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The effects of progressive lateralization of the joint center of rotation of reverse total shoulder implants

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Background: There has been a renewed interest in lateralizing the center of rotation (CoR) in implants used in reverse shoulder arthroplasty. The aim of this study was to determine the sensitivity of lateralization of the CoR on the glenohumeral joint contact forces, muscle moment arms, torque across the bone–implant interface, and the stability of the implant.

Methods: A 3-dimensional virtual model was used to investigate how lateralization affects deltoid muscle moment arm and glenohumeral joint contact forces. This model was virtually implanted with 5 progressively lateralized reverse shoulder prostheses. The joint contact loads and deltoid moment arms were calculated for each lateralization over the course of 3 simulated standard humerothoracic motions.

Results: Lateralization of the CoR leads to an increase in the overall joint contact forces across the glenosphere. Most of this increased loading occurred through compression, although increases in anterior/posterior and superior/inferior shear were also observed. Moment arms of the deltoid consistently decreased with lateralization. Bending moments at the implant interface increased with lateralization. Progressive lateralization resulted in improved stability ratios.

Conclusions: Lateralization results in increased joint loading. Most of that loading occurs through compression, although there were also increases in shear forces. Anterior/posterior shear is currently not accounted for in implant fixation studies, leaving its effect on implant fixation unknown. Future studies should incorporate shear forces into their models to more accurately assess fixation methods.

Level of evidence: Basic Science, Computer Modeling.

Keywords: Reverse total shoulder arthroplasty; biomechanical study; computer modeling; lateralization; glenoid loading; implant design; muscle forces; moment arms

Reverse shoulder arthroplasty (RSA) is effective in treating pain and loss of function for patients with cuff tear arthropathy.[16,28,40] Over the years, the indications for RSA have expanded to include irreparable rotator cuff tears,[16] complex proximal humeral fractures,[16,28] and revision arthroplasty.[16]

Investigational Review Board approval was approval was not required for this study.

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Although Grammont-style prostheses have enjoyed improved longevity relative to previous designs, numerous studies have reported issues such as scapular notching,[8,20,31] adduction deficit,[17] significant losses in internal/external rotation,[8,31] instability,[12,13,19] and change in the cosmetic appearance of the shoulder.[8,15] Of these, scapular notching is one of the most prevalent issues and can be associated with decreased range of motion. To address this issue, there has been a renewed interest in lateralizing the center of rotation (CoR). Studies on RSA implants with lateralized rotation centers have shown improved range of motion and minimal scapular impingement.[8,12,17,20,31] There are also potential benefits of improved stability and better cosmetic contour of the shoulder.

RSA designs predating Grammont's incorporated similar concepts of lateralizing the articulation. One of the goals in these designs was to match the shoulder's native joint center.[9,14] These designs were abandoned due to high rates of short-term glenoid loosening. This loosening was attributed to increased loading at the joint center, which was converted to torque at the bone–implant interface due to the displacement of the joint center from the fixation surface.[9] The sensitivity of lateralization to loosening risk was high enough that even early designs from Grammont that provided smaller lateralizations were abandoned due to unacceptable loosening rates.[9]

Current lateralized designs have used improved fixation techniques to mitigate the loosening risks to acceptable levels. After screw fixation was incorporated into the RSA design, several studies have evaluated means to optimize screw purchase in bone,[17] resistance against shear,[29] and pull-out strength.[4] To determine acceptable levels of these variables, American Society for Testing and Materials (ASTM) testing standards[28] have been developed for shoulder implants, which have been used to prove the safety of lateralized designs. These standards, however, were modeled after contact loads in the healthy shoulder.[6] The contact load in an anatomic total shoulder replacement has been shown to be similar to the healthy shoulder but is different from those estimated for an RSA.[7,29,36] The aim of this study was to determine the sensitivity of lateralization of the CoR on the glenohumeral joint contact forces, muscle moment arms, torque across the bone–implant interface, and the stability of the implant.

Methods

A 3-dimensional virtual model, the Newcastle Shoulder Model[10,29] (NSM), was used to investigate how lateralization affects deltoid muscle moment arm and glenohumeral joint contact forces. This model was virtually implanted with 5 progressively lateralized reverse shoulder prostheses. The joint contact loads and deltoid moment arms were calculated for each lateralization over the course of 3 simulated standard humerothoracic motions. These values were compared to assess the sensitivity of these outcome measures to lateralization of the joint CoR.

Shoulder model

The original NSM[10] describes the normal shoulder and full arm. It consists of 6 rigid bone segments (thorax, clavicle, scapula, humerus, radius, and ulna) that were digitized from the Visible Human dataset.[34] The bone segments are connected by 3 spherical joints, each with 3 degrees of freedom (sternoclavicular, acromioclavicular, glenohumeral), and 2 hinge joints, each with 1 degree of freedom at the elbow. Muscles, whose morphology was taken from the literature,[37,27] are represented as elastic strings that wrap about simple geometric shapes, such as spheres and cylinders. This function allows for modeling muscle lines of action as they wrap around bones. Muscles with wide origin or insertion sites are represented with multiple lines of action that follow anatomic fascicle divisions. The virtual model simulates the actions of 31 muscles and 3 ligaments (sternoclavicular, conoid, and trapezoid) of the shoulder complex, arm, and forearm that are divided into 96 lines of action. The model can predict muscle and joint contact forces using inverse dynamics and static optimization methods[10]

The model was adapted to describe the geometry of the commercially available DELTA III reverse shoulder prosthesis (DePuy, Warsaw, IN, USA) with a 36-mm glenosphere diameter[29] (fully conformed design). The new prosthetic glenohumeral joint is modeled as a ball and socket (3 rotational degrees of freedom, no translations), where the centers of the humeral cup and glenosphere are concentric (kinematic constraint). No friction was assumed for the prosthetic joint. A full-thickness rotator cuff tear was simulated by deactivating the supraspinatus, infraspinatus, and subscapularis muscles to recreate a typical scenario by which the RSA would be used.

The model can also detect impingement between the scapula (inferior border) and the humeral cup, which is a simple virtual graphic overlapping of their 3-dimensional models. Impingement does not affect motion (kinematics) or force calculation in the model.

Implant positioning and lateralization

The original model represents a healthy, nonarthritic glenoid. The standard surgical guidelines for the DELTA prosthesis were used to virtually implant the prosthesis into the model. For this study, an initial fixation position was chosen at 5 mm medial to the native face of the glenoid to represent a glenoid that is severely eroded and needs extra reaming, hereafter referred to as the reference position (−5 mm). A second fixation was performed at the native glenoid face (simulating very small reaming/flattening of the glenoid). This represented the 0-mm lateralization position. Three additional lateralized glenospheres were created and fixed at the original glenoid face, thus lateralizing the CoR, in +5-mm increments from the 0-mm position: +5, +10, and +15 mm. This range covers all commercially available RSA implants and published lateralization techniques.[8,12,38] In all cases, the glenosphere was fixed with 0° of version and tilt, following the manufacture's guidelines and the description of Kontaxis and Johnson.[29] According to the same guidelines, neutral (0°) version was also chosen for the humeral fixation.

Kinematic inputs to the model

The model simulated 3 standardized motions: humeral elevation in abduction (ABD), the scapular plane (SC), and forward flexion (FF) for each glenosphere configuration. All motions were