Eccentric Reaming is Biomechanically Superior to Posterior Augmented Glenoid Prosthesis when Addressing Posterior Glenoid Wear during Total Shoulder Arthroplasty

Six word short form: Eccentric Reaming vs Posterior-Augmented Glenoid

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ABSTRACT

Level of Evidence: Basic Science

Background

Increased glenoid component loosening may be seen in patients with uncorrected glenoid retroversion after total shoulder arthroplasty. Posterior-augmented glenoid components have been introduced to address posterior glenoid bone loss but few biomechanical studies have evaluated their performance.

Methods

A twelve-degree posterior glenoid defect was created in composite scapulae. In the posterior-augment group, glenoid version was corrected to eight-degrees and an eight-degree augmented polyethylene glenoid component was placed. In the other group, eccentric anterior reaming was performed to neutral version and a standard polyethylene glenoid component was placed. Specimens were potted in cement and tested via cyclic loading in the superior-inferior direction to 100,000 cycles. Superior and inferior glenoid edge displacements were recorded. Student t-test and Mann-Whitney U tests were performed with an alpha value of 0.05 set as significant.

Results

Three of six specimens (50%) in the posterior-augment group and five of six (83%) specimens in the eccentric reaming group achieved the final endpoint of 100,000 cycles without catastrophic failure. Surviving specimens in the posterior augment group demonstrated greater displacement of superior (1.01±0.02 vs. 0.83±0.10 mm; p=0.025) and inferior markers (1.36±0.05 vs. 1.20±0.09 mm, p=0.038) during superior edge loading, as well as greater displacement of the

superior marker during inferior loading (1.44±0.06 vs. 1.16±0.11 mm, p=0.009). No difference was seen with the inferior marker during inferior edge loading (0.93±0.15 vs. 0.78±0.06mm, p=0.079).

Discussion

Eccentric reaming with standard glenoid prosthesis provides decreased edge displacements and decreased failure rates when compared to posterior-augmented glenoid components for treating posterior glenoid wear.

Key words:

Total Shoulder Arthroplasty, Glenoid Loosening, Posterior Glenoid Wear, Augmented Glenoid Component, Eccentric Reaming, Glenoid Edge Displacement

Introduction

The number of total shoulder arthroplasty procedures performed has been increasing rapidly, with nearly 27,000 surgeries performed annually in the United States in 2008.[22] This represents an increase of 250% over a 10-year period, with recent population-based studies predicting continuing increased demand.[1; 11] Primary glenohumeral osteoarthritis has been cited as the most common indication for total shoulder arthroplasty (TSA), accounting for 77% of cases.[22] Of patients diagnosed with primary glenohumeral arthritis, Walch et al reported 41% of these patients have preoperative posterior glenoid wear or posterior subluxation of the humeral head.[35]

Late radiographic lucency and clinical loosening of the glenoid component has been a concern in long-term survivorship of total shoulder arthroplasty implants.[14; 17; 23; 32] In a review of nearly 3,000 total shoulder replacements, Bohsali reported the incidence of aseptic loosening in total shoulder arthroplasty to be 39% at an average of five years follow-up, with 83% of the loosening attributable to failure of the glenoid component.[5] Shoulder replacement in the setting of posterior glenoid bone loss is associated with a three-fold increase in stress within the cement mantle and seven-fold increase in glenoid component micromotion.[12; 13; 33] Glenoid component retroversion decreases glenohumeral contact area, increases contact pressure, and may lead to eccentric loading resulting in glenoid component loosening.[13; 33]

Despite the frequency of irregular glenoid vault morphology, treatment guidelines to address glenoid bone loss have not been clearly established.[18; 20] Many surgeons neglect mild peripheral bone deficiencies and accept a nonanatomic orientation of the glenoid component. For larger defects, eccentric anterior reaming and posterior bone graft augmentation are two commonly used techniques, performed either alone or in combination.[32] However, eccentric

reaming of the anterior portion of the glenoid in the setting of severe glenoid morphologic changes may lead to removal of significant bone stock and increase the risk of glenoid vault perforation or instability. The technique of eccentric reaming is limited by the amount of healthy bone that can be removed from the anterior glenoid without compromising implant fixation and is therefore recommended for mild defects with less than 15 degrees of glenoid retroversion.[9; 15] Posterior corticocancellous bone graft is another option for treating larger posterior glenoid deficiencies. Though it allows for preservation of glenoid bone stock and restoration of anatomic joint line, bone grafting remains a technically challenging procedure with variable results.[19; 34] Complications such as graft loosening, subsidence, and resorption have been observed in 18-30% of cases.[20]

