Analysis of Reverse Total Shoulder Joint Forces and Glenoid Fixation

Young W. Kwon, M.D., Ph.D., Rachel E. Forman, M.S.E., Peter S. Walker, Ph.D., and Joseph D. Zuckerman, M.D.

Abstract
Reverse total shoulder arthroplasty (rTSA) implants are intended to restore stability and function to shoulders with rotator cuff deficiency. The implant consists of a glenosphere projecting from a glenoid baseplate and articulating in a socket at the proximal end of a humeral component. Despite the demonstrated clinical efficacy, little information is available regarding the joint forces about this construct and the stability of the glenoid component against these forces. Our hypotheses were that the joint forces about the rTSA were comparable to that about a normal shoulder joint, and that the micromotion between the baseplate and the scapula against these loads would be sufficiently low to induce bone ingrowth. To investigate this, a custom testing rig was constructed to simulate active shoulder elevation in fresh-frozen shoulder specimens. The forces about the rTSA were calculated and found to include compressive and shear forces up to 0.7 and 0.4 BW, respectively. In contrast to a normal shoulder, where the joint forces peak at 90° of abduction, forces about the rTSA were highest at about 60° of abduction. These forces were then applied in cyclic loading conditions to the glenoid baseplate, and the micromotion of the implant relative to the bone was measured in the four quadrants of the component. For two different rTSA designs (DePuy Delta II® and Encore RSP®) and in the entire range of the fixation testing, the cyclical micromotions were always less than 62 µm. Thus, under loading conditions similar to physiological shoulder elevation, micromotion of the glenoid component was sufficiently low and within previously published limits to induce bone ingrowth.

Many patients suffer from shoulder disorders that are characterized by rotator cuff dysfunction and glenohumeral joint arthrosis, and may demonstrate findings, such as pain, inability to raise their arm (pseudoparalysis), and proximal migration of the humeral head. In order to regain functional improvement in these patients, reverse total shoulder replacements (rTSAs) have recently been utilized. 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, while the “socket” component is fixed in the proximal humerus (Fig. 1). This altered anatomy is intended to provide a greater lever arm for the deltoid muscle, allowing the patients to regain active shoulder elevation. Hence, in addition to relief of pain, these patients are able to regain an average active shoulder elevation of 105° to 138° and perform various activities of daily living.14

Despite promising results, there are concerns regarding premature mechanical failure of shoulder prostheses.7 Specifically for the rTSA, the longevity of the glenoid prosthesis may be compromised due to the potentially higher shear forces and bending movements about the component.8 Initial fixation is achieved using four or five screws in order to
provide sufficiently rigid fixation to induce bone ingrowth. Subsequently, stable and permanent fixation of the prosthesis to the scapula is intended to be obtained through osteointegration.

In a previous study to evaluate rTSA glenoid fixation, Harman and colleagues mounted the components in polyurethane foam blocks and applied forces that were “similar to the rocking-horse loosening mechanism that has been observed in patients with shoulder prostheses.” Component-foam micromotion was used as the measure of fixation. However, in order to obtain micromotion values that were a closer simulation of the in vivo environment, it would be necessary to apply forces more specific to the geometry of the rTSA designs and to mount the glenoid components in cadaveric scapulae.

Therefore, the scheme of our study was first to determine the forces about the specific rTSA being tested and then to apply these forces cyclically to test the glenoid fixation.

We hypothesized that the joint forces about the rTSA construct is comparable to that of a normal shoulder joint and that, against these forces, the screw fixation of the glenoid component would provide sufficient rigidity to induce bone growth.

**Materials and Methods**

**Preparation of Specimens**

The Delta III (DePuy Orthopaedics, Warsaw, Indiana) and the Ecore Reverse Shoulder Prosthesis RSP® (Encore Medical, LP, Austin, Texas) implants were provided by the companies for this study. Each system consisted of a polyethylene lateralized cup fixed into a cemented humeral stem and a glenosphere attached to a metal baseplate. The Delta III baseplate was fixed to the scapula with a central peg and four peripheral screws. The inferior and the superior 4.5 mm screws locked into the plate, while the anterior and the posterior 4.5 mm screws were non-locking cortical screws.

![Figure 1](image1.png)

**Figure 1** A. Traditional shoulder replacement designs emulate the normal “ball-and-socket” anatomy of the shoulder. B. In the reverse shoulder replacements, this anatomy is “reversed” such that “ball” component is placed on the glenoid while the “socket” component is fixed in the proximal humerus.

