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Three-dimensional kinematics of reverse shoulder arthroplasty: a comparison between shoulders with good or poor elevation

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A R T I C L E I N F O

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Level of evidence: Level III; Case-Control Design; Treatment Study

Background: Various factors may be related to outcomes of reverse shoulder arthroplasty (RSA) including patient and surgical factors. Differences in shoulder kinematics might be associated with poor function after RSA; however, kinematic differences between shoulders with good or poor elevation have not been elucidated. The purpose of this study was to compare RSA kinematics between shoulders with good or poor elevation.
Methods: The study included 28 shoulders with a minimum 6-month follow-up after RSA using Grammont-type prostheses. Subjects comprised 17 men and 11 women with the mean age of 75 years (range, 63-91). Subjects underwent fluoroscopy during active scapular plane abduction. Computed tomography of their shoulders was performed to create 3-dimensional scapular implant models. Using model-image registration techniques, poses of 3-dimensional implant models were iteratively adjusted to match their silhouettes with the silhouettes in the fluoroscopic images, and 3-dimensional kinematics of implants were computed. Kinematics and glenosphere orientation were compared between shoulders with good (>90 degree) or poor (<90 degree) scapular plane abduction.
Results: Nineteen and 9 shoulders were assigned to the good- and poor-elevation groups, respectively. There were no significant differences between the groups in age, sex, height, weight, preoperative range of motion, or Constant score, but body mass index in the poor elevation shoulders was significantly larger than that in the good elevation shoulders. There were no significant differences in glenosphere (upward/downward rotation, anterior/posterior tilt, internal/external rotation) or glenohumeral (internal/external rotation, abduction/adduction) kinematics between the good and poor elevation shoulders. Scapulohumeral rhythm was significantly higher in the good elevation shoulders than the poor elevation shoulders ($P = .04$). Glenosphere superior tilt was $2.3° \pm 4.2°$ in the good-elevation group and $8.1° \pm 8.9°$ in the poor-elevation group, and the difference was statistically significant ($P = .03$).
Discussion: Shoulders with good elevation after RSA demonstrated better scapulohumeral rhythm than those with poor elevation, though there were no significant differences in glenosphere and glenohumeral kinematics. It may be important for better elevation to achieve good glenohumeral motion in shoulders with RSA. Glenosphere orientations may affect postoperative shoulder function.

Reverse shoulder arthroplasty (RSA) is widely accepted as an effective treatment option for patients with rotator cuff function deficit such as irreparable rotator cuff tears and rheumatoid arthritis with a rotator cuff tear, and the indication of RSA has been expanded to various shoulder pathology including osteoarthritis with excessive erosion and fracture sequelae after proximal humeral fracture.[11,19] The biomechanical changes after RSA, such as the medialized center of rotation and the increased deltoid moment arm, compensate for the loss of rotator cuff function.[7] Most patients improve their function including shoulder elevation after surgery, but some patients show less improvement than expected.[18] Various factors have been reported that are related to the poor improvement of shoulder function after RSA including

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age,[15,18] sex,[15] patients' stature,[27] obesity,[39] deltoid muscle volume,[43] preoperative range of motion,[14] preoperative diagnosis,[11,19,42] and glenosphere size and position.[6,10,30,32,33]

Differences in shoulder kinematics might be associated with poor function after RSA. There have been, however, no studies that compared RSA kinematics between shoulders with good or poor elevation.

Many studies have evaluated kinematics in patients with RSA using various techniques.[2,3,9,13,21,28,40] Three-dimensional/2-dimensional model-image registration techniques represent 1 method for measuring joint kinematics that has been proven to have sufficient accuracy.[5,24,26] Several articles have reported shoulder kinematics using these techniques including RSA kinematics.[28,40] The purpose of this study was to compare RSA kinematics between shoulders with good or poor elevation. We hypothesized that shoulders with poor elevation would demonstrate less glenohumeral contribution to scaption compared with those with good elevation.

