics

Keywords: Reverse total shoulder arthroplasty; critical shoulder angle; stability; glenocoracoid distance; inclination

The design of reverse total shoulder arthroplasty (RTSA) has been continuously modified and the indications for the implantation have been extended. Currently, research and development initiatives focus on glenosphere lateralization and variation of the humeral inclination to improve the biomechanics and outcome after RTSA. One of the most common complications of the RTSA is instability; the dislocation rates were reported between 2% and 31% and the most common direction is anterior.[6,7,8,15,16,22,25]

The stability of RTSA is multifactorial and is influenced by humeral cup depth, compressive force of the deltoid muscle, arm position, inferior offset of the glenosphere,

The Ethics Committee of the Medical School Hannover approved the study (7842_BO_K_2018). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or with comparable ethical standards.

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inclination of the glenosphere, and glenosphere size.[3,10,11,13,18,28,30,32,34] Inferior tilt of the glenosphere was associated with reduced[32] and superior inclination with increased instability of RTSA.[34]

Basically, glenosphere lateralization and reduction of the humeral inclination have advantages. These 2 factors influence the range of motion[17,20,24,26,33] and reduce the scapula notching.[5,12,23] The lateralization of the center of rotation increased the anterior stability of the RTSA, but the humeral neck-shaft angle affected the anterior stability less.[14,21] In one previous study, we already investigated the influence of glenosphere lateralization on the anterior stability of RTSA. The biomechanical study on 19 human shoulder specimens with RTSA showed that the lateralization of the glenosphere results in increased anterior stability. In that study, hemispherical glenospheres with different magnitudes of lateralization, together with 3 types of humeral inclination, were investigated.[12] The humeral inclination had a minor influence on the anterior stability. From a clinical point of view, we wanted to learn more about the anterior dislocation of the RTSA and identify individual risk factors for patients to suffer a dislocation based on the anatomic geometry of the scapula. Therefore, we investigated this relationship by a radiographic analysis of the 19 previously tested shoulder specimens and correlated the anatomic factors with the corresponding stability values from the previous study. The results of the study should help to identify patients at risk for anterior instability of the RTSA and to reduce the overall dislocation rate.

The first hypothesis was that the glenocoracoidal distance in 2 planes has negative correlation with the anterior stability of the RTSA. Further, we hypothesized that the inferior inclination and a greater critical shoulder angle (CSA) had positive correlation with the anterior stability. Another aim of the study was to validate the CSA for 3-dimensional (3D) models and measurement by showing a good positive correlation between the 2-dimensional (2D) and 3D measurements.

Material and methods

Stability data of the previous biomechanical study

Biomechanical data on dislocation force as a function of implant configuration after RTSA treatment from a previous biomechanical study were used in the present study to investigate the influence of anatomic parameters on joint stability.[12]

The extracted data are based on investigations on 19 cadaveric right shoulder specimens, without documented rotator cuff tear and shoulder injury in their medical history. The mean age and body mass index of the specimens (male, 13; and female, 6) were 70.2 years (standard deviation [SD] 10.9) and 23.4 (SD 2.9), respectively. For embedding, the lower part of the scapula was freed from the soft tissue and the humerus was cut approximately 20 cm distal to the humeral head center. For the implantation of the RTSA, a deltopectoral approach was used, so that the infraspinatus tendon was intact and the subscapularis tendon was detached. After implantation of a RTSA, the shoulders were further investigated after mounting in a robot-based testing setup without muscle loading.

The robot applied an anterior force on the humerus until dislocation of the shoulder joint occurred. This test was repeated for different joint positions and implant configurations.

For the present study, dislocation force data for the implant configurations with 0- and 9-mm glenospheric lateralization at 135° and 155° neck-shaft angles were extracted for the following arm positions: 0° and 30° of glenohumeral abduction with the arm in 0° and 30° of external rotation.

Radiologic measurements

The same specimens that were already used for the biomechanical analysis were analyzed for further radiologic measurements. The specimens were thawed at room temperature for 24 hours before investigation.

Radiographs of the specimens were performed using a x-ray c-bow (Ziehm Exposcop 8000; Ziehm GmbH, Nürnberg, Germany). Therefore, the specimens were positioned in the ray path in a way to create images in a true anteroposterior plane. The anteroposterior radiographs were further analyzed and the critical shoulder angle (CSA) was measured according to Moor et al[25] by use of the software ImageJ (US National Institutes of Health, Bethesda, MD, USA) (Fig. 1). Therefore, 2 lines were created. The first line was drawn from the most superior edge to the most inferior edge of the glenoid. The second line connected the most inferior margin of the glenoid to the most lateral edge of the acromion. The angle was measured between these 2 lines.

