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Kinematic analysis of dynamic shoulder motion in patients with reverse total shoulder arthroplasty

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Background: Reverse total shoulder arthroplasty (rTSA) has been used to treat patients with irreparable rotator cuff dysfunction. Despite the proven clinical efficacy, there is minimal information regarding the underlying changes to the shoulder kinematics associated with this construct. Therefore, we sought to examine the kinematics of dynamic shoulder motion in patients with well-functioning rTSA.
Methods: We tested 12 healthy subjects and 17 patients with rTSA. All rTSA patients were able to elevate their arms to at least 90° and received the implant as the primary arthroplasty at least 6 months before testing. On average, the rTSA patients elevated their arms to 112° ± 12° (mean ± SD) and reported an American Shoulder and Elbow Surgeons outcome score of 90.6 ± 6.3. A 3-dimensional electromagnetic motion capture device was used to detect the dynamic motion of the trunk, scapula, and humerus during bilateral active shoulder elevation along the sagittal, scapular, and coronal planes.
Results: In both healthy and rTSA shoulders, the majority of the humeral-thoracic motion was provided by the glenohumeral motion. Therefore, the ratio of glenohumeral to scapulothoracic (ST) motion was always greater than 1.62 during elevation along the scapular plane. In comparison to healthy subjects, however, the contribution of ST motion to overall shoulder motion was significantly increased in the rTSA shoulders. This increased contribution was noted in all planes of shoulder elevation and was maintained when weights were attached to the arm.
Conclusion: Kinematics of the rTSA shoulders are significantly altered, and more ST motion is used to achieve shoulder elevation.
Level of evidence: Basic Science Study, Kinesiology Study.

Keywords: Scapula; shoulder; reverse total shoulder arthroplasty; scapulohumeral rhythm; dynamic shoulder kinematics

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Many patients have shoulder disorders that are characterized by rotator cuff dysfunction and glenohumeral (GH) joint arthrosis and may show findings such as pain, inability to raise the arm, and proximal migration of the humeral head. To regain functional improvement in these patients, reverse total shoulder arthroplasty (rTSA) has recently been

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used. In addition to pain relief, these patients are able to obtain mean active shoulder elevation of 105° to 138°.[3,6,9,11,27,28] As a result, the majority of these patients are able to perform various activities of daily living and regain their functional capacity.

Unlike the traditional replacement systems that emulate the standard ''ball-and-socket'' anatomy of the shoulder, in this reverse design, the ''ball'' component is placed on the glenoid whereas the ''socket'' component is fixed to the proximal humerus. This altered anatomy is associated with several important changes in the biomechanical properties of the joint that can compensate for the loss of rotator cuff function. Specifically, the rTSA construct provides a medialized center of rotation, a stable and fixed fulcrum for elevation, and increased resting length/tone of the deltoid muscles.[4,20]

These changes in the biomechanical properties of the joint are likely to result in significant changes to the kinematics of the shoulder girdle. As such, in a study of 4 patients who were treated with rTSA reconstruction after tumor resection, lateral rotation of the scapula was noted to increase by 15%.[7] Similarly, Kontaxis and Johnson[17] used static measurements of the scapula position in 10 shoulders treated with rTSA for various pathologies and calculated an increase in scapula rotation of 24%.

Despite these reports, there is minimal information in the available literature regarding the kinematics of the entire shoulder girdle (both GH and scapulothoracic [ST] motion) after rTSA. In addition, it is unknown whether the shoulder kinematics after rTSA is changed in a more clinically relevant scenario when the arm is elevated against resistance. Therefore, we sought to test the hypotheses that both GH and ST joint kinematics during rTSA shoulder elevation in patients with good functional outcomes are significantly altered in comparison to normal healthy shoulders, and that the relative contribution of ST motion to humeral elevation is significantly increased in rTSA shoulders.

Methods

Study population

A control group of healthy subjects included 4 men and 8 women with a mean age of 62.8 ± 11.4 years. All patients denied any history of shoulder pathology or surgery and reported no pain with the use of their arms. Their mean American Shoulder and Elbow Surgeons (ASES) score was 96.0 ± 2.9. Subjects were excluded if they reported any musculoskeletal disease within the previous 12 months.

