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Biomechanical comparison of zoned-conformity glenoid versus standard glenoid in total shoulder arthroplasty: impact on rotator cuff strain and glenohumeral translation

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Background: Current standard total shoulder arthroplasty glenoid implants allow for high levels of glenohumeral mismatch and associated high levels of humeral head translation to improve range of motion and reduce rim stresses on the glenoid. However, high levels of glenohumeral mismatch could also increase glenoid edge loading, eccentric wear, and rotator cuff strain. A zoned-conformity glenoid may be able to reduce the forces on the rotator cuff and glenoid. We compared rotator cuff strain and glenohumeral translation between a standard glenoid (SG) with moderate glenohumeral mismatch and a zoned-conformity glenoid (conforming glenoid [CG]) that limits mismatch. We hypothesized that the CG would have lower levels of strain on the rotator cuff and lower levels of humeral head translation compared with the SG.

Methods: Eight fresh frozen cadaveric shoulders, aged 72 years (range, 67-76 years), were used in this biomechanical study. The specimens were first tested in the intact state. We cycled them 3 times from 0° to 60° of abduction and measured the superiorly-inferiorly and anteriorly-posteriorly directed forces at the joint, compressive forces applied to the glenoid, and humeral head translation. The specimens were then implanted with a standard press-fit humeral component and a polyethylene glenoid with 3 peripherally cemented pegs and a central press-fit peg. Testing was repeated. Finally, the SG was removed, the CG was implanted, and each specimen was tested a third time.

Results: The average superiorly directed force at the glenohumeral joint was significantly lower in the intact and CG groups (18.1 ± 18.6 N and 19.8 ± 16.2 N, respectively) than in the SG group (29.3 ± 21.9 N, $P = .024$). The maximum force directed against the glenoid was also significantly lower in the CG group (87.6 ± 11.7 N) than in the SG (96.0 ± 7.3 N) and intact (98.9 ± 16.5 N) groups ($P = .035$). No difference was observed in humeral head translation in the anterior-posterior plane from 0° to 60° of abduction ($P = .998$) or in the superior-inferior plane ($P = .999$).

Conclusion: A zoned-conformity glenoid was associated with similar humeral head translation but significantly lower superior forces against the rotator cuff and a significantly lower maximum force against the glenoid compared with an SG implant. These biomechanical findings suggest that a zoned-conformity implant warrants further study in the effort to maintain humeral head translation while reducing rotator cuff and glenoid forces for successful outcomes of total shoulder arthroplasty.

Level of evidence: Basic Science Study; Biomechanics

Keywords: Shoulder arthroplasty; glenohumeral mismatch; rotator cuff strain; glenoid wear; glenohumeral biomechanics

Institutional review board approval was not required for this basic science study.

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Glenohumeral mismatch describes the difference in the radii of curvature between the humeral head and the glenoid. It allows for obligate translation of the humeral head on the glenoid during active and passive range of motion and contributes to shoulder mobility. The ideal glenohumeral mismatch in anatomic total shoulder arthroplasty (TSA) has not been well defined, with extensive variation in the mismatch of currently available implants, from 1 to 38 mm.[16] The original Neer prosthesis was a congruent system with identical radii of curvature between the glenoid and humeral head.[9] Newer implants typically have higher levels of mismatch to improve range of motion and avoid rim stresses on the glenoid; however, this may come at a cost.[16]

High levels of mismatch and subsequent high levels of glenohumeral translation can lead to edge loading, glenoid loosening, and catastrophic failure in TSA.[16] Clinical studies have identified mismatch between 6 and 10 mm as the ideal level for minimizing radiographic signs of loosening but found no correlation with clinical outcome scores.[19] Biomechanical studies have similarly found that mismatch $>$ 10 mm results in increased glenoid micromotion, surface wear, and polyethylene fracture.[1,14] High levels of mismatch and translation may also contribute to rotator cuff failure over time because of increased strain on the rotator cuff as it works to keep the humeral head centered. Cadaveric studies have shown increased translation when rotator cuff muscles are not loaded and in the setting of partial-thickness tears.[6,11] In vivo studies have similarly shown that contraction of rotator cuff muscles limits glenohumeral translation and translation increases in patients with symptomatic rotator cuff tears.[12,13] Computational models have provided further evidence of the increased forces on the rotator cuff as mismatch and translation increase in TSA.[10] Over time, these altered forces may compromise the rotator cuff.

