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How sensitive is the deltoid moment arm to humeral offset changes with reverse total shoulder arthroplasty?

David R. Walker, PhD[a], Allison L. Kinney, PhD[b], Thomas W. Wright, MD[c,*], Scott A. Banks, PhD[a]

[a]*Department of Mechanical Engineering, University of Florida, Gainesville, FL, USA*
[b]*Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL, USA*
[c]*Orthopaedics and Sports Medicine Institute, University of Florida, Gainesville, FL, USA*

Background: Reverse total shoulder arthroplasty commonly treats cuff-deficient or osteoarthritic shoulders not amenable to rotator cuff repair. This study investigates deltoid moment arm sensitivity to variations in the joint center and humeral offset of 3 representative reverse total shoulder arthroplasty subjects. We hypothesized that a superior joint implant placement may exist, indicated by muscle moment arms, compared with the current actual surgical implant configuration.
Methods: Moment arms for the anterior, lateral, and posterior aspects of the deltoid muscle were determined for 1521 perturbations of the humeral offset location away from the surgical placement in a subject-specific musculoskeletal model with motion defined by subject-specific in vivo abduction kinematics. The humeral offset was varied from its surgical position ±4 mm in the anterior/posterior direction, ±12 mm in the medial/lateral direction, and −10 to 14 mm in the superior/inferior direction.
Results: The anterior deltoid moment arm varied in humeral offset and center of rotation up to 20 mm, primarily in the medial/lateral and superior/inferior directions. The lateral deltoid moment arm varied in humeral offset up to 20 mm, primarily in the medial/lateral and anterior/posterior directions. The posterior deltoid moment arm varied up to 15 mm, primarily in early abduction, and was most sensitive to humeral offset changes in the superior/inferior direction.
Discussion: High variations in muscle moment arms were found for all 3 deltoid components, presenting an opportunity to dramatically change the deltoid moment arms through surgical placement of the reverse shoulder components and by varying the overall offset of the humerus.
Level of evidence: Basic Science Study; Computer Modeling

Keywords: Deltoid components; deltoid muscle; humeral offset; joint center; muscle moment arm; reverse total shoulder arthroplasty

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*Reprint requests: Thomas W. Wright, MD, Orthopaedics and Sports Medicine Institute, University of Florida, 3450 Hull Rd, Gainesville, FL 32611, USA.

E-mail address: wrightw@ortho.ufl.edu (T.W. Wright).

Reverse total shoulder arthroplasty (RTSA) has become a popular treatment for shoulders with symptomatic cuff tear arthropathy, irreparable rotator cuff tears, and osteoarthritis associated with rotator cuff insufficiency; however, complication rates ranging from 19% to 68% (for implant loosening,

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acromial fracture, scapular notching, frozen shoulder, dislocation, and so on) are still reported.[20,28,32] Different RTSA designs have now been developed by changing implant joint geometry to address these complications.[6,10,21] For example, the Grammont-type design (eg, Delta III [DePuy, Warsaw, IN, USA]) places the center of rotation medial and inferior to improve the deltoid moment arm, whereas the Frankle-type design (RSP; DJO Surgical, Austin, TX, USA) lateralizes the joint center (JC) using a lateralized glenosphere with a more neutral superior/inferior placement. Humeral implants that sit on top of the humerus with low neck-shaft angles are another design strategy to lateralize the humeral bone.[24] Clinical and biomechanical studies have been performed to support each design theory, but there is still a need for quantitative work to relate JC changes and clinical/functional outcomes.[3,15,18,23,24]

Many cadaveric and computational biomechanical studies have evaluated the influence of RTSA joint geometry changes on muscle moment arms and range of motion.[3,14,15,18] For example, Roche et al[24] assessed the relationship between reverse shoulder design parameters and range of motion, impingement, and stability. Gutiérrez et al[11,13] reported a series of studies evaluating the effects of implant design and surgical factors on shoulder mechanics during different motions. Henninger et al made the case for in vitro biomechanical studies, stating "In contrast to surrogate and computational models, cadaveric studies include the effects of soft-tissue tension, subject-specific anatomical variability, and surgical implementation."[1,3,14,15] Cadaveric studies have the specific advantage of being able to precisely manipulate the joint geometry and measure resulting changes in muscle moment arms. However, the results from previous studies were limited because the studies were largely performed in healthy shoulders (which would not capture the anatomic characteristics of the diseased shoulder); the studies primarily focused on a single implant device within a study (so the range of joint variation was typically small); the studies assumed a fixed pattern of movement between the humerus and scapula that may not accurately represent cuff tear shoulders; and the studies typically used implant placements that did not reproduce surgical placement in actual subjects. In an effort to address some of these limitations, we sought to assess the sensitivity of deltoid muscle moment arms using subject-specific data sets and models.

Implant designers and previous biomechanical studies agree that changing the humeral offset (HO) and JC changes the shoulder muscle moment arms. The challenge remains to determine how the shoulder HO and JC should be placed in a specific subject to obtain the best possible muscle moment arms for abduction. Therefore, the goal of this study was to use subject-specific models of 3 RTSA subjects to determine the sensitivity of deltoid muscle moment arms to changes in RTSA joint configuration over the anterior/posterior, medial/lateral, and superior/inferior directions of the joint.

Materials and methods

Overview

A 12-*df* subject-specific 3-dimensional (3D) musculoskeletal model was used to simulate dynamic abduction for 1521 surgical implementations for 3 representative RTSA subjects that spanned the range of subject body sizes from our previous work.[17] Three-dimensional kinematic fluoroscopy and motion-capture data collected from our previous work were used to define the nominal joint geometry and prescribe humeral and scapular motions in each of the 3 subject-specific RTSA models.[19,31] Each model was scaled according to that subject's humeral length. The nominal RTSA joint geometry was modified by changing the humeral stem offset along the medial/lateral, superior/inferior, and anterior/posterior directions. Deltoid moment arms were predicted for each subject, and sensitivity was assessed in the medial/lateral, superior/inferior, and anterior/posterior directions.

Data collection

Kinematic data were collected using fluoroscopy and model-image registration for each RTSA subject performing arm abduction.[4,31] In addition, 3D motion-capture data were collected for each subject performing a variety of activities.[31] The kinematic data were used to scale, configure, and drive the subject-specific musculoskeletal models.[8,17] Subject A received an Equinoxe reverse implant with a medialized glenosphere and lateralized humerus (Exactech, Gainesville, FL, USA),[10,24] and subjects B and C received a reverse shoulder prosthesis with a lateralized glenosphere and medialized humerus (RSP; DJO Surgical).[10,24]

Model definition

Our subject-specific musculoskeletal models were adapted from Holzbaur et al[17] and consisted of a 12-*df* shoulder model with 3 muscle actuators representing the aspects of the deltoid. Each model was scaled by the subject's humeral length relative to the humeral length of the generic model in OpenSim[8] (subject A, 89%; subject B, 98%; and subject C, 105%).[17] The fluoroscopic kinematic data were used to prescribe the motions of the humerus and scapula. Therefore, no relationship was assumed between scapular and humeral motion.

Shoulder joint geometry

We used 3D reconstructions of bone and 3D meshes of the implants (provided by the manufacturers [DJO Surgical and Exactech]) to perform 3D to 2-dimensional image registration and measure the bone and implant positions and orientations (Fig. 1).[4,10,30] These data defined the 3D