More recently, glenoid components with posterior augmentation have been introduced to compensate for posterior glenoid deficiency. Though proponents advocate the ability to restore the anatomic joint line, relatively few biomechanical or clinical studies have evaluated the performance of these components. Anatomic studies have shown that these augmented glenoid component may decrease the amount of glenoid vault medialization necessary and more accurately correct glenoid retroversion.[31] Clinical series have been published using augmented glenoid components but are often limited by sample size and follow-up period, [27; 31] with results of persistent glenohumeral instability and increased failure rates.[8]

To our knowledge, this is the first study that evaluates the performance of posterior-augmented glenoid component using an anatomic scapula model to evaluate stability in the setting of glenoid anatomy, version, and glenoid plane medialization. Previous biomechanical studies of posterior-augmented glenoid components have been performed in composite bone foam testing substrate. We hypothesize that angled-back posterior augmented glenoid, when

subjected to cyclic loading, would demonstrate increased edge displacement and decreased edge load and glenoid vault perforation as compared to standard glenoid implantation after eccentric reaming.

Materials and Methods

Twelve composite scapulae were obtained for biomechanical testing (Fourth Generation Sawbones Scapula, Part # 3413, Pacific Research Laboratories, Vashon, WA). These models are composed of an outer synthetic cortical shell with inner cancellous bone analogue, which simulates the mechanical properties of natural bone. A Kirschner guidewire was placed in the center of the articular surface using a drill guide manufactured with a twelve-degree posterior angle referenced from the glenoid face.[28] A cannulated reamer was used in line with the guidewire to create a posterior glenoid defect at a4 twelve-degree angle in all specimens.[10] Reaming was stopped prior to removal of bone from the anterior rim of the glenoid to maintain a consistent amount of substrate among specimens.

In the posterior augment group, the glenoid face was corrected to eight degrees of posterior wear and an eight-degree all-polyethylene pegged angle-backed posterior-augmented glenoid was cemented in place according to standard manufacturer's protocol (Exactech Equinoxe® Total Shoulder Arthroplasty system, Gainesville, FL). The posterior-augmented glenoid component design consists of three pegs perpendicular to the articular surface of the implant. Any instances of glenoid vault perforation during the process was noted. In the other group, eccentric reaming of the anterior glenoid was performed to create a neutral-version glenoid and a standard pegged all-polyethylene glenoid was cemented according to standard manufacturer's protocol (Exactech Equinoxe® Total Shoulder Arthroplasty system, Gainesville, FL). Both glenoid components have identical material properties and radius of curvature, with staggered peg design (Figure 1). Prior to implantation and cementing of the polyethylene component, all synthetic scapula were sectioned to isolate the bone surrounding the anatomic glenoid to facilitate potting in polymethylmethacrylate (PMMA).

Testing was performed using a custom apparatus (Figure 2) attached to an ElectroPuls E10000 materials testing machine (Instron Corporation, Norwood, MA) according to the American Society for Testing and Materials (ASTM) Standard F2028.[2; 4; 29] Glenoid specimens, potted to the same anatomical level in PMMA, were secured to a testing block and positioned against the corresponding Cobalt-Chromium humeral-head prosthesis. Specimens were oriented such that the glenoid face was directly perpendicular with the humeral head prosthesis. Care was taken such that there was no posterior subluxation by seating the humeral head component at the deepest point on the glenoid during initial alignment. Both the posterior-augmented and standard glenoid component designs articulate with an the same sized humeral-head prosthesis.

Prior to cyclic loading, each specimen underwent subluxation translation testing in the superior-inferior directions by displacing the humeral head component either superiorly or inferiorly at 50 mm/min while under a constant axial load of approximately 70 N. The low axial force was selected to avoid damaging the specimens prior to cyclic testing. Axial and shear (superior-inferior) loads were applied via an air cylinder and the Instron test machine actuator, respectively. Subluxation translation was defined as the displacement corresponding to the instant in which the peak shear load was observed.