Increasing the glenohumeral mismatch and translation in TSA can improve range of motion and reduce rim stresses compared with a conforming implant, but there are other implications for both glenoid loading and rotator cuff strain that must be considered. The aim of this study was therefore to compare the glenohumeral translation and rotator cuff strain between a standard TSA glenoid implant (standard glenoid [SG]) with moderate glenohumeral mismatch and a zoned-conformity implant (conforming glenoid [CG]) with minimal glenohumeral mismatch. We hypothesized that the CG would have lower levels of strain on the rotator cuff in the superior and anterior-posterior planes and lower levels of humeral head translation compared with the SG.

Materials and methods

Eight fresh frozen cadaveric shoulder specimens (6 female and 2 male specimens), aged 67-76 years (mean, 72 years; standard deviation, 3.6 years), were used in this biomechanical study. The specimens were thawed and diagnostic arthroscopy was performed before dissection to ensure that the specimens had no signs of arthritis and no rotator cuff tears. The specimens were then dissected, with removal of soft tissues but preservation of the pectoralis major, deltoid, latissimus dorsi, rotator cuff muscles, capsule, and coracoacromial arch. Krackow stitches with No. 2 polyester suture (Ethibond; Ethicon, Somerville, NJ, USA) were applied to the preserved muscle-tendon junctions for muscle loading. Specimens were kept moist using 9.9% saline solution during testing.

Testing conditions

All specimens were initially tested in the intact state to determine normal glenohumeral biomechanics (control group). After a specimen was tested in the intact state, a standard anatomic TSA was implanted including a stemmed anatomic humeral component (Aequalis; Wright Medical Group, Memphis, TN, USA) and cemented pegged glenoid component (Perform; Wright Medical Group) (SG group; Fig. 1). The deltopectoral interval was opened in each specimen, and the subscapularis was tenotomized just medial to its insertion on the lesser tuberosity. An anatomic head cut was made in each specimen, matching the native inclination and version. The glenoid was prepared, and the appropriate-size glenoid (Perform) was then cemented into place. Minimal centralized reaming was performed, and no changes in version were created. The humerus was then prepared for each specimen using the standard instrumentation, and the appropriate-size stem (Aequalis) was press fit into place. Humeral heads were trialed to re-create the normal anatomy including head size, diameter, thickness, and offset, and the appropriate humeral head size was then selected and impacted into position in each specimen. Mismatch between the selected humeral and glenoid implants was moderate by current standards, between 11.4 and 15.6 mm for all specimens. After the implant was placed, the subscapularis was anatomically repaired with a No. 5 nonabsorbable polyester suture (Ethibond), and a single lateral rotator interval closure suture was placed in each specimen.

After testing with these standard TSA components, each specimen was prepared for testing with the zoned-conformity glenoid implant (Ignite Orthopedics, Warsaw, IN, USA) (CG group; Fig. 1). The deltopectoral interval was reopened in each specimen, and subscapularis tenotomy was repeated. The SG component was carefully removed using a Cobb elevator to avoid damage to the glenoid. No glenoid fracture or compromise of the peg holes occurred in any specimen. The glenoid was then sized and prepared for the zoned-conformity glenoid and its central fluted peg fixation using the corresponding instrumentation (Fig. 2). The implant size was based on the appropriate size for the specimen to ensure full backside support and no overhang. The implant was placed low in the bottom circle of the glenoid, and fixation was achieved using the press-fit central fluted peg and peripheral cemented ring (Fig. 2). We were able to achieve full backside support and secure fixation to the glenoid with all of the CG implants because of the different positions and configurations of the pegs between the 2 implants. The same humeral component used for the standard TSA testing condition (Aequalis) was left in place. The subscapularis was anatomically repaired for a second time with a No. 5 nonabsorbable polyester suture (Ethibond), and a single stitch was again placed to close the rotator interval.