Furthermore, computed tomographic (CT) scans of the shoulders were undertaken (Revolution EVO, General Electric Boston,

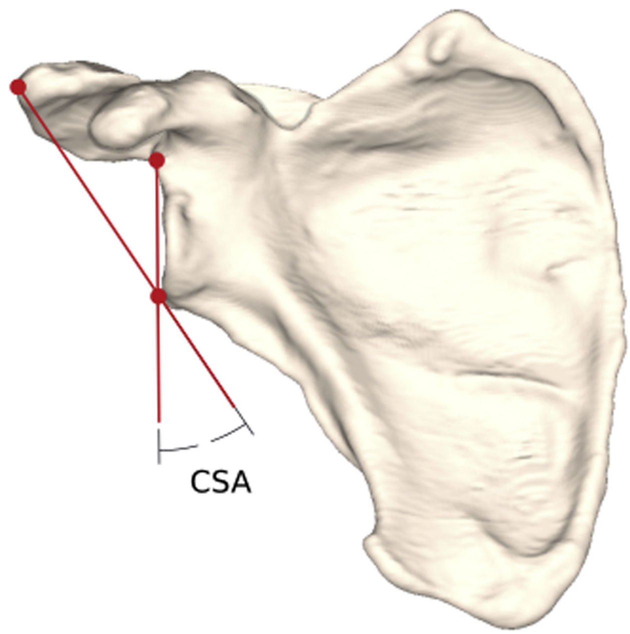

Figure 1 Measurement of the CSA of the shoulder in a 3D bone model of the scapula according to Moor et al.[25] *CSA*, critical shoulder angle.

MA, USA) by use of a standard protocol. Image segmentation was performed on CT data to create 3D models of each scapula by use of a special segmentation software (AMIRA, v.5.5.3; FEI Visualization Sciences Group, OR, USA).

The 3D bone models that were created based on the segmentations of the CT images were further investigated by use of GOM Inspect, an evaluation software for 3D measurement data (GOM GmbH, Braunschweig, Germany). The glenocoracoid distance in the mediolateral direction initially described by Dugarte et al[9] was adapted to be applicable to 3D models. Therefore, based on 3 landmarks that were the most superior, inferior, and anterior aspects of the glenoid rim, a plane was created on the glenoid (glenoid plane), and the shortest, perpendicular distance between this plane and the tip of the coracoid was measured, and then the perpendicular distance between this plane and the tip of the glenoid was measured (Fig. 2). Furthermore, the glenocoracoid distance was measured in the anteroposterior direction. Therefore, additionally to the glenoid plane, a second plane was then placed perpendicular to the first plane and oriented along the superoinferior axis of the glenoid (SI plane). The distance between the SI plane and the tip of the coracoid was measured. The metaglene inclination was measured as described by van Haver et al.[16] First, an anatomic plane of scapula was created. An angle was measured between the fossa supraspinatus line and a parallel line to the metaglene. Furthermore, the CSA was measured in the 3D models according to measurements in the radiographs.

The measurements were performed by 2 independent investigators.

Statistical analysis

The anatomic parameters metaglene inclination, CSA, and anteroposterior and mediolateral coracoidal distance were correlated with the dislocation force values of the previous study for statistical evaluation.

Statistical analysis was performed using SPSS 24.0 (IBM, Armonk, NY, USA) to analyze data with a bivariate correlation (Pearson test). The correlations were performed between the mean anterior dislocation forces of each hardware configuration and arm positions and the anatomic factors.

The significance level was set to $P < .05$. All data are presented as means and SDs.