Following subluxation tests, specimens were preconditioned under cyclic loading in the superior and inferior directions to 90% of the previously determined subluxation translations at 0.25 Hz for ten cycles while under a constant axial load of 750 N. Finally, specimens were cyclically loaded for 100,000 cycles at two Hz using the aforementioned loading magnitudes. This loading protocol represents approximately 25 higher load activities a day for 10 years.[4] Cyclic loading was performed in the superior-inferior direction to reproduce the rocking-horse mode of failure in total shoulder arthroplasty as documented in the ASTM standard.[4]

Superior-inferior edge loads were monitored throughout the cyclic testing protocol. All subluxation, preconditioning, and cyclic testing were performed with the specimens immersed in a circulating heated water bath maintained at 37 degrees Celsius.

Edge displacements were determined by imaging spherical markers (two mm diameter) attached to the superior and inferior edges of the glenoid component as well as the glenoid neck (Figure 3). Images for analysis were obtained using a Digital SLR Camera fitted with a 55-250mm f/4-5.6 lens. Markers were aligned along the central superior-inferior axis of the glenoid. Images were recorded with the humeral head positioned at the glenoid origin and then translated to 90% of the subluxation translation in the superior and inferior directions while specimens were subjected to a constant axial load of 750 N. A custom MATLAB program was used to analyze the acquired images and calculate the displacement, measured perpendicular to the glenoid plane, of the superior and inferior markers under edge loading relative to their positions with the humeral head positioned at the origin. Edge displacements were measured following preconditioning and after 100, 1,000, 10,000, 50,000, and 100,000 cycles. The average of three individual edge displacement measurements performed at each time point was used in the subsequent data analysis. The accuracy of this measurement method is approximately ±0.03 mm.

Testing was terminated, and defined as failure, prior to 100,000 cycles when the extent of glenoid subsidence (defined as the displacement of the glenoid component into the glenoid bone perpendicular to the glenoid plane) resulted in the loosening or destruction of the markers used for edge displacement measurements. For all specimens that suffered catastrophic failure, edge displacement measurements were attempted but physically unable to be attained because of frank instability of the glenoid component within the bone model. Consequently, edge displacement and load calculations were only determined for specimens that survived testing to each time

point. Subsidence was measured following testing using ImageJ (U.S. National Institutes of Health, Bethesda, Maryland).

Initial pilot testing data indicated that a sample size of six specimens in each group would provide a power of 0.80 to detect a difference in edge displacement of 0.20mm when tested at the 100,000 cycle, assuming a standard deviation of 0.10mm. Additionally, the number of specimens in each group used in this study was double the sample size as recommended in the ASTM standard.[4] Edge displacements and loads were compared between test groups at designated time point using t-tests. Additional outcome measures included subluxation translation and post-test subsidence, which were compared using a t-test and Mann-Whitney U test, respectively. For all comparisons, significance was set as $p < 0.05$.

Results

All specimens were prepared without evidence of scapula fracture, peg penetration, or cortical breach during prosthesis implantation. When examined in aggregate, specimens in the eccentric reaming group demonstrated a statistically significant, slightly greater displacement distance before subluxation in the superior-inferior distance than specimens in the posterior augment group (3.97±0.14 vs 3.69±0.25 mm; $p = 0.036$). Three of six specimens (50%) in the posterior augment group and five of six (83%) specimens in the eccentric reaming group achieved the final endpoint of 100,000 cycles without catastrophic failure (Table 1). The specimens that did fail had significant comminution of the glenoid bone stock with gross loosening and instability of the polyethylene glenoid component. As testing progressed, all specimens in both groups experienced evidence of fracture formation extending from the underside of the glenoid implant along the glenoid neck.

No significant differences in edge displacements were found between the posterior augment and eccentric reaming groups after preconditioning and cycles 10, 100, 1,000, 10,000, and 50,000. However, statistically significant differences in edge displacements were observed during both superior and inferior loading at the 100,000 cycle time point. Surviving specimens in the posterior augment group demonstrated significantly increased displacement of the superior (1.01±0.02 vs. 0.83±0.10 mm; $p = 0.025$) and inferior markers (1.36±0.05 vs. 1.20±0.09 mm; $p = 0.038$) during glenoid component superior edge loading than specimens in the eccentric reaming group (Figure 4). Similarly, the posterior augment group exhibited significantly greater displacement of the superior marker during inferior loading as compared to specimens in the eccentric reaming group (1.44±0.06 vs. 1.16±0.11 mm; $p = 0.009$) while the inferior marker did not demonstrate a significant difference (0.93±0.15 vs. 0.78±0.06 mm; $p = 0.079$) (Figure 5). No

156 significant differences were found for superior and inferior edge load measurements of surviving
157 specimens at any of the designated time points during cyclic loading. However, the difference in
158 inferior edge load between posterior augment and eccentric reaming groups at the final 100,000
159 cycle time point approached significance (186±45 vs. 242±27 N; $p = 0.063$).

