The effect of humeral polyethylene insert constraint on reverse shoulder arthroplasty biomechanics

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Abstract

Background: There is little information on the effects of altering reverse shoulder arthroplasty (RSA) polyethylene constraint on joint load, load angle and deltoid force. The present biomechanical study aimed to investigate the effects of changing RSA polyethylene constraint on joint load, load angle, deltoid force and range of motion.

Methods: A custom RSA implant capable of measuring forces across the joint with varying polyethylene constraint was tested in six cadaveric shoulders. Standard-, low- and high-constraint (retentive) polyethylene liners were tested, and joint kinematics, loads and muscle forces were recorded.

Results: When polyethylene constraint was altered, joint load and load angle during active abduction were not affected significantly ($p > 0.19$). Additionally, the force required by the deltoid for active abduction was not affected significantly by cup constraint ($p = 0.144$). Interestingly, active abduction range of motion was also not affected significantly by changes in cup constraint ($p > 0.45$).

Conclusions: Altering polyethylene cup constraint in RSA to enhance stability does not significantly alter resultant joint loads and deltoid forces. Surprisingly, terminal abduction range of motion was also not significantly different with varying cup constraint, indicating that terminal impingement may be tuberosity related rather than polyethylene.

Keywords

complication, constraint, instability, polyethylene, reverse total shoulder arthroplasty, rotator cuff tear arthropathy

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Introduction

Reverse shoulder arthroplasty (RSA) is a common and successful treatment option for cuff tear arthropathy, arthritis, complex fractures and as a revision procedure for failed primary arthroplasty.^{1–9} RSA aims to invert the natural geometric anatomy of the glenohumeral articulation where the humerus is converted into a socket and the glenoid is converted into a ball, at the same time as medializing and distalizing the joint centre of rotation. This configuration constrains the joint to increase stability and creates a fixed and more efficient fulcrum for the deltoid to elevate the arm when preventing superior humeral migration during abduction.^{10,11} Clinical studies have provided evidence of substantial functional improvements as well as decreased pain following RSA.

Implant instability is a complication that can be encountered intra-operatively and/or postoperatively

following RSA. A surgical management option for instability is use of a polyethylene insert with increased constraint (or increased cup depth) to achieve implant stability. Alternatively, in an attempt to increase range of motion (ROM), some implant manufacturers offer high mobility polyethylene inserts, which have decreased cup depth. These lower-constraint inserts are theorized to allow greater ROM before insert related impingement that blocks further motion. Computer-based collision detection and finite element studies have suggested that the level of polyethylene constraint

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Figure 1. Custom modular instrumented reverse total shoulder arthroplasty implant (left) with load sensing device (A), glenoid base plate (B), glenosphere (C), adjustable humeral insert constraint level (D) and humeral component (E); as well as the three humeral cup constraints investigated (right) including low-constraint, normal, and high-constraint. The implant centre of rotation is constant for all constraints tested, and shown as a blue cross at the centre of the glenosphere.

influences ROM, joint stability and articular contact stresses,¹² although there is a paucity of information regarding the effects of constraint on joint load and resultant joint load angle.¹³ Also, it is anecdotally assumed that increasing polyethylene constraint increases stresses on the glenoid base plate with increased shear and altered joint loading. Additionally, no clinical or cadaver-based studies exist that confirm the findings of the computer-based studies with respect to ROM. The present *in vitro* biomechanical study aimed to investigate the effects of altering humeral polyethylene insert constraint on joint load, joint load angle, deltoid force and ROM in RSA. We hypothesized that loading parameters would not be significantly different as a result of the unaltered centre of rotation, and that ROM would decrease with increased constraint.

Materials and methods

Modular instrumented RSA implant

A custom modular RSA implant system was used that allowed for polyethylene insert constraint to be changed and the articular joint load to be measured using an integrated six degrees-of-freedom load sensor (Nano25; ATI-IA, Apex, NC, USA), which was inserted between the native glenoid baseplate and the glenosphere (Figure 1).