![Figure 2](image2.png)

**Figure 2** The overall shape of the glenospheres with a “+” marking the center of rotation. The force vectors for the four abduction angles are shown, with the forces in newtons and the angles to the vertical in degrees. These force vectors were calculated from the initial set of joint forces experiment and applied to the glenospheres in the micromotion experiments.
The glenosphere had a diameter of 36 mm and an offset of 16 mm from the glenoid surface (Fig. 2). The RSP® baseplate was fixed to the glenoid, using a large central screw and four 5.0 mm peripheral locking screws. This baseplate was mated with a glenosphere, the diameter of which was 32 mm with a lateral offset of 27 mm from the glenoid surface.

Each of the components was implanted into a fresh-frozen cadaveric shoulder specimen by an experienced shoulder surgeon, according to the guidelines provided by the manufacturers. All screws for the glenoid baseplates achieved excellent purchase into the scapula. The supraspinatus and the infraspinatus tendons were resected from the specimen, while the subscapularis and the teres minor tendons were maintained. The remaining humerus was cut just distal to the deltoid tendon insertion. Mass was added so that total weight of the humerus with its fixtures and the moment about the center of the shoulder simulated that of an average arm, which was taken to be 5.6% of 80 kg body weight (BW).10

For all specimens, the scapula was analyzed using computed tomography (CT) to determine cortical and cancellous bone densities about the glenoid. Calibrated Hounsfield unit values were determined, using 3D-Doctor (Able Software Corp, Lexington, Massachusetts) and bone density was calculated from these values using a linear approximation.11 The first pair of shoulders demonstrated cortical bone densities of 1.5 g/cm³ and 1.3 g/cm³, and cancellous bone densities of 0.35 g/cm³ and 0.36 g/cm³. In the second pair of shoulders, the cortical bone densities were 0.89 g/cm³ and 0.89 g/cm³, while the cancellous bone densities were 0.45 g/cm³ and 0.39 g/cm³. Therefore, these matched pairs had nearly identical densities, with the values being similar to those reported previously for shoulders from cadavers aged 62 to 96 years.12 One Delta III® component and one RSP® component were inserted into a matched pair of shoulders whose bone densities were measured to be equivalent. This process was repeated with another set of components for another matched pair of cadaveric shoulders. Thus, in all, four shoulder specimens were utilized for this project.

**Determination of Joint Forces**

A shoulder was mounted to a custom-built testing machine (Fig. 3). A fabric strap was then sutured to the deltoid tendon insertion, guided over the acromion, and finally attached to a motor, which applied the simulated deltoid force and elevated the humerus. Thus, the deltoid was the only “active” muscle in our configuration. The scapula was fixed to a second motor shaft and rotated about its center. Currently, there are no published data regarding the scapula-thoracic motion in patients with rTSA. Hence, software was written to control the rotation of the scapula, such that there was a constant 2:1 glenohumeral to scapulothoracic rotation ratio throughout arm elevation, approximating normal shoulder motion.13

The angles of rotation for the scapula and the humerus were continuously recorded with a stepper motor and an optical rotary encoder, respectively. The force applied to the deltoid was recorded with a 250-lb max miniature load cell (Honeywell, Columbus, Ohio). Total arm elevation was simulated from approximately 10º to 120º. The test was performed in two planes of shoulder elevation: first, in the plane of the scapula and, second, in a plane that was rotated internally 35º with respect to the scapular plane. Elevation along each plane was controlled by a guide rod. All tests were recorded with a video camera, and the images were subsequently analyzed to obtain the geometry around the shoulder joint. The magnitude and direction of the joint forces were then calculated using a free body diagram analysis (Fig. 3). At various angles of shoulder elevation, both compressive and shear forces were calculated. When appropriate, statistical analysis was performed using Student’s t-tests, and significance was assigned at p < 0.05.

**Measurement of Glenoid Component Micromotion**

After measuring the joint forces, each scapula was separated from the humerus, and all soft tissues were removed. Medial and inferior aspects of the scapula were then resected. Soft putty was placed over any protrud-
ing screws to avoid rigid contact with the cement. The construct was cemented (Surgical Simplex™ P, Stryker® Howmedica Osteonics, Mahwah, New Jersey) into an aluminum frame (Fig. 4). A custom steel ring was rigidly clamped around the base of the glenosphere. Five ultra precision linear variable displacement transducers (LVDTs) with 2.54 μm sensitivity (Honeywell Sensing and Control, Golden Valley, Minnesota) were mounted onto the frame and placed against the steel ring. One LVDT was located in each of the four quadrants (superior, inferior, anterior, and posterior) perpendicular to the glenoid face, while another was placed parallel to the glenoid face in the superior-inferior direction to measure shear motion.