160 Implant subsidence (defined as the displacement of the glenoid component into the
161 glenoid bone perpendicular to the glenoid plane) was not significantly greater for specimens in
162 the posterior augment group than the eccentric reaming group (3.3±3.3mm vs. 1.1±1.6 mm; $p =$
163 0.310). Regardless of test group, all specimens that failed to survive the full 100,000 cycles of
164 testing exhibited greater than 4 mm of glenoid subsidence, while those that survived displayed
165 less than 0.6 mm of subsidence.

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Discussion

This study evaluated two common techniques to address mild to moderate posterior glenoid wear in total shoulder arthroplasty. Eccentric reaming allows placement of a standard polyethylene glenoid component but may result in loss of glenoid bone stock, whereas the implantation of a posterior augmented glenoid component may better maintain the preexisting glenoid bone architecture but uses additional polyethylene material on the backside of the glenoid component. Our data demonstrates that eccentric reaming with a standard glenoid component is biomechanically superior to an angle-backed posterior augmented glenoid component, as measured by decreased edge displacement and increased implant survival, when subjected to cyclical testing in a posterior glenoid wear environment.

As expected, cyclical loading over time resulted in progressive implant loosening in both posterior-augmented and eccentric reaming groups. Although one specimen in the eccentric reaming group sustained catastrophic failure prior to the study end-point, this occurred far earlier than all other specimens in the study in either the posterior augment or eccentric reaming group (prior to 10,000 cycles). At the initial time point (prior to cyclical loading), this implant exhibited slightly lower superior edge load and increased distractive edge displacement of the inferior marker during superior edge loading when compared to the mean value of the remaining specimens in the same group. During post-testing analysis, it was determined that this specimen had insufficient cement mantle along the inferior edge used to fix the glenoid component. Although presumed an outlier, the failed eccentric reaming specimen was still included in the final analysis.

Subluxation translation, which is dependent on geometry alone,[3] was determined in each specimen prior to cyclic loading while the specimen was under a nondestructive axial load.

Although the ASTM standard recommends that subluxation testing be performed on separate samples from those undergoing cyclic loading, we chose to perform nondestructive subluxation tests on all specimens in order to increase the group sample sizes. The eccentric reaming group translated approximately 0.28 mm more than the posterior augment group prior to subluxation in either the superior or inferior directions. As a result, specimens in the eccentric reaming group were subjected to greater translation per cycle than specimens in the posterior augment group. Despite the difference in translation, no statistically significant differences in edge loads were found at the initial time point.

Surviving specimens in the posterior augment group demonstrated significantly greater edge displacement than surviving specimens in the eccentric reaming group at 100,000 cycles, indicating increased component loosening for the posterior augment group. Additionally, this group also trended towards decreased inferior edge load after 100,000 cycles when compared to the eccentric reaming group. It important to note that all specimens that suffered catastrophic failure were not included in the final analysis as they were too unstable and physically unable to undergo edge displacement testing. The incidence of implant catastrophic loosening and failure to achieve 100,000 cycles was higher in the posterior augment group (50%) than for the eccentric reaming group (17%).

One possible explanation for the increased instability and failure rates of the posterior augment components may be due to the morphology of the polyethylene glenoid component itself, as the component used in this study has an angled-backside interface where the prosthesis meets the native bone. Under axial load, the backside of a standard flat-backed polyethylene glenoid component is perpendicular to the load applied. However, with an angle-backed component, the glenoid component backside is oblique to the vector of axial load, which

214 introduces shear stresses to the implant-bone interface.[16] This may lead to increased wear and
215 instability at the undersurface of the prosthesis under cyclical loading.