One of three commercially available polyethylene inserts (Delta XTEND; Dupuy, Warsaw, IN, USA) of varying cup depths, including low- (shallow cup),

standard- (normal) and high-constraint/retentive (deep cup), were affixed to the custom humeral component, which was configured to have a 155° head-neck angle and 0° retroversion. The glenoid base plate was fixed to the lowest rim of the glenoid, placing it as low as possible, with the centre of rotation at the glenoid articulation.⁷

Shoulder preparation and testing protocol

The instrumented RSA construct was implanted into in six fresh-frozen cadaveric shoulders [mean (SD) age: 73 (8) years] using the delto-pectoral approach. The shoulders were pre-screened to exclude those with trauma, prior surgery and/or anatomic deficits. Access to the glenohumeral joint was achieved by elevating the subscapularis muscle off the scapula with preservation of its tendinous attachment to the proximal humerus. Complete tears of the supraspinatus and the superior infraspinatus tendons were then simulated via resection. The six degrees-of-freedom load cell was buried into the glenoid vault, such that the glenoid base plate was positioned flush and on the inferior rim of the glenoid, resulting in the centre of rotation being located at the articular surface. Humeral lengthening was standardized by consistently aligning the lateral edge of the cup with the greater tuberosity of the humerus. The three deltoid heads were affixed at their insertion mid-humerus, and the musculotendinous junctions of the rotator cuff were secured with a running locking stitch. The scapula was then cemented into a shoulder simulator capable of independently loading the muscles

Figure 2. Lines of action of the three heads of the deltoid (red), infraspinatus (green), and subscapularis (orange) muscles.

around the shoulder girdle to produce active glenohumeral and scapulothoracic motion, and optical trackers were affixed to both the scapula and to an intramedullary rod inserted into the humerus (OptoTrak Certus; NDI, Waterloo, ON, Canada). All muscles were coupled to pneumatic load actuators using physiologic lines-of-action (Figure 2) and loading was dictating using a previously validated kinematics driven muscle loading control system.¹⁴

For each shoulder, the testing order of the constraint conditions was randomized. Three humeral polyethylene insert conditions were tested (low-, standard- and high-constraint) using a 38-mm diameter polyethylene insert/glenosphere combination. For each condition, active abduction was simulated from 0° (or the minimum allowed by implant impingement) to 90° at 1°/second with scapular rotation applied at a 2: 1 glenohumeral-to-scapulothoracic ratio.¹⁵ Internal rotation (IR) and external rotation (ER) ROM were assessed at 0° of flexion/extension and abduction both actively and passively. Maximum active IR was recorded when the subscapularis, infraspinatus and anterior deltoid muscles were ramped to 38 N, 6 N and 6 N, respectively. Maximum ER ROM was recorded when the infraspinatus, subscapularis and posterior deltoids and middle deltoids were ramped to 27 N, 9 N, 8 N and 6 N, respectively. These muscle loads were derived from loading ratios in the literature for these two motions.^{16,17} Passive testing was performed with 0.8 Nm of torque

applied to the humerus, whereas the deltoids and rotator cuff tendons were loaded to 5 N and 7.5 N, respectively.^{18,19} Passive abduction and adduction ROM of the humerus was recorded when the humerus encountered bony, implant or soft tissue resistance. This angle was identified as that corresponding to the point in time at which a rapid change in the loading data was recorded by the glenoid load sensor as a result of implant impingement with gapping open or decoaptation.

Outcome variables and statistical analysis

The effects of polyethylene constraint on joint load, joint load angle and total deltoid force during active abduction was measured at 7.5° increments between 22.5° and 82.5° of abduction, which was the range over which all specimens achieved active abduction. The effect of polyethylene constraint on ROM was assessed using peak internal rotation and external rotation angles, and peak adduction and abduction angles for both active and passive testing.

A two-way (polyethylene constraint, abduction angle) repeated measure analysis of variance was carried out for joint load, joint load angle and deltoid force ($p < 0.05$ was considered statistically significant) and a paired *t*-test was conducted for the ROM outcomes. Sample size calculations were performed for each outcome variable and it was shown that ≥80% power could be achieved in each with the use of six specimens.

Results

No significant effects on RSA joint load were detected throughout active abduction when the polyethylene insert constraint was altered ($p=0.42$). Joint load was lowest at the beginning of active abduction and reached maximum levels during mid-abduction. The mean (SD) maximum loads achieved were 62 (9), 64 (9) and 62 (9) percent of body weight (%BW) for the low-, standard- and high-constraint polyethylene inserts, respectively, at an abduction angle of approximately 60° (Figure 3).

Mean (SD) joint load angle decreased as abduction angle increased (Figure 4), ranging from 32 (6)°, 36 (8)° and 34 (6)° at the beginning of abduction to 12 (6)°, 14 (6)° and 14 (4)° at the end of abduction for the low-, standard- and high-constraint polyethylene inserts, respectively. No significant effects were detected for polyethylene constraint on joint load angle ($p=0.186$). A joint load angle of zero degrees indicates pure compression on the baseplate, whereas positive angle values indicate superiorly directed and negative angles indicate inferiorly directed loads.

