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Effects of osteoarthritis on load transfer after cemented total shoulder arthroplasty

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Background: Total shoulder arthroplasty is commonly performed to treat glenohumeral osteoarthritis (OA); however, little is understood of the mechanics of the reconstructed OA shoulder. We sought to establish the effects of OA-induced changes in bone density and retroversion angle on load transfer and stress distribution in the bone-implant system of the scapula.

Methods: We developed finite element models of reconstructed healthy and OA scapulas with a virtually implanted glenoid prosthesis design. For the OA scapula, models with uncorrected and corrected retroversion were created. Loads were applied at the center or posteriorly on the glenoid surface.

Results: Our results suggest that with reconstruction of the corrected glenoid with a contemporary implant, cement stresses increase and the load transfer pattern changes with eccentric loads. The load transfer and local stresses in the bone-implant system in the retroverted glenoid are less sensitive to changes in loading location. Furthermore, the load transfer in the OA glenoid is less sensitive to the effect of peg proximity to the cortical shell than in the healthy glenoid.

Conclusion: We provided evidence of how load sharing is altered among healthy, corrected OA, and retroverted OA glenoids. We demonstrated that correction of retroversion in OA glenoids may actually increase the risk for stress shielding and cement failure compared with retroverted glenoids, and OA patients can accommodate shorter pegs because of the higher glenoid bone stiffness in the OA glenoid.

Level of evidence: Basic Science, Computer Modeling.

Keywords: Total shoulder arthroplasty; osteoarthritis; load transfer; finite element analysis; eccentric loading; retroversion; implant peg length

Total shoulder arthroplasty (TSA) is commonly performed to treat glenohumeral osteoarthritis (OA); however, the complication rate of this surgery has been reported as high as 14.7%.[1] The most common complication is glenoid component loosening.[1] Although implant designs have been created in attempts to reduce implant failure, the rate of radiolucencies is still as high as 36% to 83%.[29,44] Previous experimental and computational studies proposed conflicting failure mechanisms, suggesting that failure occurs in the bone, cement, or interface.[20,21,24,39,44]

Load transfer patterns and local stress distributions in the bone-implant system are the common focus of most mechanical analyses of TSA.[4,30,40] In a previous study, we showed that high-magnitude and eccentric loading

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increased tensile stresses in the cement layer and surrounding glenoid bone.[30] We also showed that the compressive joint load bypassed the cancellous bone region and was transferred directly to the scapular cortical shell when the ends of the implant pegs were close to the scapular cortical bone of a healthy joint.[30] We do not know, however, if the same load transfer pattern would occur when the ends of the pegs are farther away from the cortical bone. We also do not know if the same load transfer pattern would be observed in an osteoarthritic shoulder.

OA is associated with increased bone density and retroversion of the glenoid that could affect load transfer in the bone-implant system.[2,5,7,19,28,35,38] However, most finite element (FE) studies have focused on understanding the local stresses generated in the reconstructed healthy specimen.[24] Furthermore, the effect of retroversion has been modeled only in healthy specimens.[7,39] Increased retroversion (typically $> 10°$) can lead to eccentric contact on the glenoid.[7,28] The ‘‘rocking horse’’ phenomenon induced by eccentric loading is commonly attributed to glenoid loosening.[8,43] Current surgical procedures aim to correct excessive retroversion by methods such as posterior bone grafting or more commonly by reaming the anterior part of the glenoid to correct version.[7,16,28] Unfortunately, significant eccentric posterior contact remains in TSA patients with anteriorly reamed glenoids.[25]

We sought to establish the effects of OA-induced changes in bone density and retroversion angle on load transfer and stress distribution in the bone-implant system of the scapula. Two specific questions were addressed: (1) How does implant peg proximity to cortical bone affect load transfer in OA compared with healthy glenoids? and (2) How are local stress distributions and load transfer affected among healthy, retroverted OA, and corrected OA glenoids under central and eccentric joint loads? To answer these questions, case studies of glenoid replacement on a healthy and an OA scapula are performed. We developed FE models of a healthy and OA reconstructed scapula implanted with a contemporary glenoid component. Stress distributions in the bone-implant system and load carried by cement, implant, and bone were determined and compared among the models.