216 Analogous findings have been described in the knee arthroplasty literature when
217 addressing tibial bone defects. Chen et al evaluated a variety of tibial augment implants in order
218 to compensate for tibial bone stock deficits.[7] The authors reported that wedge-shaped defects
219 introduced destabilizing shear forces and decreased stiffness under axial load. The conversion of
220 an oblique wedge defect into a step-cut pattern improved implant rigidity by 28-36%. This
221 increased stability of the step-cut components was even more pronounced when a fibrous
222 interface was introduced between the bone and cement interface; 100% of wedge-shaped
223 constructs failed while none of the step-cut constructs failed under axial load. After converting
224 an oblique defect to step-cut construct, shear stress is decreased and results in increased rigidity
225 and stability.[26] Clinically, the use of oblique metal wedge augments for tibial bone stock
226 deficiency has been associated with incidence of radiolucent line formation at the bone-cement
227 interface 27-46% between three to five years postoperatively.[6; 24-26]

228 Similarly, Iannotti et al compared a variety of glenoid components in cyclic loading in a
229 synthetic bone block model. When comparing posterior-augment glenoid components with either
230 an angle-back or step-cut design, the step-cut glenoid component produced decreased anterior
231 glenoid edge liftoff values when loaded eccentrically to cyclical loading. The authors conclude
232 that in-vitro glenoid component stability is better with a stepped segmented glenoid design.[21]

233 Published clinical studies with use of posterior-augmented glenoid components have
234 demonstrated inconsistent results. Rice et al reported on a series of fourteen patients treated with
235 total shoulder arthroplasty using a five-degree posteriorly augmented polyethylene glenoid
236 component.[27] Though 86% of patients had a satisfactory or excellent result, the authors found

this implant did not predictably improve glenohumeral instability and the manufacturer has discontinued its production. Close scrutiny of the implant used in this study also reveals that the pegs were perpendicular to the backside of the glenoid implant, rather than perpendicular to its articular surface.

Cil et al reviewed 38 patients treated with modified glenoid components and found a relatively high failure rate, with only 31% survival rate for patients treated with metal-backed posterior augmented glenoid component. Failure was often due to glenoid component loosening and these implants only demonstrated limited success in correcting subluxation.[8]

Limitations of this study include the synthetic scapula model used for testing, which is composed of a hard cortical shell and a synthetic cancellous foam interior. Our group's initial pilot testing was performed with cadaveric scapulae; however in doing so, we noted that the significant variability between the bone quality of the samples was having a much greater effect on implant stability than prosthesis design. All cadaveric specimens resulted in comminuted fractures far earlier than the proposed final outcome time point and failed due to material properties and dissolution of the bone in the heated, circulating water bath testing environment. As a result, cadaveric model was deemed inadequate for our study design. The synthetic scapulae provide a more consistent test bed than cadaveric specimens and are more anatomically relevant than foam blocks as performed in previous studies.[21; 29] The use of this synthetic bone model has been previously reported on in the literature for glenoid prosthesis testing.[30] Though the manufacturing of the synthetic scapulae result in circular shaped weak regions within the cortical shell, the locations of these regions are consistent in size and location among all specimens. These weak regions in the specimens may have influenced the cortical failure patterns observed in this study.

Additionally, there was potential variability in the loading parameters of each glenoid. This was minimized by the fact that specimens in both groups were oriented such that the glenoid face was directly perpendicular to the humeral head prosthesis, with the head centered along the superior-inferior axis of the glenoid. No posterior subluxation of the humeral head was present during testing. Lastly, all glenoid segments were potted in PMMA to the same anatomical location and height along the glenoid neck. As a result, slightly more unsupported bone was present in the posterior augment group than the eccentric reaming group due to the fact that more bone is preserved during implantation of the posterior augment glenoid components. Consequently, during edge loading specimens in the posterior augment group are exposed to slightly higher bending moments at the bone-potting cement interface. The extent to which this may have contributed to specimen loosening is unknown.

Conclusion

This investigation found significantly increased edge displacements and failure rates during cyclical testing in specimens prepared with an angle-backed posterior-augmented glenoid component when compared to those prepared with a standard glenoid component after eccentric reaming. The use of angle-backed posterior augment glenoid components may introduce shear stress across the glenoid bone interface during axial loading, potentially compromising stability and leading to early failure due to loosening. Further in vitro studies and long-term clinical investigations are needed in order to further evaluate this component design.

Figure 1:
Pegged polyethylene glenoid components used in this study. Eight-degree posterior augment glenoid component (left) and standard glenoid component (right).