When polyethylene insert constraint was altered, we did not find a significant effect on total deltoid force

required to achieve active abduction ($p=0.144$) (Figure 5), which reached maximum values of 66 (7), 69 (9) and 67 (9) %BW for the low-, standard- and high-constraint polyethylene inserts, respectively.

No significant differences in abduction ROM were detected between the low-, standard- and high-constraint polyethylene inserts ($p>0.5$ for all). The peak adduction angles obtained for the low-, standard- and high-constraint polyethylene inserts were -1 (7)°, 0 (4)° and -1 (8)°, respectively, and the peak abduction angles obtained were 81 (8)°, 79 (10)° and 79 (9)°, respectively (Figure 6).

With respect to both passive and active internal and external rotation, no statistically significant differences were found when the standard polyethylene insert was replaced with the low-constraint insert ($p>0.242$ for passive, $p>0.241$ for active) or with the high-constraint insert ($p>0.368$ for passive, $p>0.150$ for active). However, when comparing the low-constraint insert [mean (SD) external rotation 57 (26)°] with the high-constraint insert [mean (SD) external rotation 51 (27)°], there was a statistically

Figure 3. Mean (SD) reverse shoulder arthroplasty joint load versus abduction angle for all three polyethylene insert constraints investigated (low-, standard- and high-constraint). BW, body weight.

Figure 4. Mean (SD) reverse shoulder arthroplasty joint load angle as a function of abduction angle for all polyethylene constraints investigated (low-, standard- and high-constraint).

Figure 5. Mean (SD) deltoid force required to achieve active shoulder abduction versus abduction angle for all three polyethylene insert constraints investigated (low-, standard- and high-constraint). BW, body weight.

Figure 6. Mean (SD) abduction arc of motion for all three polyethylene insert constraints investigated (low-, standard- and high-constraint). ROM, range of motion.

Figure 7. Mean (SD) passive (top) and active (bottom) range of motion in internal (left) and external (right) range of motion for all three polyethylene insert constraints investigated (low-, standard- and high-constraint). ROM, range of motion.

significant increase in passive external rotation ($p = 0.038$) (Figure 7).

Altering polyethylene constraint was found to significantly affect the angle between the joint load and the edge of the polyethylene cup ($p < 0.001$) (Figure 8). The standard insert had a mean joint load to polyethylene cup edge angle of 50 (5)° throughout abduction, whereas the low-constraint polyethylene insert had a lower mean angle of 40 (5)° ($p < 0.001$) and the high-constraint polyethylene insert had a higher angle of 62 (4)° ($p < 0.001$).

Discussion

Obtaining and maintaining a stable articulation is a vital component to the success of total joint arthroplasty. Similar to total hip arthroplasty,^{20,21} increasing cup constraint in reverse total shoulder arthroplasty has been shown to enhance overall stability of the prosthesis.²² However, very little has been carried out aiming to investigate the effects of increasing polyethylene constraint on joint load, load angle, deltoid force and ROM in reverse total shoulder arthroplasty.

Knowledge of the joint load and the load angle, especially as it pertains to a reverse total shoulder arthroplasty implant, is important because it characterizes the magnitudes and types of forces experienced by the modular connections, the bearing surface and the implant, including the glenoid baseplate. Increased forces, and in particular shear, can affect glenoid baseplate fixation and may result in incomplete bone

Figure 8. Mean (SD) angles between joint load and polyethylene cup edge throughout abduction for all three insert constraints investigated (low-, standard- and high-constraint).

ongrowth or possibly implant failure. Our findings suggest that increasing polyethylene constraint to enhance joint stability will have limited effect on the resultant joint load. Therefore, the baseplate does not experience increased shear with increased constraint. This is counter intuitive to traditional idea that increasing RSA constraint will increase glenoid baseplate shear and potential failure. The results of this study support our hypothesis and are logical because the centre of rotation is unchanged when increasing or decreasing polyethylene constraint in an already constrained articulation.

The deltoid is the most important muscle group with respect to achieving functional abduction in reverse total shoulder arthroplasty. We found that deltoid force did not substantially change with increased polyethylene constraint. This finding is important because any implant configuration or joint position that places increased demands on the deltoid muscle could lengthen the time for recovery of active abduction after surgery, increase deltoid fatigue in the longer term, and/or potentially increase the risk of acromial stress fractures.^{23,24} Our finding that the required deltoid muscle force for achieving active abduction was not substantially increased with increasing constraint suggests that deltoid fatigue may not be an important consideration when increasing humeral polyethylene constraint to obtain optimal stability.

