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In Vivo Determination of the Dynamics of Normal, Rotator Cuff-Deficient, Total, and Reverse Replacement Shoulders

Mohamed Mahfouz, PHD; Gregory Nicholson, MD; Richard Komistek, PHD; David Hovis, MD; Matthew Kubo, BS

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Introduction

Patients with osteoarthritis of the shoulder experience pain and decreased range of motion, which compel them to seek care. The vast majority of osteoarthritic shoulders have an intact rotator cuff. However, the rotator cuff may function poorly because of osseous deformity and soft-tissue contracture. Total shoulder arthroplasty has proved to be a reliable procedure for pain relief and improved function[1-5]. The ultimate functionality of the arthroplasty depends on multiple factors, including alignment of the prosthetic implant, rotator cuff muscle belly health, soft-tissue balance achieved at the time of surgery, and patient compliance with rehabilitation[3-6].

Rotator cuff deficiency most commonly occurs as a degenerative condition (rotator cuff tear arthropathy). In these cases, the rotator cuff is irreparable. Shoulder function can be very poor, especially with regard to active forward elevation. When a severe fracture is treated with hemiarthroplasty, there can be subsequent loss of fixation of the greater tuberosity or the tuberosity can undergo lysis. This leaves the patient essentially rotator cuff-deficient. The loss of rotator cuff function can lead to the development of anterosuperior instability of the shoulder. With attempted active forward elevation, the humeral head translates superiorly and function is very poor. This same problem can occur after failed rotator cuff surgery in association with incompetence of the coracoacromial arch. In that situation, there is no fulcrum of the coracoacromial arch to stop superior humeral head translation, often resulting in a very debilitating condition[7].

Reverse shoulder arthroplasty has been utilized to treat rotator cuff deficiency, joint injury, and shoulder dysfunction when no other satisfactory option is available[7-9]. Previously, fluoroscopy has been used to analyze the in vivo, three-dimensional kinematics of other joints. However, only in vitro analyses have been conducted on the shoulder joint, and research has not yet been conducted to derive the in vivo kinetics of this joint. Therefore, the objective of the present study was to use fluoroscopy, computed tomography, and mathematical modeling to determine the three-dimensional in vivo shoulder motions and forces for various shoulder conditions.

Materials and Methods

In vivo, three-dimensional shoulder kinematics were derived for twenty subjects. Five subjects had a normal shoulder, five had a shoulder that was rotator cuff-deficient, five had undergone a total shoulder arthroplasty (Bigliani/Flatow Shoulder; Zimmer, Warsaw, Indiana) for the treatment of osteoarthritis in the presence of an intact rotator cuff, and five had undergone a custom reverse shoulder arthroplasty (custom product; Zimmer). The five patients who had undergone a reverse shoulder arthroplasty had done so for the treatment of chronic rotator cuff deficiency, anterosuperior instability, pain, and shoulder dysfunction. The reverse implants were customized for each patient on the basis of design principles and geometry utilized in Europe. With institutional review board approval, all twenty subjects were scanned with use of a sixteen-detector computed tomography scanner (slice interval, 0.3 mm). Three-dimensional computer-aided-design bone models of the scapula and humerus of each subject were created from the three-dimensional bone-density data. For the subjects with implants, an algorithm was used to remove any metal artifact from each slice. The computed tomography slices were then used to create three-dimensional computer-aided-design models of the components of the total shoulder implant to more accurately determine the orientation of the humeral head on the humeral stem, which was unobtainable with use of fluoroscopy alone. While under fluoroscopic surveillance, each subject performed a dynamic box-lifting exercise with two hands on the box throughout the motion cycle[10-14]. The computer-generated three-dimensional models of the scapula and humerus of each subject were precisely registered to the two-dimensional digital fluoroscopic images with use of an optimization algorithm that automatically adjusts the pose of the models at various orientations (Fig. 1)[15-18]. A mathematical model based on Kane's theory of dynamics was then created to predict the in vivo bearing surface forces in the shoulder joint[19-22]. The in vivo motions were plotted and the data were curve-fit to derive temporal motion functions that were input to the mathematical model. With use of this mathematical model, the forces and torques acting at the shoulder, elbow, and wrist joints were determined.