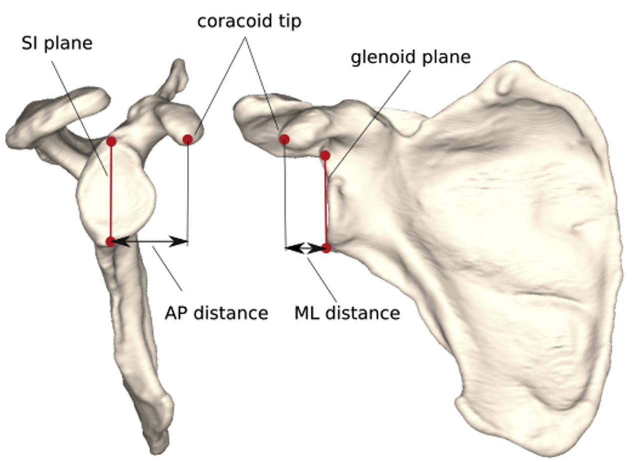

Figure 2 Measurement of the glenocoracoid distance in the anteroposterior and mediolateral directions in a 3D bone model. *AP*, anteroposterior; *ML*, mediolateral; *SI*, superoinferior.

Results

The measurement of the CSA in native radiographs and 3D CT showed a mean angle of 33.1° (SD 4.4°) and 30.0° (SD 4.1°), respectively. The correlation for both of these values was significant (P = .012), although neither in the radiographs nor in the 3D CT did the CSA have a significant correlation with the anterior stability of the RTSA in each configuration and arm position.

The mean glenocoracoid distance in the anteroposterior and mediolateral directions was 32.1 mm (SD 5.0) and 13.9 mm (SD 3.0), respectively. The details of the correlations and associated P values as well as the results of the stability testing are shown in Table I.

The data reveal a significant negative correlation of the anteroposterior glenocoracoid distance with the mean value of configurations with a 9-mm lateralized glenosphere and 155° inclination for all arm positions (r = –0.641, P = .006). The configuration of the lateralized glenosphere and 155° inclination showed a significant negative correlation in 30° of glenohumeral abduction with the arm in neutral rotation (r = –0.614, P = .009), as well as in 30° of external rotation (r = –0.662, P = .004). The same implant configuration also had a negative correlation in 60° of glenohumeral abduction with the arm in 30° of external rotation (r = –0.794, P = .011). RTSA with a hemispherical glenosphere and 155° inclination had a significant negative correlation with the glenocoracoid distance in the anteroposterior direction (r = –0.505, P = .028) when the glenohumeral joint was in 30° of glenohumeral abduction and neutral rotation (Fig. 3).

The glenocoracoid distance in the mediolateral direction also had a significant negative correlation with the RTSA in 155° of humeral inclination and the 9-mm lateralized glenosphere in all combined arm positions (r = –0.538, P = .026). Furthermore, this hardware configuration showed a significant negative correlation in the arm position of 30° of glenohumeral abduction and neutral rotation (r = –0.542, P = .025), as well as 30° of glenohumeral abduction and 30° of external rotation (r = –0.497, P = .042) (Fig. 4). The mean glenoidal inclination was 82.0° (SD 4.9°) and had no significant correlation with the anterior stability of the RTSA.

Discussion

For this radiologic study, we hypothesized that the glenocoracoid distance in the mediolateral and anteroposterior directions has a negative correlation with the anterior

Table I Correlations and *P* values of the glenocoracoid distance and each hardware configuration and arm position

Hardware configuration	Glenocoracoid distance AP, cm		Glenocoracoid distance ML, cm		Dislocation force, N
	r value	*P* value	*r* value	*P* value	
135° humeral inclination and hemispherical glenosphere	0.094	.729	0.159	.556	59.0
135° humeral inclination and 9-mm lateralized glenosphere	−0.135	.619	−0.344	.192	90.6
155° humeral inclination and hemispherical glenosphere	−0.35	.142	−0.376	.112	57.5
155° humeral inclination and 9-mm lateralized glenosphere	−0.641	.006	−0.538	.026	92.5
155° humeral inclination and hemispherical glenosphere and 30° abduction with neutral rotation	−0.505	.028	−0.296	.218	40.1
135° humeral inclination and hemispherical glenosphere and 30° abduction with neutral rotation	0.068	.801	0.182	.5	40.6
155° humeral inclination and 9-mm lateralized glenosphere and 30° abduction with neutral rotation	−0.614	.009	−0.542	.025	91.8
135° humeral inclination and 9-mm lateralized glenosphere and 30° abduction with neutral rotation	−0.176	.515	−0.269	.313	86.7
155° humeral inclination and hemispherical glenosphere and 30° abduction with 30° external rotation	−0.299	.213	−0.394	.095	52.0
135° humeral inclination and hemispherical glenosphere and 30° abduction with 30° external rotation	0.109	.7	−0.044	.877	70.5
155° humeral inclination and 9-mm lateralized glenosphere and 30° abduction with 30° external rotation	−0.662	.004	−0.497	.042	78.9
135° humeral inclination and 9-mm lateralized glenosphere and 30° abduction with 30° external rotation	−0.042	.887	−0.518	.058	90.4
155° humeral inclination and hemispherical glenosphere and 60° abduction with neutral rotation	−0.307	.201	−0.348	.144	64.2
135° humeral inclination and hemispherical glenosphere and 60° abduction with neutral rotation	−0.065	.826	−0.104	.724	48.6
155° humeral inclination and 9-mm lateralized glenosphere and 60° abduction with neutral rotation	−0.368	.239	−0.231	.471	92.4
135° humeral inclination and 9-mm lateralized glenosphere and 60° abduction with neutral rotation	−0.064	.843	−0.007	.982	79.0
155° humeral inclination and hemispherical glenosphere and 60° abduction with 30° external rotation	−0.153	.545	−0.258	.301	76.2
135° humeral inclination and hemispherical glenosphere and 60° abduction with 30° external rotation	−0.155	.612	0.223	.464	84.6
155° humeral inclination and 9-mm lateralized glenosphere and 60° abduction with 30° external rotation	−0.794	.011	−0.316	.407	82.5
135° humeral inclination and 9-mm lateralized glenosphere and 60° abduction with 30° external rotation	−0.073	.864	−0.217	.605	88.5