Methods

Patients

Twenty-eight patients (28 shoulders) who underwent RSA provided informed consent to participate in this institutional review board–approved study. The patients consisted of 17 men and 11 women with a mean age of 75 years (range, 63-91). There were 18 dominant and 10 nondominant shoulders. Diagnoses were as follows: irreparable massive rotator cuff tear/cuff tear arthropathy, 21 shoulders; fracture sequelae, 4 shoulders; osteoarthritis/rheumatoid arthritis, 2 shoulders; implant failure after hemiarthroplasty, 1 shoulder. Aequalis Reversed (Wright Medical, Memphis, TN, USA) was used in all shoulders with a concentric 36-mm glenosphere.

One of the senior surgeons (K.M., H.S., N.T., and M.T.) preoperatively evaluated patients with active range of motion, which was measured using a goniometer, and Constant score.

Image acquisition

Fluoroscopic images of scapular plane abduction were recorded at a mean of 12 months (range, 6-20) after surgery (Plessart Zero, Toshiba, Tochigi, Japan). Images were acquired at 7.5 frames/s with 310 × 310-mm field of view and 1024 × 1024 image matrix. The patient stood with their torso at approximately 30° to the plane of the image intensifier, so that the scapula body was perpendicular to the x-ray beam.[25,26,28] Scapular plane abduction was performed from arm at side to maximum abduction in approximately 5 seconds. During the activity, the elbow was fully extended, and the palm was directed forward (thumbs-up position). The body of the patient was not constrained to allow natural motion of the arm, and the speed of motion was not strictly controlled. The patients practiced the motion several times until they felt comfortable, and then, the activity was recorded.

The patients also underwent computed tomography scans of the shoulder (Alexion, Toshiba, Tochigi, Japan). The imaging parameters were as follows: slice pitch, 0.3 mm; image matrix 512 × 512; pixel size, 0.468 × 0.468. Iterative reconstruction techniques were used to minimize metal artifact.

Three-dimensional implant models

Computer-aided design models of humeral implants were obtained from the manufacturer (Wright Medical, Memphis, TN, USA). Three-dimensional surface models of scapular implants including glenosphere, baseplate, and screws were created from the computed tomography images using segmentation software (ITK snap, Penn Image Computing and Science Laboratory, Philadelphia, PA, USA).[44] The modeling accuracy has been confirmed by deviation analysis with the root mean square error of 0.41 mm when comparing computed tomography–derived models to the corresponding computer-aided design models.[28] Anatomic coordinate systems were embedded in the humeral and scapular implant models as per the reported convention (Fig. 1).[28] In brief, the origin of the humeral implant model was set at the center of the curvature of the polyethylene insert, and the origin of the scapular implant model was set at the center of the glenosphere. The X-axes of both models were set in the mediolateral direction, the Y-axes in the superoinferior direction, and the Z-axes in the anteroposterior direction. Surface models of the combined scapula and implant were also created for each patient to measure the glenosphere orientations.

Model-image registration and data processing

Model-image registration techniques were used to determine the 3-dimensional position and orientation of humeral and scapular implant models.[5,24] The implant models were projected onto the distortion-corrected fluoroscopic image, and the silhouettes of the models were matched with the silhouettes in the fluoroscopic image to determine their 3-dimensional poses (Fig. 2). The accuracy of these techniques for the shoulder was 0.5 mm for in-plane translation, 1.5 mm for out-of-plane translation, 0.8° for in-plane rotation, and 3.7° for out-of-plane rotation.[26] The model-image registration was performed with a series of images from the arm at side to maximum abduction.

The kinematics of humeral and scapular implant models relative to the x-ray coordinate system were determined using Cardan angles (z-x-y order).[23] The humeral implant model kinematics relative to a scapular implant model were also calculated from these kinematics using Cardan angles. Abduction of a humeral implant was defined as rotation about the humeral Z-axis and internal/external rotation as rotation about the humeral Y-axis. Forward/backward rotation of a glenosphere was defined as rotation about the scapular X-axis, internal/external rotation as rotation about the scapular Y-axis, and upward/downward rotation as rotation about the Z-axis (Fig. 1). Scapulohumeral rhythm was defined as $(\Delta H - \Delta S)/\Delta S$ as per the reported method, where ΔH is the increment in humeral elevation angle and ΔS is the increment in scapular upward rotation angle.[25,40]

Glenosphere orientations

Glenosphere orientations were measured with the combined scapula and glenosphere models, using a modification of a previously reported method for measurement of glenoid orientation.[29] A polar line describing the glenosphere implant was measured relative to a line connecting the origin of the glenosphere implant and the medial border of the scapular spine. Superior/inferior inclination and anterior/posterior version of the glenosphere were defined as the angles between the implant polar line in the XY plane (Fig. 3, *A*) and the XZ plane, respectively (Fig. 3, *B*).