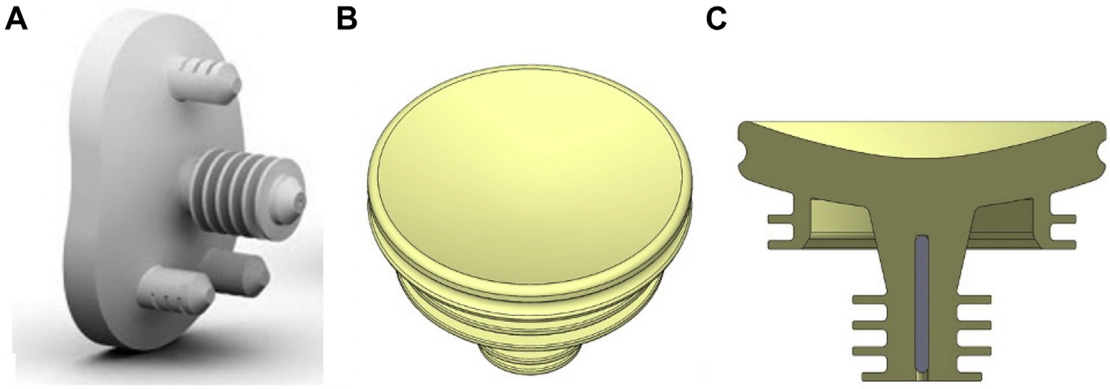

Figure 1 (**A**) Perform-Cortiloc glenoid (Wright Medical Group), with single radius of curvature. (**B, C**) Top-down and cross-sectional schemas of zoned-conformity glenoid (Ignite Orthopedics). The glenoid has multiple radii of curvature, allowing glenohumeral conformity regardless of humeral head size. Images courtesy of Wright Medical Group and Ignite Orthopedics, respectively.

Testing protocol

Each specimen was tested in all 3 conditions described earlier: intact, SG, and CG. Specimens were attached to a custom shoulder testing system with the scapula fixed to a central baseplate tilted 20° anteriorly in the sagittal plate. The humerus was fixed distally to a cup attached to an arch positioned to align the humerus in the scapular plane, allowing for controlled abduction and rotation. Adjustable pulleys allowed for loading of muscles to approximate physiological force vectors. The loading configuration was based on cross-sectional muscle-area measurements and electromyography studies.[7,8] We used an unbalanced condition to better simulate active abduction, with 80 N for the deltoid, 20 N for the supraspinatus, 20 N for the combined infraspinatus and teres minor, and 20 N for the subscapularis.[7] Previous studies have demonstrated that the unbalanced condition provides a more realistic testing scenario for rotator cuff loading by re-creating active abduction.[6,7]

The specimens were cycled on the frame from 0° to 60° of abduction, corresponding to 0° to 90° of glenohumeral abduction. A 6-axis load sensor was used to assess the force of the humerus at the glenohumeral joint in 3 different planes at a data acquisition rate of 100 Hz: superior-inferior plane, anterior-posterior plane, and a plane directed against the glenoid (Mini58E; ATI Industrial Automation, Apex, NC, USA). We recorded the average force for an entire cycle in each plane, in addition to the force in each plane with the specimen at 0° and 60° of abduction. Maximum forces in each plane were also recorded for each specimen in each testing condition. Finally, the humeral head position relative to the glenoid was recorded using a 3-dimensional digitizer with 0.3 mm of accuracy (MicroScribe 3DLX; Immersion, San Jose, CA, USA). Positioning was determined using 3 points on the scapula and 3 noncollinear points on the humerus. The position of the humeral head at 0° of abduction was set to 0 in the x-axis (anterior-posterior) and y-axis (superior-inferior). This zero point was reset for each specimen for each testing condition. Subsequent recordings