AP, anteroposterior; *ML*, mediolateral.
The mean dislocation forces of each hardware configuration and arm positions (N = Newton).

stability of the RTSA. This was partly supported by our data as we found a negative correlation particularly between the glenocoracoid distance and the RTSA with 155° humeral inclination and a lateralized glenosphere. Furthermore, neither the CSA in native radiographs nor in the 3D CT and the inclination of the glenoid baseplate correlated significantly with the anterior stability of the RTSA, independent of the implant configuration. However, we were able to show a good correlation of $r = 0.578$ between the 2D and 3D measured CSA values. The mean CSA value in the 3D CT was 3° lower than the measurement in the native radiographs. The mean CSA values were concurrent with those reported in literature.[1,4,19] The dimension of the bony roof of the RTSA in the frontal plane, which is reflected indirectly in the CSA, showed no correlation with the anterior stability. Thus the extent of the bony acromial extension cannot serve as a predictor of stability or instability of the RTSA. Further, missing correlation could be due to the small variance of the CSA.

Good negative correlation was observed between the glenocoracoid distance in the mediolateral direction and all arm positions (30° and 60° of glenohumeral abduction with the arm in 0° and 30° of external rotation) with 155° humeral inclination and a 9-mm lateralized glenosphere. Furthermore, good correlation was observed between the glenocoracoid distance in the mediolateral direction and the