We identified and recruited 17 patients, 9 men and 8 women, with rTSA from the patient database of the Foundation for Orthopaedic Research and Education at the Florida Orthopaedic Institute (Tampa, FL, USA). Inclusion criteria were rTSA procedure at least 6 months before testing and active shoulder elevation to at least 90°. Exclusion criteria included prior arthroplasty of the involved shoulder, inability to raise the contralateral arm, and inability to follow simple commands. The mean age in this group was 69.8 ± 5.8 years, and the patients were tested at a mean of 21.1 ± 12 months after surgery. At the time of testing, these patients were able to actively raise the tested shoulder to 112° ± 12.0° and reported an ASES outcome score of 90.6 ± 6.9.

One patient had one prior arthroscopic rotator cuff repair surgery on the tested shoulder. In all other patients, no previous surgeries were performed on the tested shoulder. The rTSA procedures were performed for rotator cuff arthropathy in 10 patients, irreparable and painful rotator cuff tears in 2 patients, rheumatoid arthritis with rotator cuff tear in 1 patient, proximal humeral fractures in 2 patients, and proximal humeral fracture sequelae in 2 patients. All rTSA procedures were performed through the anterior deltopectoral approach. In 11 of the 17 patients, the subscapularis tendon was released during the surgical approach and then repaired during closure. In the remaining 6 patients, the subscapularis tendon had been torn and was not repairable. All patients received the RSP system (DJO Surgical, Austin, TX, USA) with cemented humeral stems. The glenoid baseplates were fixed to the scapula with a large central screw and 4 peripheral 5.0-mm locking screws. Unlike the traditional Grammont-style glenosphere with a center of rotation that is located on the native glenoid surface, the RSP system offers lateralization options such that the center of rotation may be at the native glenoid surface or up to 10 mm lateral to the glenoid surface. Inserted glenospheres in the rTSA patients were as follows: 32 mm neutral (center of rotation 10 mm lateral to glenoid surface) in 6 shoulders; 36 mm neutral (center of rotation 6 mm lateral to glenoid surface) in 2 shoulders; 40 mm neutral (center of rotation 2 mm lateral to glenoid surface) in 1 shoulder; 32 mm −4 (center of rotation 6 mm lateral to glenoid surface) in 7 shoulders; and 36 mm −4 (center of rotation 2 mm lateral to glenoid surface) in 1 shoulder.

Instrumentation and testing system

The MotionMonitor system (Polhemus, Colchester, VT, USA), composed of the Polhemus Liberty electromagnetic tracking system with 4 sensors and software for data collection, was used to collect kinematic data at 120 Hz. The scapular tracker was used to track scapular motion as described in the published literature.[8,14,21,26]

The local coordinate systems recommended by the International Society of Biomechanics (ISB) were used to describe all possible joint motions.[29] For the GH and humeral-thoracic (HT) elevations, there are planes of elevation around a longitudinal axis of the coordinate system fixed to the thorax, angles of elevation that rotate around the anterior/posterior axis of the coordinate system fixed to the humerus, and internal/external rotation that rotates around a longitudinal axis of the coordinate system fixed to the humerus. For the ST joint, the movements are protraction/retraction, medial/lateral rotation, and anterior/posterior tilt. Compared with traditional clinical descriptions, this method can describe all possible continuous movements of the scapula and the humerus.

Testing procedure

After the testing procedure was explained and informed consent was obtained, bony landmarks were marked on the subject according to the protocols described by Meskers et al[23] and the ISB.[29] The landmarks included the C7, T8, and T12 spinous processes; jugular notch; xiphoid process; acromion angle; trigonum spinae of the scapula; inferior angle of the scapula; medial epicondyle of the humerus; and lateral epicondyle of the humerus. The Polhemus Liberty system was calibrated in accordance with the manufacturer's guidelines (Innovative Sports Training, Chicago, IL, USA). The scapular tracker and sensors were attached to the subject with double-sided tape and Velcro straps. Three magnetic sensors were placed on the thorax, scapula, and upper arm, and each segmental axis was configured based on the ISB protocols.