Subjects Managed with Total Shoulder Arthroplasty

Five subjects had undergone successful unconstrained total shoulder arthroplasty through a deltopectoral approach for the treatment of osteoarthritis. These patients had undergone no previous surgery and, therefore, had an intact rotator cuff. All five patients had received a cemented polyethylene glenoid component and an uncemented humeral component. All had had tenodesis of the long head of biceps as part of the procedure, and all had performed the same aftercare protocol. The average age at the time of surgery had been sixty-three years (range, fifty-eight to sixty-five years). The average duration of follow-up at the time of the present study was 1.8 years (range, one to two years). The average visual analog score for pain decreased from 6.5 preoperatively to 0.5 postoperatively, and the average postoperative active forward elevation was 155° (range, 145° to 168°).

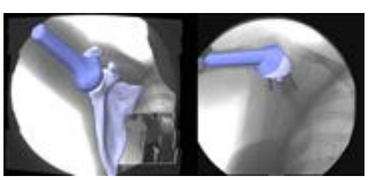

Fig. 1: Three-dimensional overlay of a shoulder without an implant (left) and a shoulder with an implant (right).

Subjects Managed with Reverse Shoulder Arthroplasty

All five patients in the present study who had undergone a reverse shoulder arthroplasty had had previous surgery and had experienced chronic extreme shoulder dysfunction, pain, and anterosuperior instability. The previous procedures had included failed hemiarthroplastyv for the treatment of fractures (three patients) and multiple failed rotator cuff repairs (two patients). These five patients had undergone an average of three procedures (range, one to five procedures). The average age at the time of the index procedure had been sixty-three years (range, forty-five to seventy-four years). Preoperatively, the average American Shoulder and Elbow Surgeons (ASES) score had been 29.6 (range, 15 to 38), the average Simple Shoulder Test (SST) score had been 1.7 (range, 0 to 3), the average visual analog score for pain had been 6.4 (range, 3 to 9), the average active elevation had been 35° (range, 10° to 60°), and the average active external rotation had been 6° (range, 15° to 20°). All subjects had undergone reverse shoulder arthroplasty through a deltopectoral approach.

Postoperatively, the average scores improved significantly ($p < 0.05$). For example, the ASES score increased by 44.4 to an average of 74 (range, 60 to 83), the SST score increased by 5.3 to an average of 7 (range, 6 to 8), and the visual analog score for pain decreased by 5.4 to an average of 1 (range, 0 to 2). In addition, active elevation increased by 64° to an average of 99° (range, 70° to 130°) and external rotation increased by 25° to an average of 31° (range, 25° to 35°). In all cases, anterosuperior instability was eliminated and limited goals were achieved. No implant loosening or scapular notching was identified on radiographs.

Implant Designs

The Bigliani/Flatow Shoulder (Zimmer) is a commercially available total shoulder implant that consists of a low-profile, Neer-style cobalt-chromium humeral stem, a modular cobalt-chromium humeral head, and an ultra-high molecular weight polyethylene glenoid. The low-profile stem preserves bone stock, and the glenoid provides a unique variable-conformity articular surface. The articular design provides joint stability throughout the range of motion while reducing edge-loading and associated wear. The reverse-style stems that were analyzed consisted of a series of custom implants that were used before the Food and Drug Administration's approval of reverse shoulder arthroplasty in the United States in 2004. The design was based on the successful reverse implants used in Europe at the time[7,8]. The stem and glenosphere base-plates were made from porous tantalum and solid titanium alloy. An ultra-high molecular weight polyethylene liner was cemented into the porous tantalum. The glenosphere was made from cobalt-chromium and was attached to the base-plate with a locking screw and taper. The tantalum surface was used to facilitate osseous ingrowth and biologic fixation following these revision procedures.

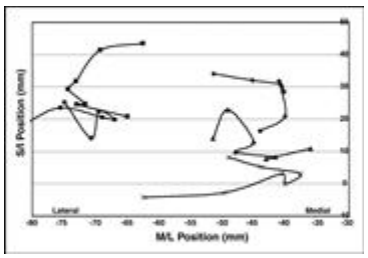

Fig. 2: Illustration depicting the motion pattern for five points on the humeral head for a normal shoulder (superior/inferior [S/I] position = 15.8 mm; medial/lateral [M/L] position = 15.4 mm).

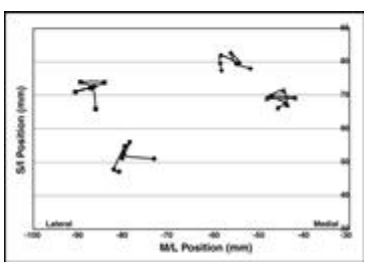

Fig. 3: Illustration depicting the motion pattern for five points on the humeral head for a rotator cuff-deficient shoulder (superior/inferior [S/I] position = 6.5 mm; medial/lateral [M/L] position = 6.9 mm).

