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Nonconforming glenoid increases posterior glenohumeral translation after a total shoulder replacement

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Background: The major complication in nonconforming total shoulder replacement (TSR) is glenoid loosening and is attributed to posteriorly directed humeral head translations. Whether the posterior translations observed clinically are induced by radial mismatch is unclear. The objective of our study was to explain the posterior glenohumeral translations observed clinically after TSR by determining the glenohumeral translation and contact force as a function of radial mismatch. We hypothesized that the posterior direction of glenohumeral translation during scaption would be related to the radial mismatch and that the joint contact force would increase as the radial mismatch increased.
Methods: A 6-degrees-of-freedom computational model of the glenohumeral joint was developed. We determined the muscle forces, joint contact force, and glenohumeral translation for radial mismatches from 1 mm to 20 mm with the shoulder positioned from 20° to 60° of scaption.
Results: As the radial mismatch increased, the contact location of the humeral head moved posteriorly and inferiorly. The middle deltoid force decreased by 3%, while the supraspinatus and infraspinatus muscle forces increased by 9% and 11%, respectively. The joint contact force remained relatively constant.
Conclusions: Increased posterior glenohumeral translations were observed with increased radial mismatch. Clinical observations of posterior translation may be attributed to the balancing forces of the middle deltoid, infraspinatus, and supraspinatus muscles. High radial mismatches may lead to eccentric posterior loading on the glenoid component, which could lead to implant loosening and failure.
Level of evidence: Basic Science, Computer Modeling.

Keywords: Nonconforming total shoulder replacement; posterior glenohumeral translation; joint contact force; muscle forces; 6-degrees-of-freedom computational model; physical shoulder simulator

The major complication in total shoulder replacement (TSR) is glenoid loosening, followed by glenohumeral instability, with associated complication rates as high as 14.7% within 12 years.[5,36] The design of the glenoid implant, specifically the degree of conformity or radial mismatch between the bearing surface of the glenoid and humeral components, has been shown to affect glenoid loosening.[35] Walch et al[35] demonstrated that a glenohumeral prosthetic mismatch significantly influences the scores for glenoid radiolucent lines. The muscles surrounding the glenohumeral joint play an important role in compressing the humeral head to the glenoid socket. Failure to do so results in humeral translation and therefore

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eccentric loading on the glenoid. The "rocking horse" phenomenon induced by eccentric loading is commonly attributed to loosening of the glenoid component because it causes compressive stresses at the fixation surface when the external load is applied at one edge of the glenoid component and causes tensile stresses on the opposite end. This phenomenon is indicative of eccentric translation of the humeral head.

Because the natural glenohumeral joint allows the humeral head to translate along the glenoid surface, contemporary implants for TSRs are often designed to be less conforming with a variety of humeral head sizes (depth and radius) and small, medium, and large glenoid sizes.[9] The flexibility provides the surgeon with a range of radial mismatches. Nonetheless, glenoid loosening continues to account for 32% of all TSR complications.[5]

Clinical and implant retrieval studies suggest that radial mismatch allows for humeral head translation posteriorly that may contribute to glenoid loosening.[7,11,15,20,22] A radiographic study showed significant posterior humeral head translation after a TSR when the shoulder was positioned at 90° of abduction across differing angles of flexion.[8] Massimini et al[20] found significant contact in the superior-posterior quadrant of the glenoid of TSR patients for various angles of abduction using biplane fluoroscopy. Retrieved glenoid implants from unconforming TSRs showed consistent patterns of wear and deformation in the posterosuperior and posteroinferior quadrants, indicating posterior, inferior, and superior glenohumeral translations.[11,22,23] Although cadaveric and computational studies support that a larger radial mismatch results in greater translations, whether the posterior translations observed clinically are induced by the radial mismatch is still unclear.[2,13,16]

Our objective was to explain the posterior glenohumeral translations observed clinically. We hypothesized that the posterior direction of glenohumeral translation during scaption would be related to the radial mismatch and that the joint contact force would increase as the radial mismatch increased. To prevent dislocation, the muscles in the shoulder would coordinate in an effort to keep the humerus centered on the glenoid, thus increasing the muscle forces across the joint and increasing the joint contact force. To test our hypotheses, we developed a 6-degrees-of-freedom computational model to predict joint contact location and magnitude during scaption. The use of a computational model allowed us to perform a sensitivity study of radial mismatch.

Materials and methods

We developed a computational model to determine the effect of radial mismatch on glenohumeral translations and joint contact force from 20° to 60° of scaption. The geometrical parameters necessary as inputs to the computational model were obtained from a cadaveric shoulder attached to a shoulder simulator. We tested radial mismatches ranging from 1 mm to 20 mm, spanning the range available commercially (Comprehensive; Biomet, Warsaw, IN, USA), by changing the radius of the glenoid surface in the computational model. Muscle forces, joint contact load, and glenohumeral head translation were calculated at desired positions to evaluate the effects of radial mismatch.

The computational model consisted of the bearing surfaces of the glenohumeral joint and 5 muscles that contribute to scaption: deltoid, subscapularis, supraspinatus, infraspinatus, and teres minor. Muscles with larger cross-sectional areas were subdivided to more accurately model the lines of action: the deltoid was divided into anterior, posterior, and middle parts, and the subscapularis was divided into superior and inferior parts. The scapular and humeral coordinate frames and all the necessary anatomical landmarks were defined according to recommendations of the International Society of Biomechanics for joint coordinate systems.[37]

To develop the computational model, a shoulder simulator was used to acquire the necessary geometry from a reconstructed cadaveric specimen. The simulator experiment was previously described.[10] Briefly, all soft tissues of the left shoulder from a 74-year-old man were dissected free of the scapula and humerus, except for the tendinous insertions of the 5 muscles that were included in our model. An experienced surgeon performed a TSR using an unconstrained Biomet implant with a 13.1-mm radial mismatch; the glenoid radius was 38.1 mm and the humeral head radius was 25 mm. A medium-sized glenoid component was selected for this specimen. The anatomic glenoid retroversion was not measured; however, a healthy specimen was used, and a typical TSR procedure was performed. The retroversion (if any) was corrected. Steel cables coated with Teflon (DuPont, Wilmington, DE, USA) were sutured to the tendon insertion sites to represent the muscles. The path of the cable represented the muscle line of action, as determined by the surgeon. The weight of the arm was simulated by a 3.5-kg weight located 315 mm from the greater tuberosity to replicate the center of gravity for the entire upper extremity.[27] The scapula was rigidly fixed to the simulator table, and the humerus was free to rotate about the glenohumeral joint.

The geometry of the glenohumeral joint was determined by using a motion capture digitizer to determine points of interest: muscle origins and insertions, epicondyles, humeral head center, and glenoid center. The humeral head center was established by tracking markers on the humerus while circulating the humeral head within the glenoid component and then applying a least squares algorithm to the resulting data.

The geometry of the shoulder obtained from the physical setup was used to create a computational model that determined the resulting glenohumeral translations, muscle forces, and joint contact force. In our model, we simulated scaption angles ranging from 20° to 60° for all radial mismatches characterizing the common daily motions during which higher glenohumeral contact forces would be expected. Only glenohumeral motion was modeled because we were primarily interested in force distributions around the glenohumeral joint, and thus, scapulothoracic motion was not included. The muscle forces required to maintain the desired scaption angle were determined by an optimization program in which a physiological cost function was used to predict the muscle forces across the joint by minimizing the sum of the stresses cubed in the muscles: $J = \min\sum_{i=1}^{8}\sigma_i^3$.[6] Muscle stresses were calculated by