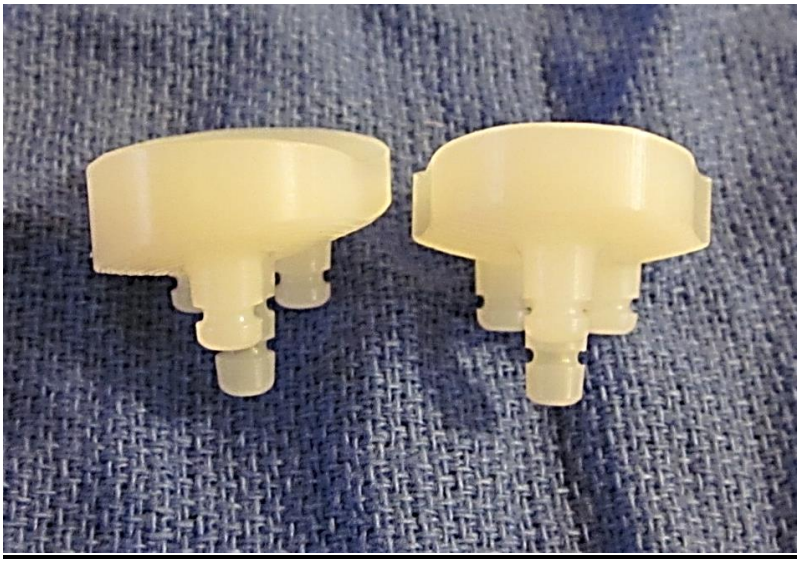

Figure 2:
Testing apparatus used to apply a constant axial load on the glenoid component and cyclic superior-inferior loads to the humeral head.

