J Shoulder Elbow Surg (2012) 21, 795-803

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Finite element analysis and physiologic testing of a novel, inset glenoid fixation technique

Stephen B. Gunther, MD[a,*], Tennyson L. Lynch, BS[b], Desmond O'Farrell, B.Eng (Hons) MM[c], Christian Calyore[d], Andrew Rodenhouse, BS[c]

[a]*Howard Memorial Hospital, Willits, CA, USA*
[b]*Temple University, School of Medicine, Philadelphia, PA, USA*
[c]*Shoulder Innovations, Ada, MI, USA*
[d]*Department of Engineering, Hope College, Holland, MI, USA*

Hypothesis: The success of shoulder arthroplasty surgery has been limited by a common complication: glenoid implant loosening. Eccentric loading of the glenoid due to migration of the humeral head is considered to be the major cause of glenoid loosening and is referred to as the rocking-horse phenomenon. Glenoid implant loosening may cause pain, limitation of function, and the need for complicated revision surgery. Our hypothesis was that an inset fixation technique could offer increased fixation strength and minimize the effects of the rocking-horse phenomenon on glenoid loosening.

Materials and methods: Fixation strength and stress distribution were analyzed using two methods. First, mechanical simulation of physiologic in vivo cyclic loading was performed on 1 inset glenoid implant design and 2 standard onlay glenoid implant designs currently on the market. Second, 3-dimensional finite element analysis was performed to compare an inset glenoid implant and a standard onlay glenoid implant with a keel and a standard onlay pegged implant.

Results: After cyclic loading to 100,000 cycles, no glenoid implants demonstrated signs of loosening. Mechanical testing after cyclic loading demonstrated less distraction of the glenoid rim using an inset technique compared with an onlay technique. Finite element analysis results indicated that the inset technique achieved up to an 87% reduction in displacement.

Conclusions: Mechanical tests and finite element analysis support the concept of inset glenoid fixation in minimizing the risk of glenoid loosening.

Level of evidence: Basic Science Study, Biomechanical and Finite Element Analysis.

Keywords: FEA; dynamic testing; finite element analysis; glenoid; inset implant; osteoarthritis; shoulder replacement; loosening

The success of shoulder arthroplasty surgery has been limited by one of the most common complications: glenoid implant loosening.[13,21,43,47,49] Eccentric loading of glenoid implants due to migration of the humeral head is considered to be the major cause of glenoid loosening and is referred to

Investigational Review Board approval was not required for this study.

*Reprint requests: Stephen B. Gunther, MD, Howard Memorial Hospital, Department of Orthopedic Surgery, 500 Martha Jefferson Dr, Charlottesville, VA 22911, USA.

E-mail address: sbgunther@aol.com (S.B. Gunther).

1058-2746/$ - see front matter © 2012 Journal of Shoulder and Elbow Surgery Board of Trustees.
doi:10.1016/j.jse.2011.08.073

as the rocking-horse phenomenon.[7,8,12,15,22,24,42,47,49] Multiple clinical studies have shown a significant incidence of postoperative lucent lines around the backside of standard onlay implants and progression to glenoid implant loosening.[43,48] Implant loosening may cause pain, functional limitation, stiffness, and the need for complicated revision surgery.[18,47,49]

The strength of initial glenoid implant fixation is important in determining the potential for glenoid loosening.[1,15,19] Glenoid implant fixation strength has been tested indirectly through micromotion measurements,[14,31,39,46] finite element analysis (FEA),[17,20,25,27,32,33,35,38,45] and nonphysiologic pull-out tests.[18,31,40] The study by Anglin et al[3] established a reproducible, physiologic protocol for evaluation of glenoid loosening by simulating rocking-horse translational forces. Using 6 different onlay glenoid implant designs, Anglin et al found that nonconforming, curved-back implants with a roughened backside surface withstood loosening in dynamic loading better than competitive implants. They also determined that distraction displacement of the inferior glenoid rim away from the foam block after superior rim loading was the best indicator of loosening.[3]

Our study is a comparative scientific analysis of glenoid loosening using an inset glenoid fixation technique vs the standard onlay technique used with a keel or pegged implant. The analysis consists of two separate methods: First, physiologic in vivo cyclic loading of glenoid implants was simulated using the dynamic model described by Anglin et al and American Society for Testing and Materials (ASTM) F2028-08 Standard Test Methods for Dynamic Evaluation of Glenoid Loosening or Disassociation.[3,6] Second, FEA was performed to estimate the glenohumeral joint stress and displacement for both standard onlay implants and an inset glenoid implant. Our hypothesis was that an inset fixation technique could offer increased glenoid implant fixation strength, which would minimize the effects of the rocking-horse phenomenon on glenoid loosening.