Statistical analysis

The patients were divided into two groups as per the maximum humeral abduction angle in the kinematic analysis: > 90° abduction, good elevation group and < 90° abduction, poor elevation group. The definition of the groups was based on the definition of pseudoparalysis (<90° of elevation) proposed by Oh et al.[36] The

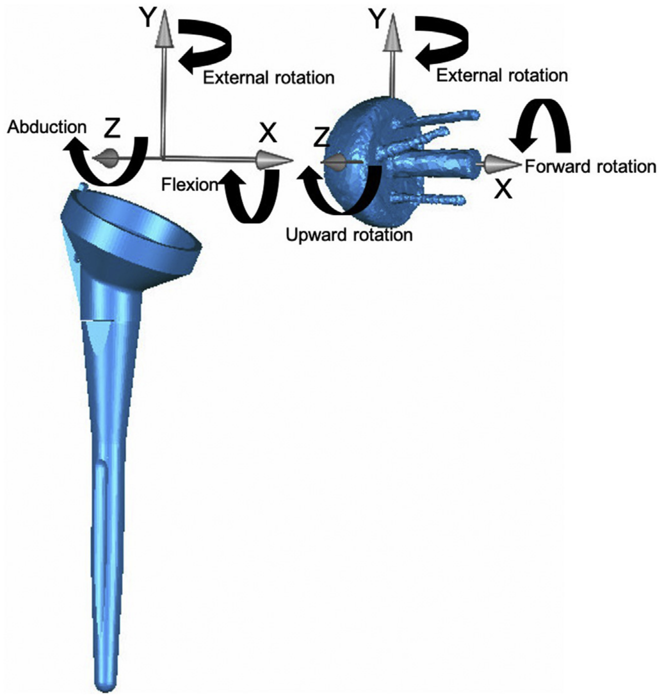

Figure 1 Coordinate systems and definition of motions for humeral and glenoid implants.

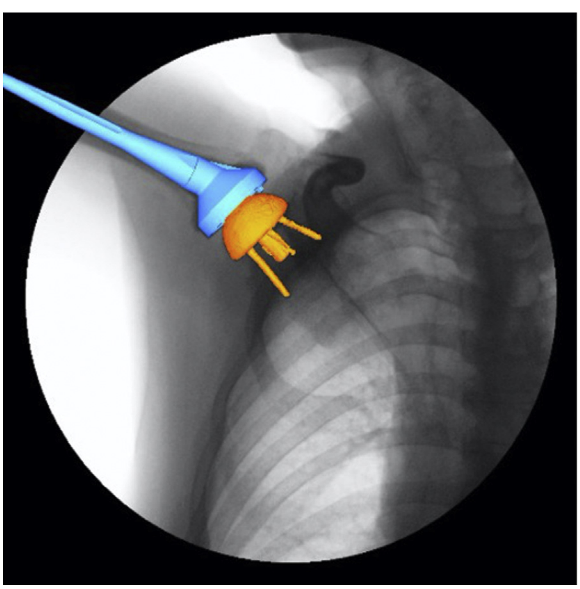

Figure 2 Model-image registration is used to determine 3D motions of implants relative to the imaging system as well as relative glenohumeral motion. *3D*, 3-dimensional.

kinematic and demographic data were compared between the groups. A Student's t-test was used to compare continuous data between the groups. A chi-square test was used to compare categorical variables. A two-way repeated-measures analysis of variance was used to compare kinematic data between the groups. A Student's t-test was used for post hoc pair-wise tests when the analysis of variance detected significant differences. The level of significance was set at $P < .05$.