Materials and methods

Study design

Models of 2 left scapulas, one healthy and the other osteoarthritic, were created from computed tomography (CT) scans of a cadaver scapula and a scapula of an OA patient, respectively. For the OA scapula, models with retroversion and corrected retroversion were created. Normal loads were applied at the center or posteriorly on the glenoid surface. The load carried by the bone, cement, and implant and the local stresses distribution were determined and compared among the models and the loading scenarios. As we used CT scan data from one healthy and one OA subject, all the results reported should be interpreted as case studies.

FE model

The left scapulas of a healthy cadaver (93-year-old woman) and an osteoarthritic (61-year-old woman) shoulder were CT scanned in the transverse plane. The cadaver CT study was performed with a GE Discovery LS with a 4-slice CT scanner (GE Healthcare, Milwaukee, WI, USA). The exact slice thickness was 1.250 mm, and in-plane pixel dimensions were 0.488 mm $\times$ 0.488 mm. The patient CT study was performed with a Philips Brilliance CT 64-channel scanner (Philips Healthcare, Bothell, WA, USA). The exact slice thickness was 1 mm, and in-plane pixel dimensions were 0.387 mm $\times$ 0.387 mm. Both shoulders were intact when scanned. The report for the healthy cadaver had established no evidence of disease, and the OA scapula had come from a patient who was clinically diagnosed with and treated for OA. The 3-dimensional scapular geometry was developed from the scans with use of Mimics software (v 12.0; Materialise, Leuven, Belgium). The bone was segmented from surrounding soft tissue by the standard thresholding process in Mimics. The scapula was then separated manually from the humerus, and the bone voids were filled. The Mimics file (.STL) was then created and imported to Geomagics (Rock Hill, SC, USA) for geometric smoothing, followed by meshing in TrueGrid (Scientific Applications, Inc, Livermore, CA, USA). Three models were created: a reconstructed healthy scapula, an OA scapula with retroversion of 18°, and a corrected OA scapula with 6° of retroversion. The geometries of the models were created from CT scans of a cadaver (for healthy) and a patient (for OA). The retroversion angle of 18° of the OA scapula is measured on the basis of the 3-dimensional geometry of the OA scapula (Fig. 1, *A*). To create the corrected OA scapula, the anterior portion of the glenoid was reamed to reduce the retroversion to about 6° (Fig. 1, *B*). The bone was not reamed all the way to 0° because the implant pegs would then cause perforation of the bone.

The reconstructed scapula included a virtually implanted glenoid prosthesis (Comprehensive; Biomet, Warsaw, IN, USA). The glenoid was virtually implanted with use of TrueGrid software (v2.3.4; XYZ Scientific Applications Inc, Livermore, CA, USA), by which bone was replaced by the implant pegs in the area in which the implant was placed. The prosthesis was a 3-pegged, asymmetric, all-polyethylene, cemented implant with a radius of curvature of 38.1 mm and was surrounded in the model by a uniform 1-mm cement layer (Fig. 2). A 1-mm layer of cement is recommended during the surgical procedure and has been commonly used in previous studies.[21,31] The face of the glenoid was reamed to match the flat-backed geometry of the prosthesis. For the healthy scapula, the prosthesis was virtually implanted to re-create native version, which is neutral to the long axis of the scapular body. The pegs were modeled as cylindrical rods 10 mm in length. To investigate peg proximity to the cortical bone in the scapula (i.e., how close the ends of the pegs are to the cortical bone), the peg lengths were lengthened or shortened. The glenoid sizes were different between healthy, corrected OA, and uncorrected retroverted OA. To model the end of the pegs at or away from the cortical bone and to prevent bone perforation with the pegs, the peg lengths needed to be lengthened or shortened either by 2 or 2.5 mm. The implant pegs were defined as touching the cortex if they were either at or near the cortical bone, namely, they were very close to the stiffer outer layer of bone, and any increase in length would cause perforation of bone with one or more pegs. The implant pegs were defined as