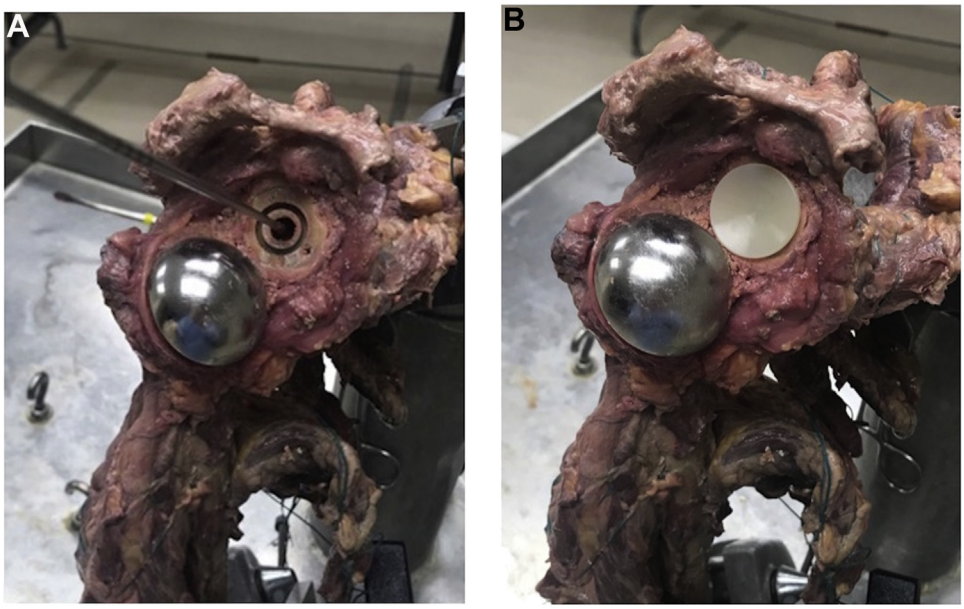

Figure 2 (**A**) Preparation of glenoid for conforming glenoid. The component uses a peripheral cemented ring and central fluted peg for stability. (**B**) Conforming glenoid cemented into place. The implant is positioned low in the bottom circle of the glenoid.

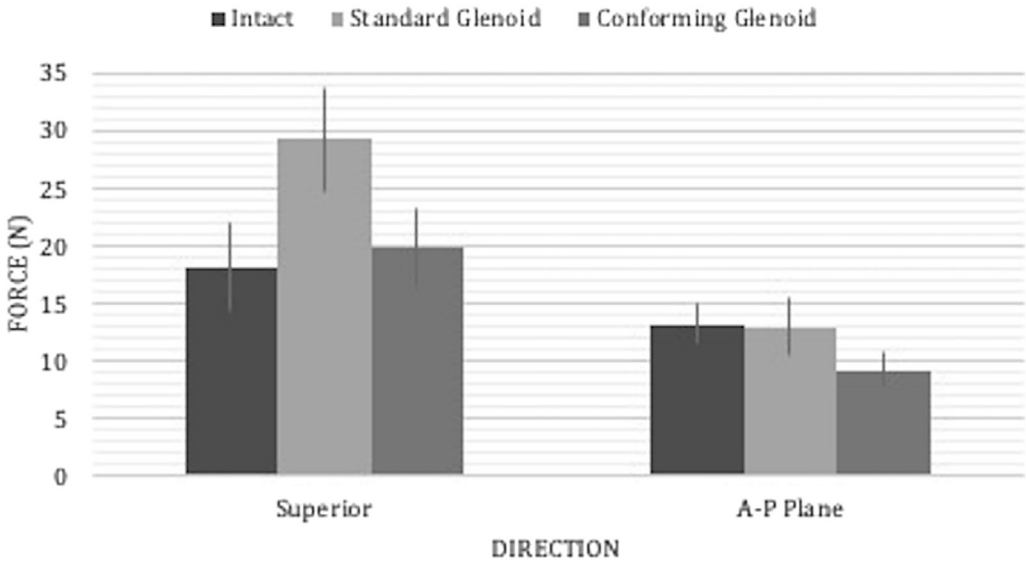

Figure 3 Average force against rotator cuff in superior-inferior and anterior-posterior *(A-P)* planes during abduction cycle. For the superior-inferior plane, all forces were directed superiorly. The absolute value of the anterior-posterior force was used because some specimens had forces directed posteriorly and some specimens, anteriorly. Either direction is indicative of strain on either the posterior or anterior rotator cuff and is thus relevant. The error bars represent the standard error of the mean.

were made at 30° and 60° of abduction, corresponding to 45° and 90° of shoulder abduction. The difference in the humeral head position relative to the glenoid from the zero point was recorded in both the x- and y-planes. A vector was also calculated to define the distance the humeral head moved as a combination of anterior-posterior and superior-inferior translation from 0° to 60° of abduction.