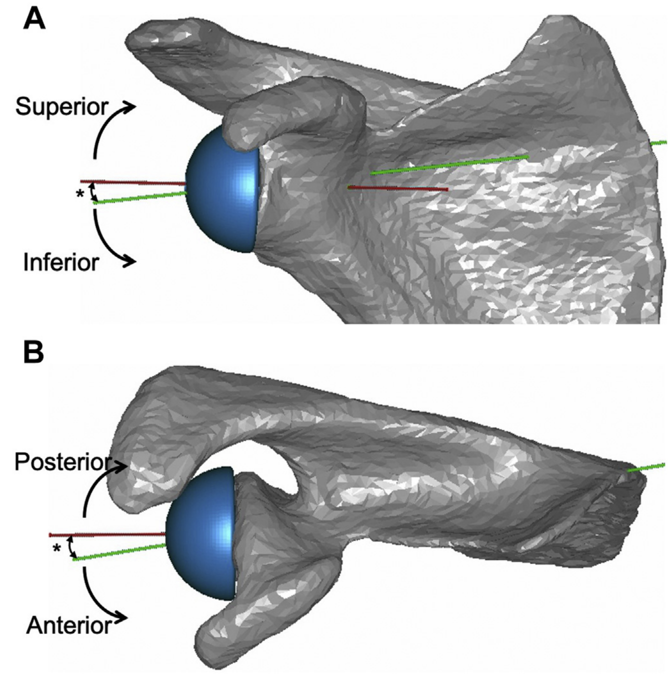

Figure 3 Glenosphere orientation relative to the scapula was measured between the implant polar line (*red*) and a line (*green*) connecting the origin of a scapular implant and the medial border of the scapular spine. Superior/inferior inclination (**A**) and anterior/posterior version (**B**) of the glenosphere were defined as the angles between the polar line (*red*) and the scapular spine line (*green*) in the XY plane and the XZ plane, respectively.

Results

The kinematic data revealed that 19 shoulders could elevate their humerus > 90° in the scapular plane and were assigned to the good-elevation group. Nine shoulders with < 90° scaption were assigned to the poor-elevation group. There were no significant differences in age, sex, height, weight, preoperative ranges of motion or preoperative Constant score between the groups, though the good-elevation group tended to have better flexion ($P = .05$, Table I). In addition, the difference in Constant score (13 points) exceeded the minimal clinically important difference (5.7 points) reported by Simovitch et al.[38] The poor-elevation group demonstrated significantly higher body mass index (BMI) than the good-elevation group ($P = .02$, Table I). Retroversion of the humeral implant was 20° in roughly half of shoulders in each group, and glenoid bone grafting using the bony increased offset technique[4,17,32] was added in two shoulders of the poor-elevation group ($P = .03$).

Kinematic data from 20° to 70° of humeral abduction were compared between the good- and poor-elevation groups, and there were no significant differences in glenosphere upward rotation, forward rotation, or internal rotation between the groups (Fig. 4). Significant changes in glenosphere upward rotation and forward rotation were detected in relation to humeral abduction ($P < .001$ for both), but no significant change was found in glenohumeral internal rotation.

There were also no significant differences in glenohumeral internal rotation or abduction between the two groups, though the good-elevation group tended to have greater abduction than the poor-elevation group (Fig. 5). Both glenohumeral internal rotation and abduction showed significant changes in relation to humeral abduction ($P < .001$ for both). The good-elevation group demonstrated significantly higher scapulohumeral rhythm than the poor-elevation group (Fig. 6, $P = .04$), and the post hoc test revealed that

Table I
Comparison of demographics between shoulders with good or poor elevation.