The scapula and the sensors were subsequently mounted to a fixture and attached to a stepper motor to control rotation. A probe tip was attached to an MTS® cyclical loading machine (MTS® Systems, Eden Prairie, Minnesota), and each sample was loaded for 10,000 cycles at 2.5 Hz at 30º of shoulder elevation. This process was then repeated at 60º, 90º, and 120º of shoulder elevation. The forces determined in the first part of this study were applied to the glenoid component by the MTS® machine for each of these angles (Fig. 2). Custom software was written to collect data from each of the five LVDTs at 17 Hz. The data was plotted and measured for final cyclic motion and migration over the 10,000 cycles of joint force application (Fig. 4). When appropriate, statistical analysis was performed using Student’s t-tests and significance was assigned at p < 0.05.

**Results**

**Joint Forces**

During elevation in the plane of the scapula, calculated joint forces for both implant designs were lower than previously reported forces across a normal shoulder, particularly after 60º of arm elevation (Fig. 5). In the normal shoulder, the joint force was reported to be at its highest value at 90º of elevation and then steadily decreased with further elevation. For the rTSA constructs, however, the greatest joint forces were typically calculated at about 60º to 70º of elevation and remained fairly constant with further elevation. In the plane that was internally rotated 35º, the joint forces were measured to be generally higher than those in the plane of the scapula. Statistical significance was noted for the Encore RSP® at 45º and 60º of elevation and then steadily decreased with further elevation. For the rTSA constructs, however, the greatest joint forces were typically calculated at about 60º to 70º of elevation and remained fairly constant with further elevation. In the plane that was internally rotated 35º, the joint forces were measured to be generally higher than those in the plane of the scapula. Statistical significance was noted for the Encore RSP® at 45º and 60º of elevation. The highest calculated force approached 0.7 BW in one specimen.

Between the two implant designs, the joint forces for the Encore RSP® were found to be slightly higher than the DePuy Delta III® in the plane of the scapula, with statistical significance at 15º and 60º. Statistical significance was also noted in the 35º internally-rotated plane at 30º and 45º. Shear forces were generally comparable between the two designs, although the Encore RSP® demonstrated higher values at 15º in the plane of the scapula and at 30º in the plane 35º internally rotated (p < 0.05).

**Glenoid Component Micromotion**

For each set of 10,000 cycles, the total migration increased initially but then tended to reach a limiting value. On the other hand, the cyclic micromotion generally remained constant.
throughout the testing. The values of the cyclical micromotion and the total migration are shown in Figures 6 and 7.

In the inferior quadrant of the Encore RSP® glenoid component, the highest cyclic motion was observed at 120º of shoulder elevation (Fig. 6A). In the remaining quadrants, the highest cyclic motion was observed at 60º of shoulder elevation. The two largest values for cyclic motion were measured to be 62 μm and 57 μm, and these were both measured at the superior quadrant at 60º of shoulder elevation. Total migration of the component was similarly found to be greatest at 60º of shoulder elevation (Fig. 6B), with the highest values (15 μm and 11 μm) measured at the superior quadrant.

For the DePuy Delta III® prosthesis, similar values of cyclic motion were observed (Fig. 7A). The largest cyclic motion values were observed at 60º of shoulder elevation, with the highest value of 59 μm measured in the superior quadrant. Compared to the Encore RSP®, however, the total migration of these components was greater in the superior (30º, 60º, 120º), anterior (90º), and posterior (30º, 60º, 90º) quadrants, with the largest value of 35 μm measured in the posterior quadrant at 30º of elevation (Fig. 7B).

Discussion

The general scheme of our experiments was to determine the joint forces during simulated shoulder elevation, using a custom motion rig, and then to apply these forces cyclically to evaluate glenoid component fixation. With this scheme, we were able to demonstrate that the joint forces about the rTSA construct are similar in magnitude to normal shoulders, with compressive and shear forces up to 0.7 and 0.4 BW, respectively. When these forces were applied in cyclic loading conditions to the glenoid baseplate, the micromotion of the implant relative to the bone was measured to be always less than 62 μm.