During testing, all movements were performed symmetrically with both arms to minimize compensatory movement of the trunk, such as side tilt, bending, and rotation. The data, however, were analyzed unilaterally. The subjects were instructed to move the arm at a slow rate without stopping. Based on available literature, an 8-second movement pace was recommended.[14] To maintain the movement within a plane of elevation, a flashlight was attached to the subject's forearm and the elbow was immobilized in full extension with a wooden stick and Velcro straps. Testing planes were marked by placing a strip of painter's tape on the floor and the walls. The subjects were then asked to follow the strip of tape with the light. Shoulder rotation was maintained in neutral by asking the subject to always point the thumb upward. Before data collection, all subjects were encouraged to practice several times to obtain consistent and reproducible movements. During data collection, however, no instructions or feedback was provided.

The testing sequence was randomized, and the subjects were asked to raise their arms along 3 different planes: sagittal plane (forward elevation), coronal plane (abduction), and scapular plane (40° from sagittal plane). Elevation along each plane was repeated 3 times during data collection. This process was then repeated with 2 lb of handheld weight and then again with 4 lb of handheld weight to approximate scenarios when activities of daily living are performed. Of the 17 patients with rTSA, 7 could not elevate the arm with 4 lb of handheld weight. Therefore, their data with the 4-lb weight were not included in the final analysis.

Data processing

Data between a range of 30° and 120° of HT elevation were processed for analysis. The angles for each joint were extracted for every degree of humeral elevation to the trunk with a tolerance of 0.25°. Scapulohumeral rhythm (SHR) was calculated by dividing GH motion by ST rotation at each angle of HT elevation. GH motion and ST rotation values used to calculate SHR were adjusted for anatomic variation between subjects by cumulatively measuring GH and ST from the initiation of HT elevation at rest. The kinematic data were analyzed with Matlab software, version 2010b (The MathWorks, Natick, MA, USA). Statistical analysis was performed with SPSS software, version 19.0 (SPSS, Chicago, IL, USA). Repeated-measures multivariate analysis of variance was used to test the systemic effect of plane and weight on the scapulohumeral kinematics. Where multivariate analyses indicated systemic changes ($P < .05$), univariate analyses were also considered. Results of the multivariate analysis showed no significant effect on individual trials ($P = .979$). Therefore, the mean value for the 3 trials of elevation was used for subsequent data processing and analysis.

Results

Figure 1 shows GH and ST motion during HT elevation along the scapular plane in the healthy subjects and rTSA subjects. For elevation in healthy shoulders, the contribution of ST rotation (medial and lateral rotation) to HT elevation was minimal at lower angles of elevation and became more pronounced at higher angles of elevation (Fig. 1, *A* and *B*). In rTSA shoulders, however, the relative contribution of ST motion to HT elevation remained fairly constant during the entire range of motion tested (Fig. 1, *C* and *D*). Thus, in comparison to healthy shoulders, the overall contribution of ST rotation to HT elevation was greater in the rTSA shoulders. Nevertheless, GH motion always contributed more than ST rotation to HT elevation in both healthy subjects and rTSA subjects.

The measurements of ST rotation and GH motion during HT elevation were then combined and analyzed as SHR, which has been previously used to describe the ratio of GH to ST motion.[13] During elevation along the scapular plane, SHR was always noted to be greater than 1.62 for both healthy shoulders and rTSA shoulders, suggesting that GH motion always contributed more to HT elevation than ST motion (Fig. 2). For healthy subjects, the values of SHR were high at lower angles and steadily decreased during HT elevation. As such, SHR values for healthy subjects at 30°, 50°, 70°, and 90° of HT elevation were 7.34 ± 5.33, 4.96 ± 2.46, 3.74 ± 1.08, and 3.03 ± 0.59, respectively. Corresponding values of SHR for rTSA shoulders, on the other hand, were 2.81 ± 1.73, 2.16 ± 0.68, 1.94 ± 0.40, and 2.03 ± 0.51. The difference in SHR between healthy and rTSA shoulders was found to be statistically significant ($P = .022$).

When hand weights were added during elevation along the scapular plane, SHR decreased significantly ($P = .030$). These changes in SHR were more pronounced at lower angles of HT elevation and were fairly minimal at higher angles of HT elevation (Fig. 3). Within each group of healthy and rTSA shoulders, however, this decrease in SHR with increased weight did not reach statistical significance ($P = .548$).

