ARTICLE IN PRESS

J Shoulder Elbow Surg (2016) ■■, ■■–■■

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

ORIGINAL ARTICLE

Effect of lateralized design on muscle and joint reaction forces for reverse shoulder arthroplasty

William Liou, PhD[a], Yang Yang, PhD[a], Graysen R. Petersen-Fitts, MD[b], Daniel J. Lombardo, MD[b], Sasha Stine, BS[b], Vani J. Sabesan, MD[b,*]

[a]*Department of Aerospace and Mechanical Engineering, Western Michigan University, Kalamazoo, MI, USA*
[b]*Department of Orthopaedic Surgery, Wayne State University School of Medicine, Taylor, MI, USA*

Background: Manufacturers of reverse shoulder arthroplasty (RSA) implants have recently designed innovative implants to optimize performance in rotator cuff–deficient shoulders. These advancements are not without tradeoffs and can have negative biomechanical effects. The objective of this study was to develop an integrated finite element analysis–kinematic model to compare the muscle forces and joint reaction forces (JRFs) of 3 different RSA designs.
Methods: A kinematic model of a normal shoulder joint was adapted from the Delft model and integrated with the well-validated OpenSim shoulder model. Static optimizations then allowed for calculation of the individual muscle forces, moment arms, and JRFs relative to net joint moments. Three-dimensional computer models of 3 RSA designs—humeral lateralized design (HLD), glenoid lateralized design, and Grammont design—were integrated, and parametric studies were performed.
Results: Overall, there were decreases in deltoid and rotator cuff muscle forces for all 3 RSA designs. These decreases were greatest in the middle deltoid of the HLD model for abduction and flexion and in the rotator cuff muscles under both internal rotation and external rotation. The JRFs in abduction and flexion decreased similarly for all RSA designs compared with the normal shoulder model, with the greatest decrease seen in the HLD model.
Conclusions: These findings demonstrate that the design characteristics implicit in these modified RSA prostheses result in mechanical differences most prominently seen in the deltoid muscle and overall JRFs. Further research using this novel integrated model can help guide continued optimization of RSA design and clinical outcomes.
Level of evidence: Basic Science Study; Computer Modeling

Keywords: Reverse shoulder arthroplasty; humeral lateralized design; finite element analysis; kinematic model; shoulder biomechanics; RSA implant design

While reverse shoulder arthroplasty (RSA) was originally designed as a solution for patients with cuff tear arthropathy, its indications have broadened considerably and now include many more complex etiologies such as rheumatoid arthritis, complex fracture fixation, shoulder girdle tumors, and revision of failed anatomic arthroplasty. Given the expanding indications, RSA is becoming an increasingly common shoulder operation with an annual growth rate of 7% to 13% since 2007, accounting for almost 40% of the shoulder

---

*Reprint requests: Vani J. Sabesan, MD, Department of Orthopaedic Surgery, Wayne State University School of Medicine, 10000 Telegraph Rd, Taylor, MI 48120, USA.

E-mail address: sabes001@gmail.com (V.J. Sabesan).

http://dx.doi.org/10.1016/j.jse.2016.09.045

arthroplasty market.[12,20] With this growth rate, it is not surprising to see the increased number of commercially available RSA implants with a spectrum of design innovations. The main design enhancements have focused on diminishing complications and optimizing performance for increased stability and better functional outcomes.

In 1985 Paul Grammont revolutionized RSA with the introduction of his novel RSA implant design.[1] The Grammont system focused on 4 principles that he identified to ensure stabilization while allowing the deltoid to compensate for the deficient or absent rotator cuff.[1,3,25] These early designs improved range of motion in patients with rotator cuff deficiencies by retensioning and repositioning the deltoid relative to the joint's fixed center of rotation (COR). In addition, the medialized COR increases the deltoid's moment arm by 20% to 42% and recruits more fibers of the anterior and posterior deltoid to assist the middle deltoid in abduction (ABD).[3,14] While the medialized design certainly improves function in patients with rotator cuff–deficient shoulders, a nonanatomic reconstruction is not without limitations that can negatively affect outcomes.