Data analysis

Data analysis was performed using Excel (2011 release; Microsoft, Redmond, WA, USA) and SigmaStat (version 4.0; Systat Software, Chicago, IL, USA). Descriptive statistics were used to characterize average forces and humeral head positions for specimens in the different test conditions. One-way analysis of variance was performed to compare the 3 different testing conditions—intact, SG, and CG—in terms of translation and forces on the rotator cuff. Statistical significance was set at $P < .05$. Our sample size was determined by an a priori power analysis based on a prior biomechanical study[15] that compared glenoid compression and translation with varying amounts of glenohumeral mismatch. The power analysis indicated that 8 samples were needed for each testing condition to detect a statistically significant difference in humeral head position at the $P = .05$ level with a power of 0.8.

Results

All specimens were cycled through all 3 testing conditions without any fractures or implant failures. The subscapularis tenotomy repair was inspected throughout all 3 rounds of testing, and there was no evidence of suture cutout or loosening at any point.

Force

The average superiorly directed force against the rotator cuff at the glenohumeral joint was significantly lower in the CG group (19.8 ± 16.2 N) and control group (18.1 ± 18.6 N) than in the SG group (29.3 ± 21.9 N) ($P = .024$; Fig. 3). At both minimum (0°) and maximum (60°) abduction, there was no difference in the superiorly directed forces in the CG group and control group compared with the SG group ($P = .180$ for minimum abduction and $P = .719$ for maximum abduction; Fig. 4, *A*). The average maximum force in the superior plane was 44.6 ± 18.6 N in the CG group, 45.5 ± 8.4 N in the control group, and 52.0 ± 18.8 N in the SG group ($P = .430$).

In the anterior-posterior plane, the CG group exerted an average force of 9.3 ± 7.7 N on the rotator cuff, which was not significantly different from that in the control group (13.2 ± 8.3 N) or SG group (13.0 ± 12.6 N) ($P = .118$; Fig. 3). At both minimum and maximum abduction, the CG group did not significantly differ from the control and SG groups ($P = .156$ for minimum abduction and $P = .531$ for maximum abduction; Fig. 4, *B*). The average maximum force in the anterior-posterior plane was 18.8 ± 6.3 N in the CG group vs. 23.3 ± 13.1 N in the SG group and 26.1 ± 9.8 N in the control group ($P = .236$).

The average force against the glenoid was consistent across the groups: 73.5 ± 25.2 N in the control group, 69.2 ± 22.1 N in the SG group, and 69.1 ± 19.6 N in the CG group ($P = .440$). However, the CG group had a significantly lower average maximum force of 87.6 ± 11.7 N compared with the SG group (96.0 ± 7.3 N) and control group (99.0 ± 16.5 N) ($P = .035$; Fig. 5).

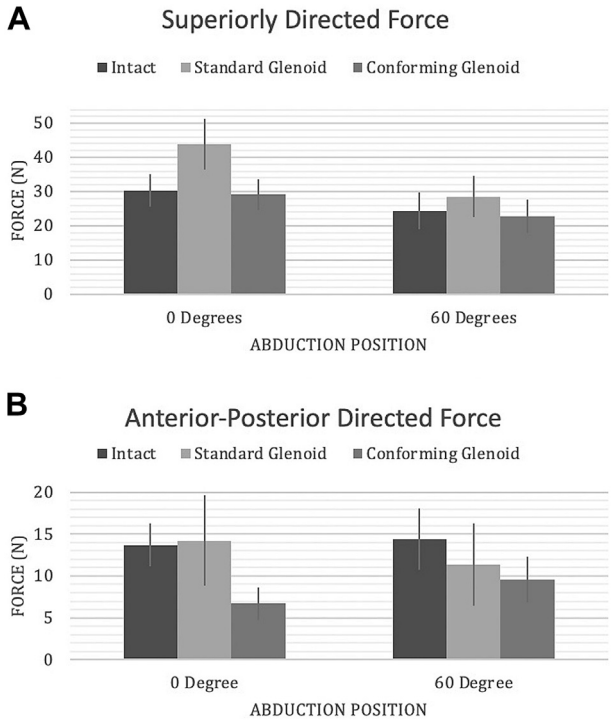

Figure 4 (**A**) Average force directed superiorly at 0° and 60° of abduction. The error bars represent the standard error of the mean. (**B**) Average force directed in anterior or posterior direction at 0° and 60° of abduction. The absolute value of the force was used because both anterior (positive) and posterior (negative) forces are relevant and direction varied by specimen. The error bars represent the standard error of the mean.