Unlike elevation in the scapular plane, elevation along the coronal and sagittal planes involves a more complicated motion of the scapula that includes rotation, protraction/retraction, and tilting. Therefore, SHR, which is the ratio of GH motion to ST rotation, may be insufficient to accurately describe the kinematics of the shoulder girdle during elevation in these planes. Nevertheless, as shown in Figure 4, similar patterns of SHR were observed between the rTSA and healthy shoulders, and the values of SHR were significantly lower in the rTSA subjects during elevation in both the sagittal ($P = .018$) and coronal ($P = .001$) planes.

Discussion

In a previously published report, Bergmann et al[2] showed that the majority of the motion derived from an rTSA shoulder was from the GH joint, which accounted for

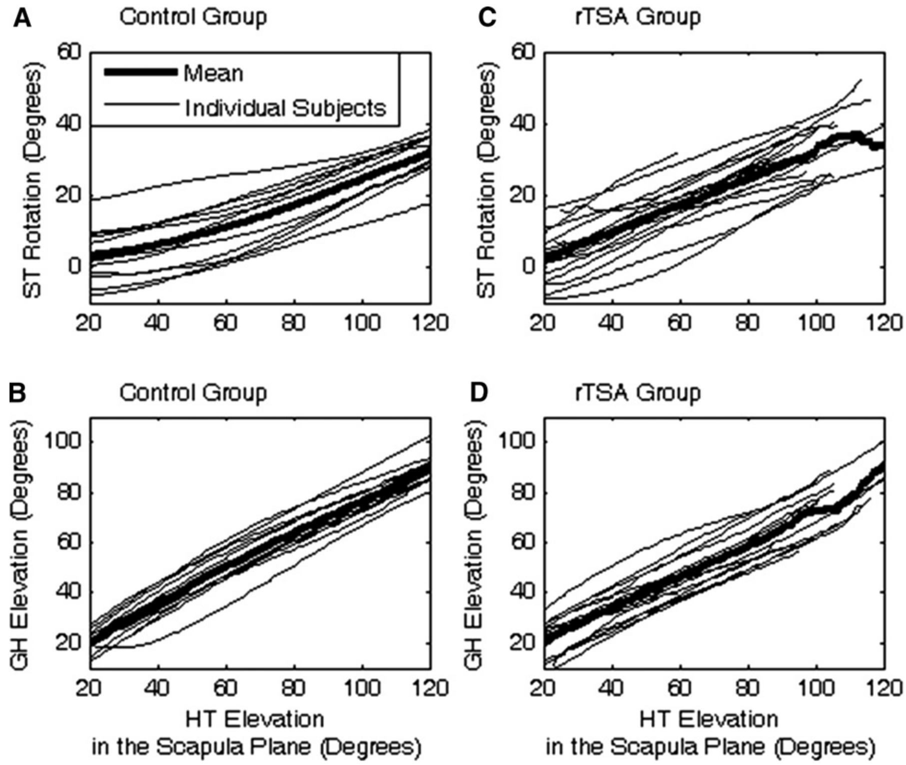

Figure 1 Scapula rotation (**A, C**) and GH elevation (**B, D**) in healthy and rTSA subjects during HT elevation along scapular plane with 0 lb of external weight.

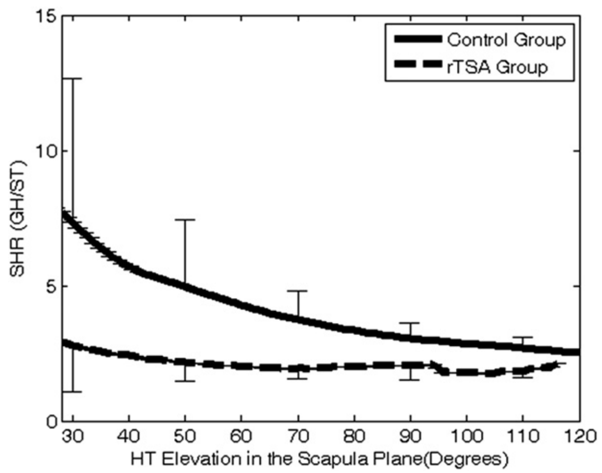

Figure 2 SHR in healthy subjects (*solid line*) and rTSA subjects (*dashed line*) during HT elevation along scapular plane with 0 lb of external weight.