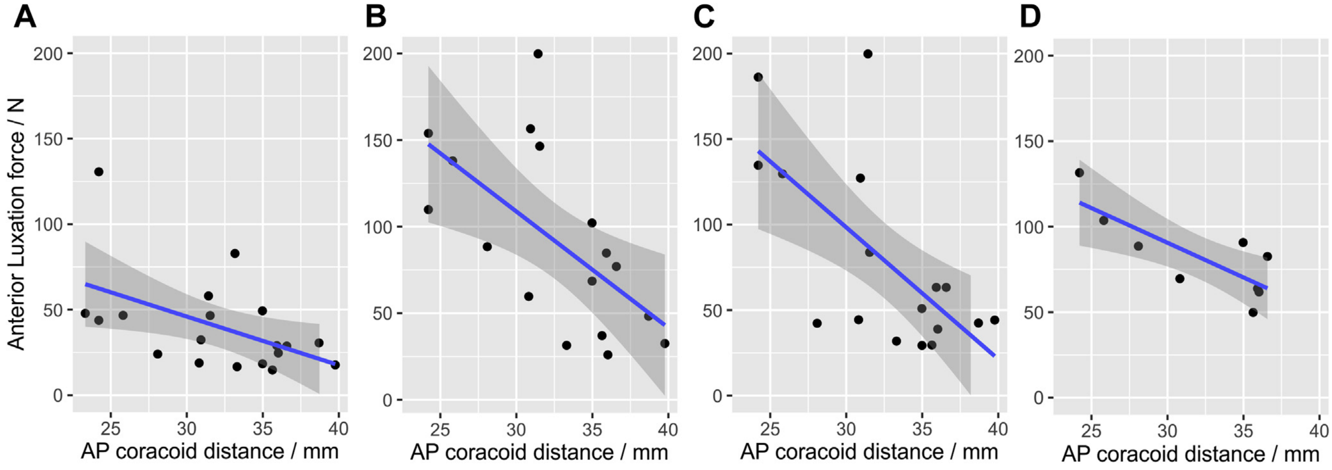

Figure 3 Correlation between anterior luxation force and anteroposterior coracoid distance. Dots represent single data points, and the gray band shows the confidence. **(A)** RTSA with 155° humeral shaft angle and hemispherical glenosphere in 30° glenohumeral abduction and neutral rotation; **(B)** RTSA with 155° humeral shaft angle and 9-mm lateralized glenosphere in 30° glenohumeral abduction and neutral rotation; **(C)** RTSA with 155° humeral shaft angle and 9-mm lateralized glenosphere in 30° glenohumeral abduction and 30° external rotation; **(D)** RTSA with 155° humeral shaft angle and 9-mm lateralized glenosphere in 60° glenohumeral abduction and 30° external rotation.

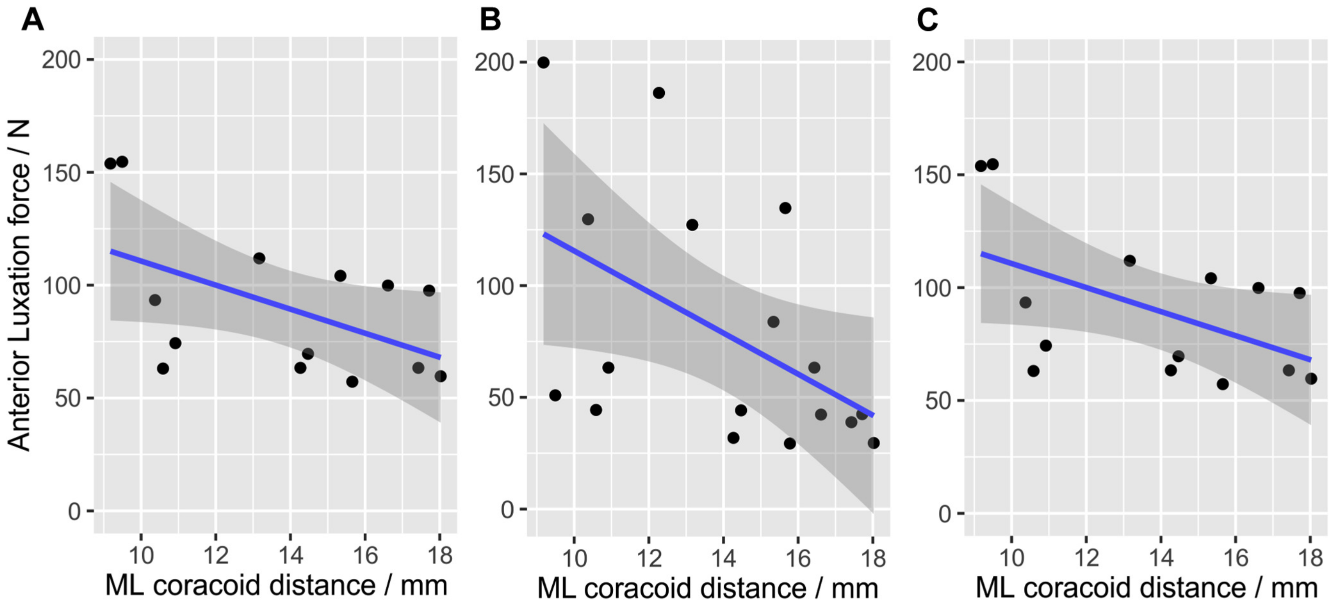

Figure 4 Correlation between anterior luxation force and mediolateral coracoid distance. Dots represent single data points, and the gray band shows the confidence. **(A)** RTSA with 155° humeral shaft angle and 9-mm lateralized glenosphere in 30° glenohumeral abduction and neutral rotation; **(B)** RTSA with 155° humeral shaft angle and 9-mm lateralized glenosphere in 30° glenohumeral abduction and 30° external rotation; **(C)** RTSA with 135° humeral shaft angle and 9-mm lateralized glenosphere in 30° glenohumeral abduction and 30° external rotation.