The recent design innovations have taken the approach of inferiorizing and lateralizing the COR. By shifting the COR inferiorly with a corresponding change in humeral position, RSAs decrease the wrapping angle of the deltoid muscle around the greater tuberosity. This may compromise stability and can create cosmetic concerns. The magnitude of change for the COR and the position of the humerus has significant consequences on the length of the deltoid and rotator cuff muscles, length of abductor moment arms, and shoulder stability.[11,21] Several studies have examined range of motion and the rate of implant failure in implants with alternate component positioning. Li et al[15] found that inferiorization or lateralization appears to have the most beneficial effects on internal rotation (IR) and external rotation (ER) in RSA. In addition, Gutierrez et al[9] found that tilt and glenosphere eccentricity affect the force distribution at the baseplate-bone interface. They found that different combinations of placement for the COR in terms of inferiorized or lateralized glenosphere position had a significant impact on force loading at the baseplate-bone interface.[9] Thus, there is an interesting body of literature comparing optimal implant positioning and specific RSA implant designs.[10,11,21]

Specific design variations have arisen in terms of methods of lateralization based on variations in glenoid or humeral components. However, there are few head-to-head comparisons of commercially available RSA implants and their effects on muscle function, stability, and joint reaction force (JRF). Given the growth in the use of RSA, the multitude of implant design philosophies, and the lack of consensus regarding optimal implant design characteristics, this study attempted to develop an innovative combined kinematic and finite element analysis (FEA) model of the shoulder to test the effects of 3 current and different RSA designs. Our main objective was to provide a comparative analysis of joint stability, JRFs, and muscle function. We believe that these findings will provide valuable insight into optimal implant design for RSA.

Materials and methods

Delft shoulder and elbow model

A novel integrated kinematic and FEA shoulder computer model was used to evaluate the JRFs and shoulder function of 3 different RSA designs. The Delft shoulder and elbow model (DSEM) was used in this study.[18,27] It is a well-validated, anatomically accurate, finite element 3-dimensional (3D) model and has been integrated into the OpenSim platform. OpenSim is a software code developed by the National Institutes of Health National Center for Simulation in Rehabilitation Research that allows for musculoskeletal modeling and dynamic simulation of movement.[4,5] The combined DSEM-OpenSim model was used to simulate shoulder mobility (ABD or adduction and extension or flexion of the humerus) in the OpenSim environment, in which bones are modeled as rigid bodies, muscles as force-generating truss elements, and ligaments as passive trusses. In the combined model, important anatomic entities such as the scapula, humerus, clavicle, and ribcage are included. Joint rotation centers, ligament attachment points, and muscle attachment points have been verified and validated during model development. Muscle groups include the deltoid, subscapularis, infraspinatus, teres major, and teres minor. Muscle forces are determined by the Schutte muscle model,[24] which assumes length-dependent tensile forces to be generated by muscle strands. Finite element nodal points are used to represent anatomically important structures of the shoulder, such as joint rotation centers and muscle attachment points. The inverse dynamic simulation method is used first to obtain muscle forces for individual muscle groups with the inputs of the motions of the bones and the appropriate external loading. The static optimization then follows to calculate JRFs.

To evaluate the effects of 3 variations in RSA designs on JRFs and muscle function, the base model has been modified to conform to the RSA configuration. A detailed account of the method of converting the original DSEM into a specific RSA shoulder model is given in the next section.

Reconstruction of RSA shoulder

Accurate 3D computer models of 3 RSA designs—humeral lateralized design (HLD), glenoid lateralized design (GLD), and Grammont design (GD)—were used to conduct parametric studies. In addition, the 3 RSA prosthesis designs were compared with a normal (anatomic) shoulder, which functions as the baseline for this comparative study. When generating these 3D models, we based the humeral offsets for the 3 different designs on the article by Mau and Zuckerman,[16] while the glenoid offsets were determined by direct measurement on the computer-aided design models.

The muscle forces and the JRFs for each implant model and the anatomic shoulder were calculated. Simulation of ABD (0°-90°), forward flexion (FF) (0°-90°), and IR and ER (0°-45°) was performed with a fixed elbow.[2] The OpenSim RSA model was verified and validated. Parametric studies were performed to examine the variation in muscle forces through the aforementioned motions.

Patient-specific computed tomography scans were obtained from cadaveric shoulder studies and processed by a senior scientific shoulder expert (Exactech, Gainesville, FL, USA). A 3D geometric reconstruction of the shoulder joint including the scapula and humerus was performed and verified by independent technical specialists. A