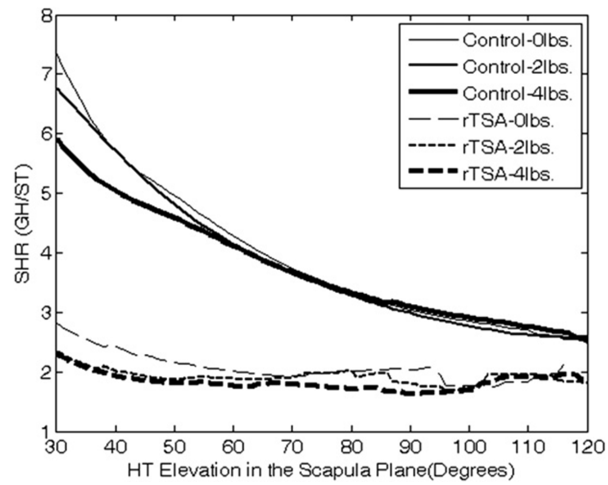

Figure 3 SHR in healthy subjects (*solid lines*) and rTSA subjects (*dashed lines*) during HT elevation along scapular plane with 0, 2, and 4 lb of external weight.

roughly two-thirds of the HT elevation. Therefore, they concluded that the overall contribution of the ST and GH joints to arm elevation was comparable to healthy subjects. In contrast, using 3-dimensional modeling of fluoroscopic data, Mahfouz et al[19] noted that scapula rotation provided a greater contribution to overall arm elevation in rTSA shoulders. Data from our study show that both GH and ST joint kinematics during rTSA shoulder elevation in patients with good functional outcomes are significantly altered in comparison to normal healthy shoulders. Although the majority of motion from both healthy and rTSA shoulders was derived from the GH joint, the relative contribution of ST motion to shoulder elevation was significantly increased in rTSA shoulders, and this contribution was more pronounced when weights were attached to the arm.

There are several inherent limitations with this study. First, the kinematics of the rTSA shoulders are compared against healthy shoulders in a slightly younger group of

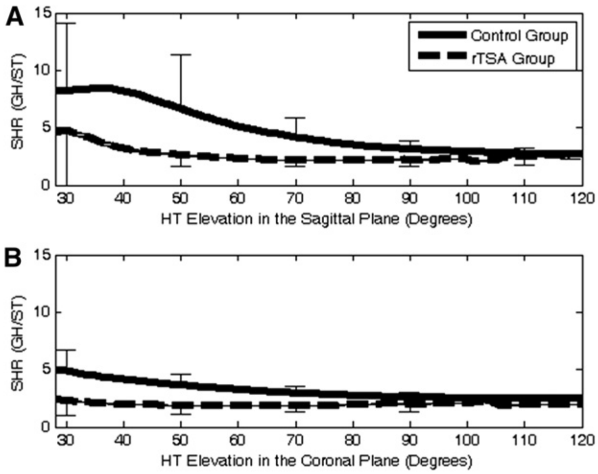

Figure 4 SHR in healthy subjects (*solid lines*) and rTSA subjects (*dashed lines*) during HT elevation along sagittal (**A**) and coronal (**B**) planes with 0 lb of external weight.