Error Analysis

An error analysis was conducted with use of a fresh cadaver. Discrete points were defined on the implanted components. With use of an Optotrak system (Northern Digital, Waterloo, Ontario, Canada), these points were digitized and the proximal component was analyzed with respect to the distal component in the distal component reference frame. Each orientation of the implanted components was evaluated with fluoroscopy. With use of the three-dimensional model-fitting software package, the relative orientation of the implanted components was predicted and compared with the known orientation as determined with use of the Optotrak system. The results of this error analysis and accuracy tests revealed that the average error (and standard deviation) for translation in the x, y, and z directions was -0.023 ± 0.473 mm, -0.086 ± 0.449 mm, and 1.054 ± 3.031 mm, respectively[23,24]. Likewise, the average error for rotation in the x, y, and z directions was -0.068° ± 0.942°, 0.001° ± 0.771°, and 0.253° ± 0.841°, respectively. These numbers represent the errors in the model-fitting process as well as the errors associated with the independent measurement system (i.e., the upper bound). As the analyzed joint is imaged in the sagittal (x-y) plane, the relative translational motion of the implants in the z direction is minimal and is not of interest for this study.

Results

Five loci points were defined on the humeral head and were tracked throughout the box-lifting activity. All five subjects who had a normal shoulder experienced similar three-dimensional motion patterns (Fig. 2), with an average length of travel of 35.6 mm (range, 27.1 to 40.8 mm) within the shoulder socket.

The subjects who had a rotator cuff-deficient shoulder experienced more variable patterns, and all five experienced a pattern different from that of the five normal shoulders that were evaluated in the present study. Also, these subjects experienced less overall motion (average, 29.6 mm; range, 24.2 to 34.2 mm) than the normal subjects did (Fig. 3). The subjects who had had a reverse shoulder arthroplasty experienced the least amount of motion of the five points fixed on the humeral head. The subjects who had had a standard total shoulder arthroplasty experienced less overall motion (average, 22.0 mm; range, 15.7 to 30.0 mm) than the normal subjects did. Also, the subjects who had been managed with total shoulder arthroplasty experienced variable kinematic patterns that were different from those in the subjects with a normal shoulder but similar to those in the subjects with a deficient rotator cuff. On the average, the subjects who had had a reverse shoulder arthroplasty experienced 14.8 mm (range, 13.4 to 17.1

mm) of motion. A comparison of motion patterns also revealed that the subjects in the normal group experienced rotation near the center of the shoulder socket. The subjects in the other three groups had an offset, often in excess of 30 mm, from the normal shoulder positions (Figs. 2 and 3). Therefore, the normal shoulders experienced a larger contact area throughout the box-lifting activity, whereas the shoulders in the other groups remained relatively similar in location, with a smaller contact area (Fig. 3).

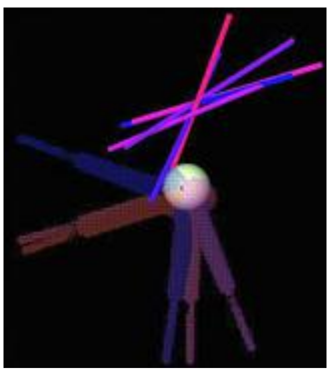

Fig. 4: Illustration depicting the location of the axode for a subject who had been managed with reverse shoulder arthroplasty.

An attempt also was made to define the axode (the intersection of the rotational axes throughout motion) and the overall range of motion for each subject. Each subject with a normal shoulder experienced a similar kinematic pattern, with the axode originating in a similar location. All other subjects experienced more random movement (Fig. 4); thus, the location of the axode was more variable and more difficult to define. Surprisingly, the overall range of motion in the subjects who had had a reverse shoulder arthroplasty (average, 85.2°) was similar to that in the subjects with a normal shoulder (average, 85.7°). The subjects with a deficient rotator cuff and those who had had a total shoulder arthroplasty experienced much smaller ranges of motion (51.1° and 18.5°, respectively). In addition, the subjects who had had a total shoulder arthroplasty had a lower average maximum torque (14.7 Nm) than did those in the other three groups (Fig. 5). Further analysis of the subjects who had had a total shoulder arthroplasty revealed that each of these subjects used a different coupled motion to lift the box. Unlike the other subjects, who used mainly flexion-extension to lift the box, the subjects who had had a total shoulder arthroplasty kept the box closer to the body, abducting the elbows away from the body while flexing the elbow joints so that the motion did not require much shoulder flexion-extension.