Translation

We observed no difference in humeral head translation in the anterior-posterior plane from 0° to 60° of abduction (3.1 ± 35.9 mm in the control group, 3.7 ± 15.7 mm in the SG group, and 2.9 ± 7.3 mm in the CG group; $P = .998$) or in the superior-inferior plane (9.4 ± 29.1 mm, 9.6 ± 12.6 mm, and 10.0 ± 13.2 mm, respectively; $P = .999$). The average calculated vector distance for the humeral head going from 0° to 60° was 34.0 ± 30.7 mm for the control group, 20.0 ± 10.5 mm for the SG group, and 17.6 ± 5.4 mm for the CG group ($P = .234$).

Discussion

In this study, a zoned-conformity glenoid in TSA showed a significantly lower force at the glenohumeral joint superiorly and lower maximum force against the glenoid itself compared with an SG, with no significant differences in humeral head translation. A zoned-conformity glenoid may allow for similar humeral head translation compared with an implant with higher mismatch while reducing the load on the rotator cuff and against the glenoid during range of motion.

Our superior-inferior and anterior-posterior plane translation data are consistent with data in other cadaveric studies, in which 1-10 mm of humeral head translation has been reported with passive glenohumeral motion.[3,6] One computational study of humeral head translation in TSA found up to 3.1 mm of translation in the anterior-posterior plane but only up to 0.4 mm of translation in the superior-inferior plane.[10] This contrast with our findings is likely because of differences between our unbalanced cadaveric model designed to replicate active abduction and a computational model that measured translation in a static equilibrium state. Because humeral head translation is critical for shoulder range of motion, our results demonstrating similar translation with a zoned-conformity glenoid compared with a higher-mismatch implant are important to note. Future clinical studies are needed to confirm the concomitant maintenance of range of motion with a zoned-conformity glenoid.

The success of an anatomic TSA relies on a functional rotator cuff. Rotator cuff failure was responsible for 15% of TSA failures (257 of 1673) in 1 large database study,[18] and some form of rotator cuff dysfunction was identified in 16% of TSAs (87 of 518) at 10 years in a large multicenter study.[20] A decrease in forces on the rotator cuff over an extended period could have the potential to decrease the rate of rotator cuff failure after TSA. We found lower superior forces against the rotator cuff with a zoned implant compared with a standard implant despite no differences in humeral head translation. In addition to the increased glenoid conformity, the low anatomic positioning of the prosthesis on the glenoid may contribute to the lower forces on the rotator cuff. Positioning of glenoid implants can have a significant impact on rotator cuff strain, with low implant positioning potentially reducing strain on the superior rotator cuff.[5] A conforming implant in a low position on the glenoid can also maintain the humeral head in that lower position, further reducing rotator cuff strain.

The CG group also showed lower maximum forces against the glenoid implant itself compared with the SG group, an important biomechanical parameter given that glenoid loosening is the most common reason for TSA failure.[2,18] Although studies have demonstrated that varying the amount of glenohumeral mismatch appears to impact glenoid wear patterns, no consensus on the optimal glenohumeral mismatch in TSA has been reported. One study found that mismatch between 6 and 10 mm minimized radiolucencies on radiography at 2 years.[19] Another reported an association between increased radiolucencies and glenohumeral mismatch < 4.5 mm.[4] Other studies have shown that too much glenohumeral mismatch can also be problematic, with mismatch > 10 mm resulting in greater glenoid micromotion and polyethylene fracture.[1,14]

The zoned-conformity glenoid differs from other implants with little to no glenohumeral mismatch, such as the original Neer prosthesis, which may explain its more favorable biomechanical parameters, such as maintenance