subjects (62.8 years vs 69.8 years). Functional capacity of the shoulder is affected by age.[5,30] Thus, although there is no evidence in the literature to suggest that kinematics of the shoulder change over time, age-related adjustments may have contributed to our findings. Ideally, kinematics of the rTSA shoulders would be best compared against those of contralateral asymptomatic shoulders in the same subjects. However, some of our rTSA patients noted mild to moderate symptoms in their contralateral shoulders. Therefore, although they were able to raise the contralateral arm to minimize the compensatory movement of the trunk, the kinematics of this joint are not likely to be representative of a ‘‘normal’’ healthy shoulder. Second, the small sample size of the rTSA group prevented subanalysis based on age, sex, primary pathology, status of the rotator cuff, and inserted glenosphere size with varying lateralization. The rTSA group was, however, fairly homogeneous with their outcome as all patients were able to elevate the arm above the level of the shoulder and reported good results based on ASES outcome score. Third, we only obtained measurements to about 120° of HT elevation rather than the entire range of shoulder motion. Currently available noninvasive systems for measuring shoulder kinematics do not provide reliable data at higher angles of elevation, and this is an inherent deficiency of the testing apparatus.[14,24] However, most rTSA patients do not regain full elevation of the shoulder, with mean maximal elevation from 105° to 138° in the reported literature.[3,6,9,11,27,28] Therefore, obtained kinematic data should represent ‘‘functional’’ shoulder motion used by these patients during activities of daily living.

Using similar noninvasive techniques, Kontaxis and Johnson[17] obtained static scapula position measurements of rTSA shoulders during elevation. Using a regression analysis, they showed that scapula rotation was increased by 24% in comparison to previously measured scapula rotation in normal subjects.[1] With dynamic measurements, our data show that ST contribution to HT elevation is increased in rTSA shoulders. It should be noted, however, that GH motion still provides a greater contribution to overall arm elevation than ST rotation even in rTSA shoulders.

Our data also show that the increased contribution of ST rotation to HT elevation was more pronounced at lower angles of elevation. Previous studies have shown that SHR does not remain constant during shoulder motion and that, at lower angles of elevation, GH motion predominantly contributes to shoulder elevation.[10,16,21,26] Our data are in agreement with these findings because SHR was noted to be greater at lower angles of HT elevation for both healthy and rTSA shoulders. However, ST contribution to HT elevation was fairly constant at both lower and higher angles of elevation in rTSA shoulders. Thus, even this relatively small contribution of ST rotation resulted in a pronounced effect on SHR at lower angles of elevation.

Because the natural anatomy of the shoulder is ‘‘reversed,’’ it is not surprising that the kinematics of the shoulder girdle is significantly altered in the rTSA shoulders. Our data suggest that ST rotation provides a greater contribution to overall shoulder motion in these shoulders, especially at lower angles of elevation. When weights were attached to the arm, which would more closely resemble the scenario during activities of daily living, the ST contribution to HT elevation was even greater. Several authors had previously shown that external loads decreased SHR in healthy shoulders.[16,25] Our data are in agreement with these observations and confirm similar findings in the rTSA shoulders. The cause for this finding is unclear. With added weight, perhaps the initial position of the scapula is rotated to increase the resting length and provide a greater mechanical advantage for the deltoid muscle.

Studies have suggested and shown that kinematics is altered in shoulders with various pathologies.[12,15,18,22] Therefore, it is unclear whether these changes in the kinematics of rTSA shoulders are due to the reversal of the anatomy after the rTSA surgery or due to presurgical adaptation that occurred as a response to the shoulder pathology. Because many of these patients are unable to raise the arm before surgery, preoperative kinematic data will be limited and difficult to obtain. However, it may be possible to obtain preoperative and postoperative kinematic data in patients who have painful rotator cuff tears but can still elevate the arm. In addition, kinematics of rTSA shoulders in patients with a good functional outcome may be significantly different from those with a poor outcome. In fact, preoperative capacity for ST motion may be a predictor of patient outcome after rTSA. These hypotheses will be tested in future studies.

Overall, our data suggest that ST motion contributes significantly to postoperative rTSA shoulder motion and that its relative contribution is augmented in clinically relevant situations when objects are carried or lifted with the arm. Therefore, it is possible that significant ST joint pathology may adversely affect the outcome after rTSA, and this possibility should be carefully considered during preoperative evaluation and discussion with patients.

Conclusions

In comparison to healthy subjects, GH and ST kinematics in rTSA shoulders are significantly altered. Although the majority of HT elevation is derived from GH motion, ST rotation in rTSA provides a greater contribution, and this contribution is even more pronounced in clinically relevant scenarios when weights are attached to the arm. Therefore, ST joint function may affect the overall outcome after the rTSA procedure and should be carefully assessed before proceeding with the operation.

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