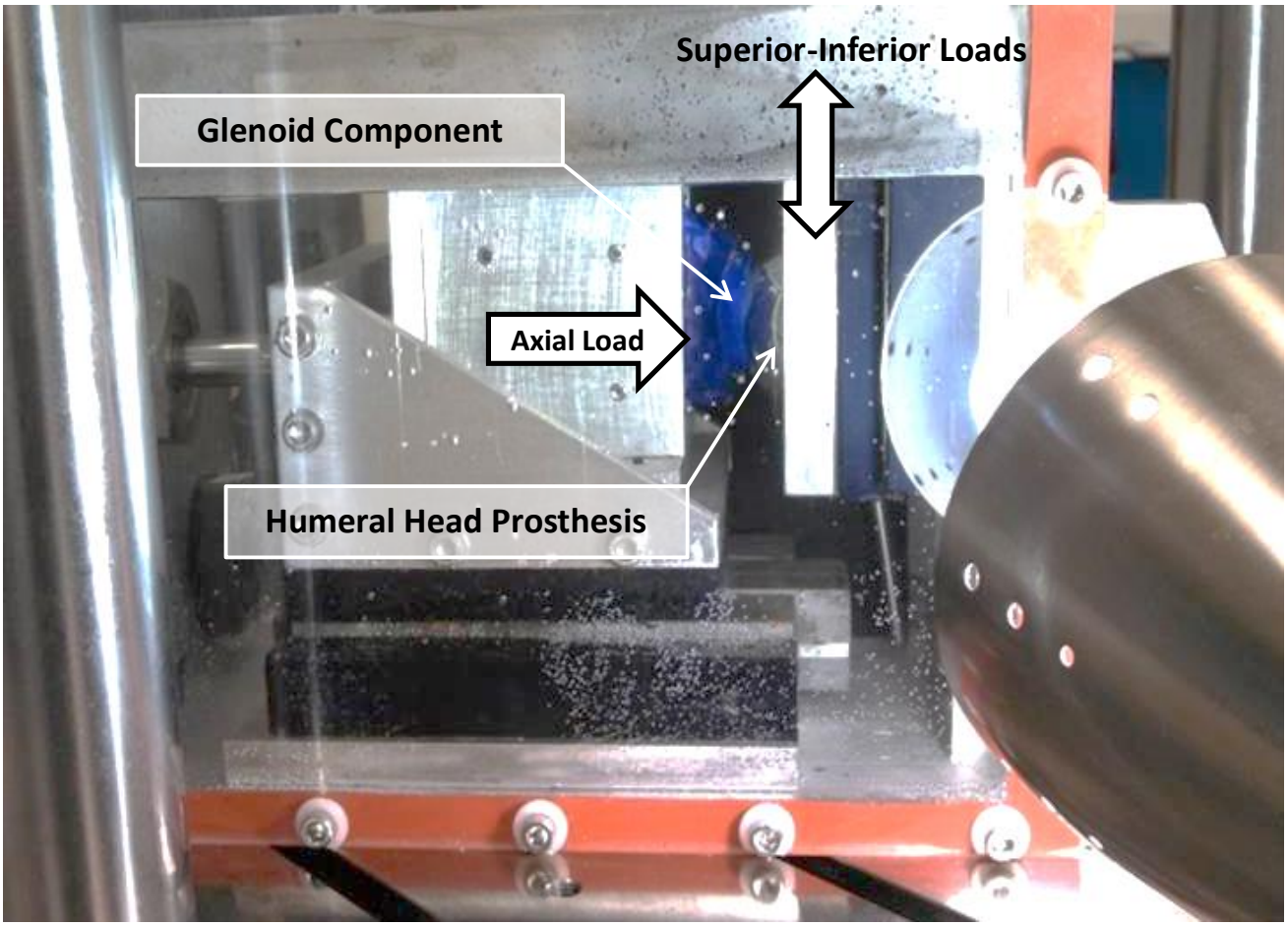

Figure 3:
Sample images recorded prior to testing (A, C) and post testing (B, D) for the eccentric reaming and posterior augment groups. Spherical markers used to measure edge displacements are attached to the superior and inferior edges of each specimen.

A) Eccentric Reaming: Initial

B) Eccentric Reaming: Post Test

C) Posterior Augment: Initial

D) Posterior Augment: Post Test

299 **Figure 4:**

300 Superior (A) and inferior (B) marker edge displacements perpendicular to glenoid plane during

301 superior edge loading. (Mean ± SD) *****Indicates statistically significant difference between groups

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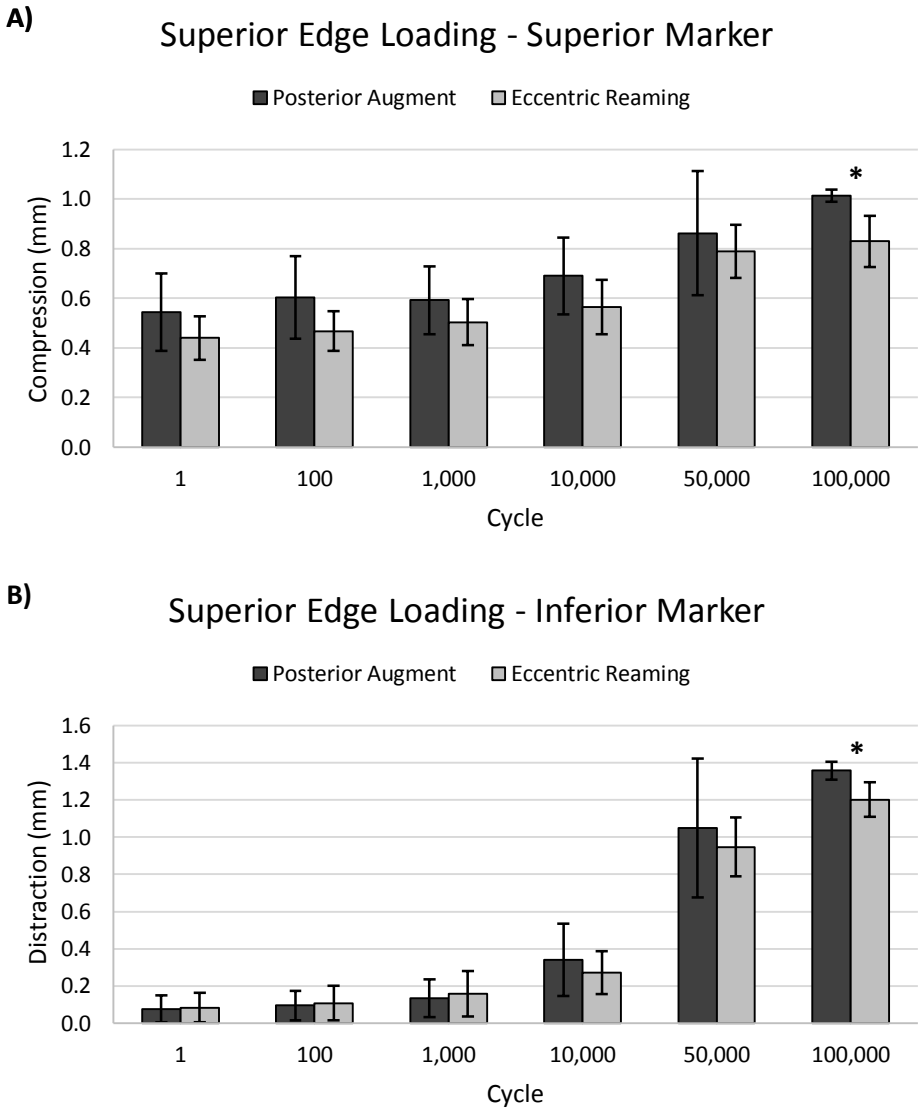