The motion rig was not designed to simulate the normal mechanism of shoulder abduction where various combinations of muscles are applied. Rather, the rig allowed for the testing of specimens where only the deltoid muscle was represented. Separate clavicular, acromial, and scapular origins of the deltoid were not defined. In patients with rTSA, the primary elevator of the shoulder is the anterior and the middle deltoid muscle. For this reason, our construct should be a reasonable simulation. The scapula was rotated about a single axis, unlike a normal shoulder where the center of rotation of the scapula moves towards the glenoid throughout abduction. A constant 2:1 glenohumeral to scapulothoracic rotation ratio was applied, even though previous literature had demonstrated that this ratio can change throughout arm abduction. However, simultaneously elevating the scapula and the humerus was necessary to obtain the correct...
The main difference between the Encore RSP® and the DePuy Delta III® implant systems was the glenoid component design, with a larger offset away from the glenoid face in the RSP®. We observed that this larger offset minimized the amount of component impingement against the inferior scapula neck at small angles of elevation, allowing for a greater range of shoulder motion. In addition, the larger offset produced greater deltoid angles and increased the joint force magnitudes. Although the joint forces were larger, the RSP® prosthesis was also associated with a greater compressive-to-shear force ratio, an advantage in reducing the moment applied to the glenoid component. For both designs, the magnitude of the joint forces was highest at about 60º of elevation, which is different than the normal shoulders where the peak force occurred at 90º of abduction. This result suggests that less effort would be required for a patient to raise their arm beyond 60° and that shoulder elevation may be restored more easily with rTSA.

We also found that differences in the anatomy can greatly affect the joint forces about the rTSA. For example, at 120° of abduction, joint forces about the Encore RSP® were calculated to be 280 N on one scapula and 450 N on the other. This difference was likely due to variations in the shoulder anatomy, such as the deltoid length and the weight of the humerus. These effects on the joint force measurements, in turn, may have been magnified in the Encore RSP® prosthesis, since it contained a larger lateral offset away from the glenoid surface.

In order to test the fixation of the glenoid components, it was logical to use the forces determined in the first part of our study. Our method can be compared to that of a previous study by Harman and coworkers, where the applied forces were “similar to the rocking-horse loosening mechanism that has been observed in patients with shoulder prostheses.” Our force calculations indicated that the resultant force always acted on the lower half of the glenosphere, with only an upwards shear force component and was clearly different than forces for a “rocking-horse” phenomenon. Our method was to apply forces calculated at each angle of elevation for 10,000 cycles each. The choice of 10,000 cycles was intended to represent the usage of the arm during the 3 months following surgery when osteointegration might take place. To our knowledge, however, data regarding typical usage of the arm during this period are not known. It is noted that in testing each angle successively, we were not obtaining data as though the arm was elevating dynamically, which would have considerably increased the complexity of the test method. Another limitation of our experiments was the small sample size and anatomic variations among the specimen, which limited the statistical power of the data. Despite these limitations, the data suggest that the screw fixation of the
glenoid component provides a fairly rigid construct against rTSA joint forces that would be anticipated during shoulder motion.

In total hip replacement systems, it had been demonstrated that bone ingrowth to the femoral component only occurred if the prosthesis moved less than 150 \( \mu \text{m} \) relative to the bone.\(^{1,2,6}\) The ideal environment for bone ingrowth required movement less than 100 \( \mu \text{m} \), while motion greater than 150 \( \mu \text{m} \) was usually associated with fibrous tissue formation. We observed cyclic motion less than 62 \( \mu \text{m} \) in all quadrants of the glenoid component, while the total migration at any angle was also less than 35 \( \mu \text{m} \). In addition, the motion measured in our experiments was actually between the glenosphere and the bone. Although the fixation between the glenoid baseplate and the glenosphere should be rigid, motion at this interface may have contributed to the measurements, as well as some deflection in the bone itself. Thus, the cyclic motion at the interface between the glenoid baseplate and the bone may have been even less than our measurements. Hence, our data suggest that both of the tested implant systems had sufficiently rigid initial stability to encourage osteointegration of the glenoid components.

This conclusion, however, has to be qualified with several pertinent issues. While the CT data of our specimens indicated that the bone density was within the normal range, scapulae with lower density would have a less secure fixation. Severe bone loss would also have a similar effect on fixation. In addition, the joint forces were calculated in a model that simulated elevation of the arm only. If additional weight was held in the hand or if external forces were exerted, the joint forces would correspondingly increase and presumably increase the micromotion of the component.

Clinical reports of the two rTSA designs demonstrated that aseptic glenoid loosening was rarely observed in the initial period, which is consistent with our data.\(^{1,2,6}\) In a longer follow-up study in Europe, however, the rate of revision surgery for glenoid loosening at 10 years was reported to be 16%, with at least a portion of these patients suffering from significant scapular notching.\(^{4}\) Thus, while screw fixation of the glenoid component may be sufficiently rigid as to allow osteointegration, there may be other postoperative factors that can affect the long-term stability of the implant.

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