RTSA with 155° humeral inclination and a 9-mm lateralized glenosphere in 30° of glenohumeral abduction with neutral rotation and 30° of external rotation. This means that a more lateral position of the coracoid tip and a consequently too lateral position of the conjoint tendon might influence the anterior stability of the RTSA, but only in the presence of glenosphere lateralization. The humeral inclination of 135° did not show a significant correlation with the glenocoracoid distance in the mediolateral direction. A biomechanical study of 19 human cadaveric shoulder specimens showed that the humeral inclination also had a minor influence on the anterior stability of the RTSA.[12] This finding was consistent with those observed in our study.

Our analysis also showed that the coracoid tip had a mean distance of 32.1 mm to the glenoid in the anteroposterior direction. Currently, no comparable studies exist for this parameter.

The results of this study showed that an implant configuration of a 9-mm lateralized glenosphere and 155° humeral inclination had a good negative correlation with the glenocoracoid distance in the anteroposterior direction. This results seems comprehensible as the closer the coracoid tip with the conjoint tendon is to the glenoid, the sooner the RTSA will be in contact with the conjoint tendon in case of an anterior load of the humerus. Hence, the conjoint tendon can increase the anterior stability of the RTSA. This could already be shown in one of our previous biomechanical studies on the anterior stability of the RTSA.[27] In case of a humeral neck-shaft inclination of 155° compared with an inclination of 135°, the polyethylene cup of the RTSA is positioned in a more flat orientation; hence, the medial portion of the humeral cup is placed closer to the lateral pillar of the scapula.[2,7] Langohr et al[24] verified these findings in their finite element analysis of the contact mechanics of the RTSA. In this study, the articular contact area was located anteroinferior in cases of a humeral inclination of 135°, and the articular contact area was more central with the humeral inclination of 145° and 155° in lower degrees of abduction.[24] The contact areas showed that the RTSA with 135° humeral inclination led to humeral lateralization, which increased the distance to the coracoid tip. Because of this, the glenocoracoid distance had no significant correlation with this implant configuration. This may allow the conclusion that the anterior stability is not influenced by the conjoint tendon in case of a humeral inclination of 135° and humeral-sided lateralization in contrast to a configuration with glenoidal lateralization. However, a previous study showed that the humeral inclination had only a minor influence on the anterior stability of RTSA, because the humeral inclination of 135° showed only higher dislocation forces comparing to a 145° and 155° inclination in the arm position of 30° abduction and 30° external rotation.[12] These findings are in line with the current literature.[10,26] Oh et al[26] also found only superior anterior dislocation forces in RTSA with 135° humeral inclination with an arm position of 30° external rotation, whereby 155° humeral inclination was more stable than 135° in internal rotation position. Further, a clinical review by Erickson et al,[10] who investigated the influence of the humeral head inclination in RTSA, showed no differences between 135° and 155° humeral inclination related to the stability of the RTSA.

The mean glenoidal inclination was 82° and had no significant correlation with the anterior stability of the RTSA. Currently, only 2 studies exist that have analyzed glenoid inclination and its influence on the RTSA.[29,31] Randelli et al[29] observed in their retrospective study on 33 patients after RTSA that an inferior glenoid tilt of 10.2° is associated with a reduced risk of dislocation compared with a neutral tilt. Furthermore, Tashjian et al,[31] who performed a clinical study with 97 patients after RTSA, found that superior glenoid tilt led to instability. The range of glenoid inclination angles observed in our study is comparable to those reported in other studies.[29,31] However, we were not able to analyze the influence of the glenoid tilt on anterior stability of the RTSA.

This study has some limitations. The anterior stability data used were based on experiments on human shoulder specimens at time point zero; hence, soft tissue healing and muscle tension could not be considered. Further, inaccuracies could occur in the process of the segmentation of the 3D model, which could have affected the measurements. As mentioned in the previous study, the 60° glenohumeral abduction position could not be reached in some cases, because of the high soft tissue tension.[12]

Conclusion

This study showed the distance of the coracoid, and thus possibly the conjoint tendon, to the glenoid in both directions had a significant correlation with the anterior stability of the RTSA with the implant configuration of 155° humeral inclination and a 9-mm lateralized glenosphere. This effect was not seen in the presence of a humeral inclination angle of 135°. This suggested that only glenoidal lateralization is influenced by the anatomic factors. Furthermore, the CSA was validated for measurement in a 3D model but showed no correlation with anterior stability. In addition, no correlation was found between glenoidal inclination and anterior stability.

Disclaimer

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