	Good (n = 19)	Poor (n = 9)	*P* value
Age (yr)	73 (63-91)	78 (65-90)	.08
Sex (male/female)	12/7	4/5	.6
Height (cm)	158 (143-173)	155 (145-170)	.4
Weight (kg)	57 (43-72)	62 (47-78)	.2
Body mass index	22.6 (19.4-27.5)	25.8 (20.6-37.1)	.02
Diagnosis			.7
Irreparable cuff tear/CTA	15	6	
Fracture sequelae	2	2	
OA/RA	1	1	
Revision after hemiarthroplasty	1	0	
Preoperative range of motion			
Flexion (degree)	65 (40-100)	46 (20-95)	.05
External rotation (degree)	19 (-20-60)	16 (-20-50)	.7
Preoperative Constant score	45 (18-84)	32 (10-70)	.1
Surgery			
Humeral retroversion	10°, 2; 15°, 6; 20°, 10; 25°, 1	10°, 3; 15°, 2; 20°, 4	.5
Bony increased offset (BIO)	0	2	.03

CTA, cuff tear arthropathy; *OA*, osteoarthritis; *RA*, rheumatoid arthritis.
Values are given as mean (range).

there were significant differences at 20°, 60°, and 70° humeral abduction (*P* = .02, .02, and 0.03, respectively).

Glenosphere superior tilt was 2.3° ± 4.2° in the good-elevation group and 8.1° ± 8.9° in the poor-elevation group, and the difference was statistically significant (*P* = .03). Glenosphere posterior version tended to be greater in the poor-elevation group than the good-elevation group, averaging 3.7° ± 8.9° posterior version and 2.8° ± 8.6° anterior version, respectively; however, the difference was not significant (*P* = .05).

Discussion

This study demonstrated that there were no statistically significant kinematic differences between shoulders with good or poor elevation except for scapulohumeral rhythm. Shoulders with good elevation showed significantly higher scapulohumeral rhythm than those with poor elevation. There were no differences between the groups in demographics except for BMI. Retroversion of the humeral implant also showed no significant difference between the groups, but BIO-RSA was only performed in two shoulders of the poor-elevation group.

The poor-elevation shoulders had lower scapulohumeral rhythm, and the value was approximately 1 throughout the activity. This means that the glenohumeral joint showed little movement during elevation and that elevation was mostly caused by scapular movement. In fact, the poor-elevation group demonstrated smaller glenohumeral abduction and larger glenosphere upward rotation than the good-elevation group, though the differences were not significant. Thus, our hypothesis was partly confirmed. It seems that these kinematics are similar to those in shoulders with massive rotator cuff tears, and the increased scapular upward rotation is probably owing to compensation for the decreased glenohumeral motion.[20,31] It may be important for better elevation to achieve glenohumeral joint motion.

The causes of poor functional improvement after RSA are still unclear. Regarding patient factors, age,[15,18] female,[15] small and large stature,[27] and high BMI[39] are reported risks for poor outcomes. High BMI was only detected as a factor associated with poor elevation in this study. Only 1 patient, however, had high BMI (37.1) in the poor-elevation group, and the others were within the overweight level (25.0-29.9) or less. The result might be different if the study was performed in a larger cohort. Preoperative diagnosis is also a possible factor that influences functional improvement. Recent systematic reviews have indicated that osteoarthritis showed the least improvement in elevation[19] and that fracture sequelae demonstrated lower postoperative flexion.[11] In fact, the poor-elevation group in this study had a larger percentage (3 of 9, 33%) of patients with these diagnoses than the good-elevation group (4 of 19, 21%).

As preoperative range of motion and functional score were also not different between the groups, surgical factors should considerably influence the kinematic differences. Both glenoid and humeral side factors have been reported to affect functional outcomes after RSA. On the glenoid side, the size and position of glenospheres have been reported as factors associated with postoperative shoulder function.[6,10,30,32,33] Several studies have demonstrated that shoulders with a larger glenosphere had better postoperative shoulder function than those with a smaller glenosphere,[6,32,33] but the same glenosphere size was used in all shoulders in this study. Glenosphere superior inclination was related to the poor outcomes in this study. Although superior inclination has been reported to be associated with scapular notching,[22] no studies have mentioned the relationship between elevation function and superior inclination. The results of this study indicated that glenosphere orientation may affect shoulder function. On the humeral side, various factors have been reported including deltoid moment arm,[29,41] neck-shaft angle,[35] and humeral offset.[16] In this study, humeral retroversion did not affect shoulder elevation unlike previous studies.[1,12,37]

There were two shoulders with BIO-RSA in the poor-elevation group, while no shoulders underwent BIO-RSA in the good-elevation group. BIO-RSA is performed for shoulders with glenoid bone erosion or deficiency to restore the glenoid bone stock and correct alignment of the implant using an autograft from the humeral head.[4,8,17,34] Good clinical outcomes after BIO-RSA have been reported previously.[4,17,34] We believe that the risk factor for poor outcomes is not BIO-RSA itself but severely altered joint structure that required bone grafting. In addition, the small number of study subjects may be inordinately influenced by these shoulders.