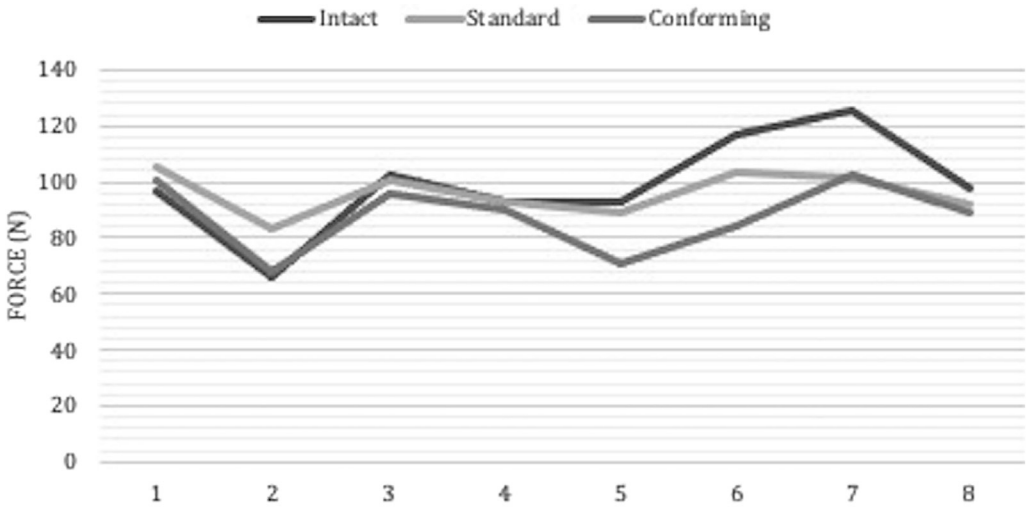

Figure 5 Maximum force against glenoid (in newtons) for each specimen in each testing condition.

of translation and lower maximum forces on the glenoid. The zoned-conformity glenoid combines multiple radii of curvature to conform with whatever portion of the humeral head is articulating throughout the range of motion. The Neer prosthesis and other prostheses without mismatch are actually constrained implants. The single radius of curvature of these implants was shown to reduce the portion of the humeral head that could articulate with the glenoid and to limit humeral head translation.[14] By conforming, not constraining, the zoned-conformity glenoid is able to maintain humeral head translation with lower forces on the rotator cuff and glenoid.

This study has limitations. It was a cadaveric study, and tissues may not have had the same quality and response to forces as living tissues. We used the same 8 specimens for each testing condition to minimize any tissue differences between specimens that could impact force or translation results. Subscapularis tenotomy repair has been shown in previous cadaveric studies to withstand force and cyclic loading beyond the test conditions used in our study.[17] We compared only 1 commercially available TSA implant with the new implant. The implant system we chose had glenohumeral mismatch in the mid range of currently available implant systems. Future studies should examine rotator cuff strain in other implant systems with different degrees of mismatch, particularly lower degrees of mismatch that may be less likely to cause glenoid lucencies. Finally, this was a time-zero biomechanical study, and therefore, the effect of repeated forces over time could not be assessed.

Conclusion

A zoned-conformity glenoid was associated with similar humeral head translation but significantly lower superior forces against the rotator cuff and a significantly lower maximum force against the glenoid compared with an SG implant. These biomechanical findings suggest that a zoned-conformity implant warrants further study in the effort to maintain humeral head translation while reducing rotator cuff and glenoid forces for successful outcomes of TSA.

Disclaimers

Wright Medical Group donated the standard TSA implants, and Ignite Orthopedics donated the zoned-conformity implants.

Anand M. Murthi is a board or committee member of American Academy of Orthopaedic Surgeons, American Shoulder and Elbow Surgeons, and American Shoulder and Elbow Surgeons Foundation; is on the editorial or governing board of *American Journal of Orthopedics*, *Current Orthopaedic Practice*, *Journal of Shoulder and Elbow Arthroplasty*, and *Journal of Shoulder and Elbow Surgery*; receives publishing royalties and financial or material support from *American Journal of Orthopedics*, *Current Orthopaedic Practice*, and Wolters Kluwer Health–Lippincott Williams & Wilkins receives research support from Arthrex; receives intellectual property royalties from Globus Medical and Ignite Orthopedics; is a paid consultant for Globus Medical and Ignite Orthopedics; and is on the scientific advisory board of Catalyst Shoulder.

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