Materials and methods

Mechanical reproduction of in vivo loading

Materials and methods complied with the ASTM F2028-08 mechanical testing specifications.[6] Test methods followed the protocol of Anglin et al[3] to create directly comparable results. The specimens tested in our study were inset, circular glenoid implants with a 35-mm diameter with one 8-mm central, posterior peg (Shoulder Innovations LLC, Ada, MI, USA), standard size 40 onlay glenoid implants with a keel (DePuy, Warsaw, IN, USA), and standard size 40 anchor peg glenoid implants (DePuy, Warsaw, IN, USA; Table I). We tested 12 specimens: 3 onlay keel and 3 onlay peg implants with their associate humeral heads, 3 inset specimens with a 38-mm humeral head, and 3 inset specimens with a 56-mm humeral head.

The inset glenoid implant (Shoulder Innovations, LLC) is an all polyethylene, circular implant designed for deficient glenoid bone. The 35-mm inset implant was chosen for testing instead of smaller sizes because it is the largest used in clinical practice by the senior author (S.B.G.). When coupled with the smallest humeral head implant currently in use (38 mm), this combination of head and glenoid sizes presents the largest potential for implant loosening because of the potential for edge loading.

A 20-pound per cubic foot block of cellular rigid polyurethane foam (Sawbones, Vashon, WA, USA) was used as a bone substitute in the fixture for the glenoid implants. According to the manufacturer's specifications, the polyurethane has an ultimate compressive strength of 8.4 MPa and a modulus of 210 MPa. This bone substitute was chosen because it meets ASTM testing standards and replicates the Anglin et al[3] protocol. This substitute represents average properties of cancellous bone and avoids the media inconsistencies of cadaveric bone.[1,3,5]

The mechanical testing and sample preparation were performed at an independent laboratory (Knight Mechanical Testing, Fort Wayne, IN, USA). The implants were installed into the test blocks according to the manufacturers' guidelines. For the inset implants, the polyurethane foam blocks were reamed with a flat back reamer to a 3-mm depth to replicate the cylindrical inset bone cavity created during the surgical procedure.[23] The technique uses a central drill hole, followed by concentric reaming to create a precise cavity for the implant. Figure 1 is a representation of a glenoid implant partially inset within the glenoid cavity to provide increased fixation without allowing the humeral head component to contact the glenoid bone substitute.

Polymethylmethacrylate bone cement with a vacuum mixing system was applied to the inset cavity within the foam block and on the back of the implant. Each glenoid implant was manually compressed into the polyurethane block, and extruded peripheral cement was removed. The bone cement was allowed to cure in ambient conditions while the implant was gently compressed in to the foam.

Holes (1 mm) were drilled in the superior and inferior edges of all the glenoid implants to allow for insertion of 1-mm stainless steel extension pins used during the testing to measure implant edge displacement. Holes were drilled parallel to the glenoid surface to avoid compromise of the implants. The DePuy glenoid implants were installed according to the manufacturer's instructions for use. The manual dual-surface cement pressure technique with a vacuum mixing system used for the onlay implants was identical to that used for the inset implants.

Subluxation translation was determined for each of the implants according to the Anglin et al[3] protocol. Subluxation translation is defined as the distance from the deepest point of the glenoid, located at the centroid, to the point corresponding to the peak shear load when the humeral head is subluxated from the glenoid.[3,4] The subluxation translation for the onlay glenoid implants was determined by testing the size 40 glenoids with the size 40 humeral head implants, as suggested by the manufacturer. The articular surface of the inset implants was flat and nonconforming (56-mm radius of curvature). Therefore, we tested the smallest and largest humeral head sizes commercially available, which thus represent the extremes of conformity that could occur in a clinical setting. The contact point of the humeral head was located against the glenoid component within 0.5 mm of its center, and the 750-N compressive load was applied. The glenoid was translated superiorly and inferiorly at a rate of 50 mm/min while