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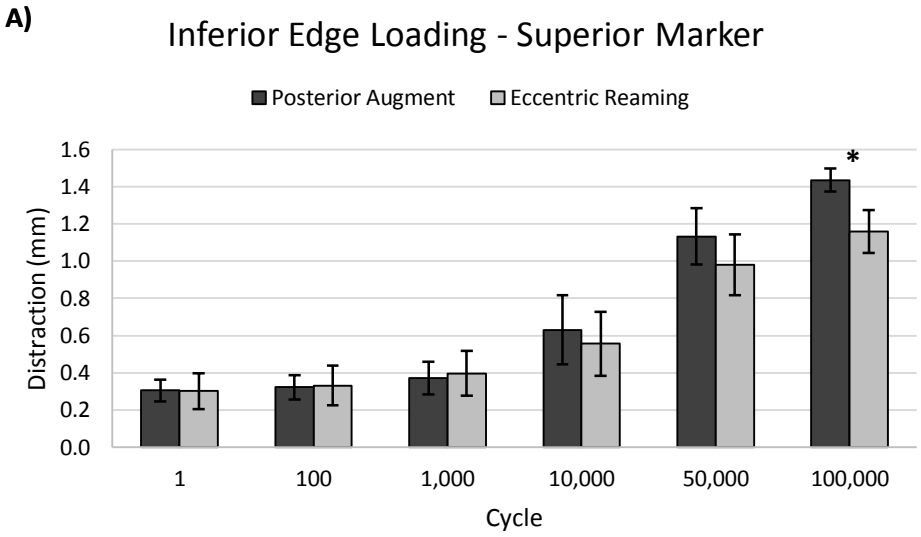
306 **Figure 5:**
307 Superior (A) and inferior (B) marker edge displacements perpendicular to glenoid plane during
308 inferior edge loading. (Mean ± SD) *****Indicates statistically significant difference between groups
309
310



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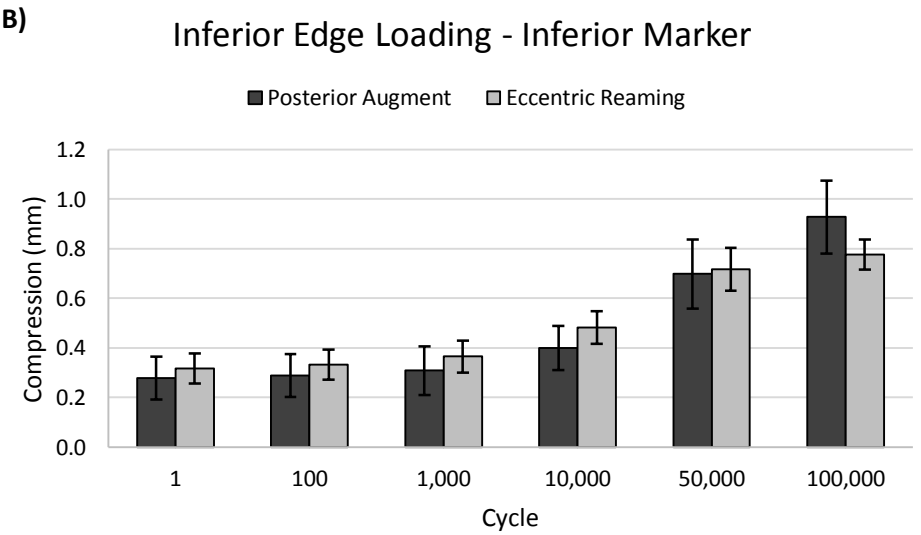

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Table 1: Specimen Survival Rate.

Total Cycles:	**1**	**100**	**1,000**	**10,000**	**50,000**	**100,000**
Posterior Augment	6/6	6/6	6/6	6/6	5/6	3/6
Eccentric Reaming	6/6	6/6	6/6	5/6	5/6	5/6

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