In the present study, increasing polyethylene constraint increased the distance between the joint load and the edge of the polyethylene insert by virtue of the larger contact area provided by the deeper insert, which results in less edge loading of the polyethylene. A retrieval study by Day et al.²⁵ found that inferior rim damage was the predominant feature of polyethylene damage in reverse total shoulder arthroplasty. Therefore, moving the joint load away from the edge of the cup by increasing constraint, as seen in the present study, may have a positive impact on wear characteristics and long term RSA performance by reducing edge loading. However, this increased constraint may also have a negative impact by increasing scapular impingement that may occur as a result of the increased inferomedial overhang of the deeper polyethylene insert. Further studies are required to assess both of these factors to determine at what point an optimized design can be created that maximizes wear characteristics and minimizes notching.

Interestingly, in the present study, we found that abduction ROM was not significantly different with increasing polyethylene insert constraint. This was unexpected, particularly because Gutierrez et al.¹³ have reported in a computer-simulated study that the combination of placing the glenoid component inferiorly, as we did in the present study, and increasing polyethylene constraint significantly reduced abduction ROM. We suspect that the variance from the computer-simulation study of Gutierrez et al.¹³ likely occurred because we used cadaveric specimens, which more closely replicate the scenario *in situ*, which resulted in terminal motion restriction by soft tissue and/or bony impingement, rather than implant-related, or constraint-related restriction. Additionally, during implantation, we endeavoured to place our glenoid component in the optimum position, as inferior as possible on the glenoid to limit impingement. It is conceivable that, if the glenoid implant would have been placed more superior, constraint-related differences in polyethylene impingement would have been more apparent. Our results with rotational ROM, however, were significantly affected by polyethylene insert constraint. As polyethylene constraint increases, there is a statistically significant reduction in active external rotation. Interestingly, there were no significant differences with passive external rotation or active/passive internal rotation. Additionally, the increased external rotation obtained with the low-constraint polyethylene insert occurred past 30° of external rotation, which may not be clinically achievable in patients with rotator cuff tear arthropathy.

As with all biomechanical cadaveric studies, our research does have some limitations. Using cadavers makes it difficult to replicate precise physiological conditions, such as soft tissue properties; however, this is

somewhat mitigated in this investigation of reverse total shoulder arthroplasty because many soft tissues are released as part of the study protocol to replicate clinical rotator cuff tear arthropathy. Furthermore, it should be noted that the muscle groups loaded in the present study were not representative of all patients treated with reverse total shoulder arthroplasty because some patients have complete rotator cuff disruption, whereas we chose to simulate cuff tear arthropathy with an intact posterior infraspinatus and teres minor.

There are several strengths to the present study. First, direct measurement of the joint loading at the glenosphere produces a more accurate description of loading that avoids the introduction of errors, which can occur when measurements are taken using instrument scapular mounts. Indirect measurement may also suffer for inaccuracy introduced by extra-articular loads caused (e.g. by muscle wrapping).^{7,14} Second, the present study was able to combine measurements of both shoulder function (ROM) and loading characteristics (magnitude and direction of force) not yet reported in the literature. Finally, our simulator controls muscle loading in real-time and can adjust for specimen-to-specimen anatomical variations rather than applying *a priori* muscle loads, which may not accurately produce the desired motion. This was important in our ability to obtain consistent and physiologically relevant measurements for our outcomes.

Conclusions

Increasing polyethylene constraint in RSA to enhance implant stability does not significantly alter resultant joint loads, glenoid baseplate shear or deltoid forces. These findings are logical because the centre of rotation is unchanged in an already highly constrained articulation. Increasing polyethylene constraint also does not significantly affect abduction ROM because terminal motion was limited by bone and/or soft tissue structures rather than polyethylene insert impingement in an ideally placed glenosphere. However, active external rotation was significantly decreased with increased polyethylene insert constraint. Finally, joint load migrated further from the edge of the polyethylene insert (was more centrally located in the polyethylene) when constraint was increased. Overall, in our biomechanical simulator model increasing polyethylene constraint, with the aim of enhancing stability in a clinically unstable arthroplasty scenario, had minimal effects on RSA kinematics.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: The authors (Irfan Abdulla, Dan

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