The average bearing-surface forces that were generated by the theoretical and mathematical model were greater for the normal shoulders than for the other three types of shoulders. At first this finding was surprising, but it does seem feasible because the subjects with normal shoulders experienced the largest range of motion and had full muscle response. The subjects with normal shoulders generated greater muscle force while performing the activity, leading to greater bearing-surface forces. During the box-lifting activity, the average maximum shoulder-joint force for the normal subjects was 82.1 N (range, 77.2 to 91.6 N) and the average maximum torque was 29.3 Nm (range, 27.4 to 30.1 Nm). Also, all five normal subjects experienced a similar motion pattern as well as similar theoretical bearing-surface force magnitudes throughout the motion cycle.

The subjects who had a rotator cuff-deficient shoulder experienced the largest bearing-surface forces among all of the groups (Fig. 6). The subjects who had had either type of arthroplasty experienced the smallest bearing-surface forces, possibly because of disruption of the muscle and soft-tissue constraints. Figure 7 illustrates the maximum resultant forces for a single subject who had a deficient rotator cuff; these forces (147.5, 122.9 and 98.2 N for the shoulder, elbow, and wrist, respectively) were the highest among all patients. These peak forces occurred at 50% of the motion cycle, similar to the findings in the other groups.

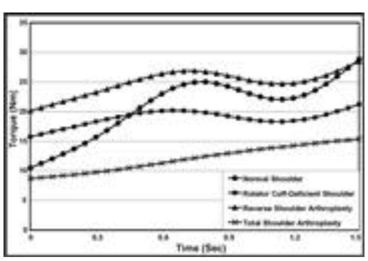

Fig. 5: Illustration depicting the average resultant torques in each group during the box-lifting motion.

The subjects with a normal shoulder and those who had had a reverse shoulder arthroplasty experienced similar torque magnitudes and patterns throughout the box-lifting motion (Fig. 7). Subjects who had had a total shoulder arthroplasty experienced the least amount of shoulder torque, and further investigation revealed that these subjects performed the box-lifting activity in a different manner than did the subjects in the other three groups. The subjects who had been managed with total shoulder arthroplasty had a tendency to abduct the humerus away from the body and to flex the elbow to perform the box-lifting motion. The average maximum torque was 24.1, 21.9, 28.3 and 14.7 Nm for the normal, rotator cuff-deficient, reverse shoulder arthroplasty, and total shoulder arthroplasty groups, respectively.

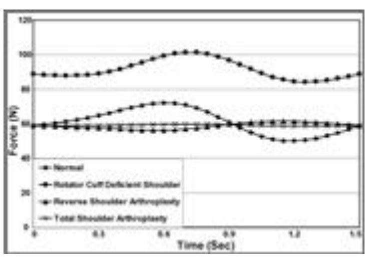

Fig. 6: Illustration depicting the average resultant theoretical bearing-surface forces in each group during the box-lifting motion.

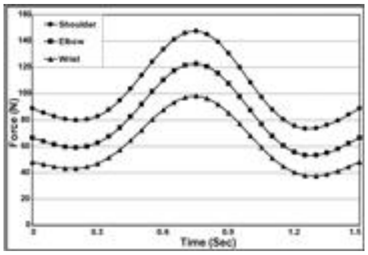

Fig. 7: Illustration depicting the resultant shoulder, elbow, and wrist forces for a single subject with a deficient rotator cuff.

Discussion

To our knowledge, this is the first study to determine in vivo motions, forces, and torques of the shoulder in live subjects with use of fluoroscopy. In the normal group it appeared that more of the shoulder socket was utilized during motion, whereas in the other three groups the humeral head tended to remain in a similar location throughout motion. The temporal force and torque functions were quite similar for all five subjects in the normal group but were variable for those in the other three groups. The subjects who had had a reverse shoulder arthroplasty seemed to experience kinematic and kinetic patterns that were most similar to those of the normal shoulder. In these subjects, scapular rotation did provide greater contributions to overall arm elevation. Thus, the glenohumeral contribution to elevation was substantially assisted by the scapula.

Individuals who have had a total shoulder arthroplasty are more reliant on the status of the rotator cuff to assist active motion and, in the present study, the subjects who had had a total shoulder arthroplasty performed differently than the subjects in the other groups did. It is unclear at this time why the subjects who had had a total shoulder arthroplasty exhibited different kinetics in vivo. All of these patients had had a successful arthroplasty at least 1.8 years previously, had no pain, and externally exhibited very normal active shoulder elevation. Further analysis of the data is ongoing. ?

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