There were several limitations in this study. First, the number of subjects was small, which had possibly some influence on statistics. Second, model-image registration techniques using single-plane fluoroscopy have relatively poor accuracy in out-of-plane rotations.[26] The techniques using biplane fluoroscopy provide better accuracy, but the space for shoulder motions is restricted and increased radiation exposure is a concern. Because this analysis is primarily focused on scapular plane motion, single-plane measurements are demonstrably adequate. Third, variations in

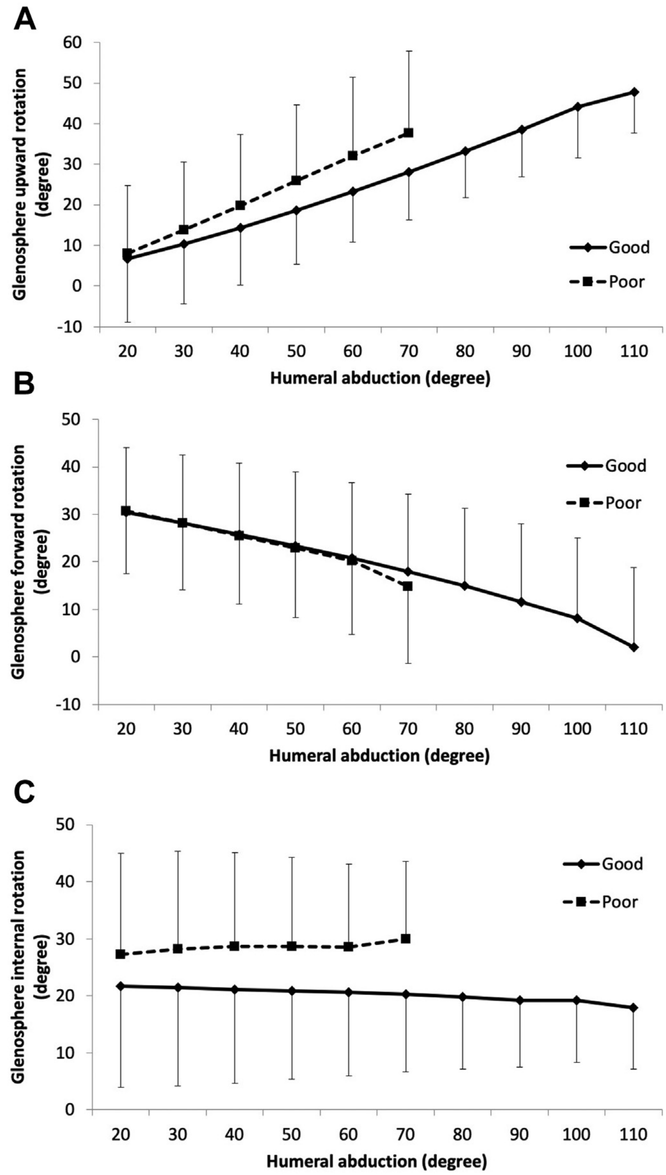

Figure 4 Glenosphere kinematics. (**A**) Upward rotation. (**B**) Forward rotation. (**C**) Internal rotation. There were no significant differences in all rotations between the good and poor elevation groups.

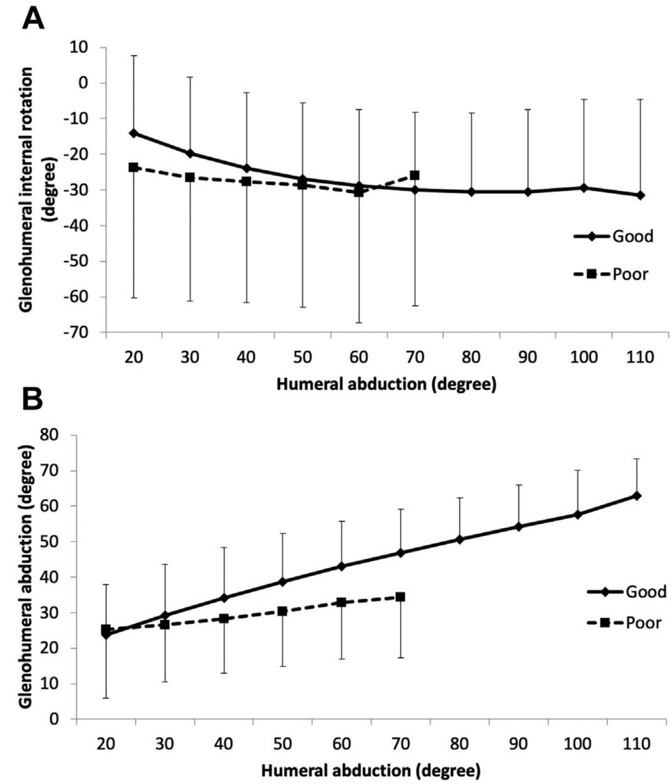

Figure 5 Glenohumeral kinematics. (**A**) Internal rotation. (**B**) Abduction. There were no significant differences in internal rotation and abduction between the good and poor elevation groups.

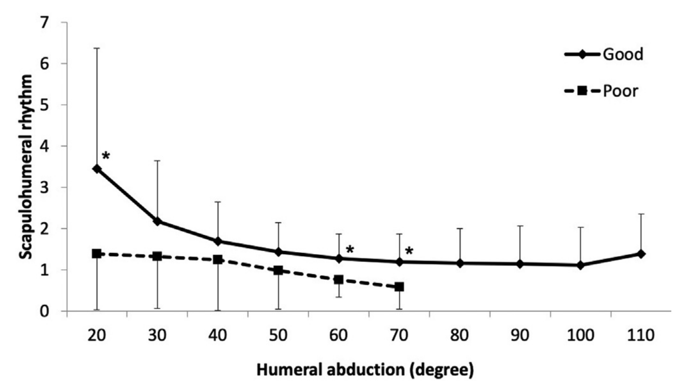

Figure 6 Scapulohumeral rhythm. The good elevation group demonstrated higher scapulohumeral rhythm than the poor elevation group ($P = .04$), and the post-hoc test revealed that there were significant differences (*) at 20°, 60°, and 70° humeral abduction ($P = .02$, .02, and .03, respectively).

kinematics were relatively large between patients, which also had some influence on interpretation of the results. This may be partly because we did not constrain patients or strictly control the arm motions to allow patients to naturally move their arms. This might cause variations in arm motion or compensative trunk motion. Because we carefully supervised patients during the elevation activity, these artifacts should be minimal. Another potential source of variation is that we analyzed humeral and scapular motions relative to the room rather than using the thorax as a reference frame because of the fluoroscope's limited field of view. Fourth, we did not assess position of implants that could affect shoulder function. As mentioned previously, this will be our next step. Fifth, the range of time between surgery and fluoroscopy was large (6-20 months). This might influence shoulder kinematics, but a previous study has indicated that there were no differences in RSA kinematics between 6 months (range, 5-8 months) and 14 months (range, 11-21 months).[28] Finally, the poor-elevation group tended to be poor in preoperative flexion and Constant score, though the differences were not statistically significant. Preoperative range of motion has been reported to influence postoperative range of motion.[14] The difference in the preoperative diagnosis also affected on postoperative range of motion.[11,19] The strength of this study was that surgeries were performed in a single institute using a single implant system.

Conclusions

Shoulders with good elevation after RSA demonstrated better scapulohumeral rhythm than those with poor elevation, though there were no significant differences in glenosphere and glenohumeral kinematics. It may be important for better elevation to achieve good glenohumeral motion in shoulders with RSA. Glenosphere orientations may affect postoperative shoulder function.

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