ABSTRACT:

Introduction: There is disagreement regarding whether, when possible, the rotator cuff should be repaired in conjunction with reverse total shoulder arthroplasty (RTSA). Therefore, we investigated the effects of rotator cuff repair in RTSA models with varying magnitudes of humeral and glenosphere lateralization (HLat & GLat).

Methods: Six fresh-frozen cadaveric shoulders were tested on a validated in-vitro muscle driven motion simulator. Each specimen was implanted with a custom adjustable, load-sensing RTSA after creation of a simulated rotator cuff tear. The effects of 4 RTSA configurations (0&10mm x HLat & GLat) on deltoid force and joint load during abduction with/without rotator cuff repair were assessed.

Results: Increasing HLat and GLat significantly affected deltoid force (-2.5±1.7%BodyWeight %BW, p=0.016 & +7.7±5.6%BW, p=0.016). Rotator cuff repair interacted with HLat & GLat (p=0.005) such that with no HLat, GLat increased deltoid force without cuff repair (8.1±5.1%BW, p=0.012) and this effect was increased with cuff repair (12.8±7.8%BW, p=0.010), but addition of HLat mitigated this effect. Rotator cuff repair increased joint load (+11.9±5.1%BW, p=0.002), as did GLat (+13.3±3.7%BW, p<0.001), and these interacted such that increasing GLat markedly increases cuff repair's negative effects (9.4±3.2%BW, p=0.001 vs 14.4±7.4%BW, p=0.005).

Conclusion: Rotator cuff repair, especially in conjunction with GLat, produces an antagonistic effect that increases deltoid and joint loading. The long-term effects of this remain unknown; however, combining these factors may prove undesirable. HLat improves joint compression through deltoid wrapping and increases the deltoid’s mechanical advantage. Therefore, it could be used in place of rotator cuff repair, thus avoiding its complications.

Level of Evidence: Basic Science Study
Rotator Cuff is Antagonist Following RTSA

24 Keywords: Reverse Total Shoulder Arthroplasty, RTSA, RSA, shoulder, rotator cuff, simulator,
25 cuff tear arthropathy
INTRODUCTION:

Reverse Total Shoulder Arthroplasty (RTSA) is primarily indicated for the treatment of rotator cuff tear arthropathy or massive rotator cuff tears that are deemed irrepairable\(^9,15,17,20\). Despite these indications, it is often possible to repair portions of the subscapularis and infraspinatus/teres minor; however, there is disagreement regarding whether these tissues should be repaired as their effects on RTSA biomechanics and outcomes remain unclear\(^6,7,10,16\). Additionally, the indications for RTSA have expanded to include surgical conditions with an intact rotator cuff, such as the management of A2, B2, or C glenoid erosions\(^8,22\). As such, the surgeon has the option to preserve or release the rotator cuff in these scenarios.

Some have advocated repair of these tissues on the basis that they increase RTSA stability and decrease the incidence of dislocation\(^6,10,21,23\) but clinical series by Clark et al. and Wall et al. have disputed this effect\(^7,24\). However, a review by Wall et al. did find that repair of the subscapularis may still be warranted because it significantly improves post-operative internal rotation\(^24\). In contrast, Boulahia et al.\(^5\) suggested that subscapularis repair may detrimentally affect external rotation through antagonistic loading against the already weakened posterior cuff; however, this has not been confirmed in other reports, which specifically investigated subscapularis repair\(^7,24\).

Although to date the discussion of whether to repair the rotator cuff has primarily focused on post-operative joint stability, the potential effect on muscle and joint loading must also be considered. As is the case in the native glenohumeral joint, the concentric loads applied by a repaired rotator cuff can be expected to counter the deltoid’s eccentric joint loads. However, in an in-vitro study of one RTSA implant configuration, Ackland et al. demonstrated that the function of the subscapularis is markedly shifted towards adduction – especially early in motion – compared to its native role\(^1\). This finding suggests that repair of the subscapularis may resist abduction and
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Thus increase muscle and joint loading, but it is unclear if this change in function holds across the full range of RTSA configurations used clinically.

With the conflicting clinical information and the relative paucity of biomechanical evidence in mind, we sought to investigate the effects of rotator cuff repair, or preservation in glenoid erosion cases, on functional shoulder outcomes and joint kinetics. As well, we investigated how these effects are influenced by changes in two geometrical implant parameters that have previously been shown to have a strong influence on shoulder biomechanics. Specifically, we wanted to clarify how rotator cuff repair affects active internal/external rotation range of motion and external rotation strength, while also determining if it had a detrimental impact on deltoid and joint loading.

We hypothesized that rotator cuff repair would resist abduction thus increasing deltoid muscle force requirements and the resulting joint load. As well, we hypothesized that glenosphere lateralization would have no effect on internal/external rotation but would exacerbate the negative effects of rotator cuff loading while humeral lateralization would improve internal/external rotation and mitigate the effects of rotator cuff repair.
MATERIALS & METHODS:

Instrumented RTSA Implant

In this in-vitro biomechanical study, it was possible to measure joint loads and investigate the effects of systematic adjustments to implant geometry using a previously described custom modular implant system with a built-in load sensor (Figure 1)\textsuperscript{14,19}. Four combinations of humeral and glenosphere lateralization were investigated (respectively: 0&0; 0&10; 10&0; 10&10mm) where, when both variables are at 0mm, the configuration is considered to be neutral, corresponding to a traditional Grammont-style implant. Specifically, neutral was defined as the glenoid baseplate level with the inferior glenoid rim, the glenosphere center of rotation coincident with the glenoid surface, neutral humeral version with a 155° head-neck angle, and a 12.5-mm lateral offset between the humeral stem and deepest point of the cup. The 10mm offset configurations were achieved by making mechanical adjustments to the custom implant without altering the surgical fixation. To ensure accurate mechanical properties, commercially available polyethylene humeral cups (38mm, Delta Xtend; DePuy, Warsaw, IN, USA) were used. The glenosphere was custom fabricated to accommodate a 6 degree of freedom load cell (Nano25, ATI-IA; Apex, NC, USA) that attached medially to a glenoid fixation baseplate, which was recessed into the glenoid vault to allow neutral glenosphere positioning.

Active Motion Simulator & Specimen Preparation

Six fresh frozen cadaveric shoulders (60±21 years) without signs of cuff deficiency or prior surgery were prepared and the humerus was transected distal to the deltoid tuberosity. To enable repeated access to the glenohumeral joint throughout the testing protocol, the subscapularis muscle was elevated from the scapula and reflected laterally without disrupting its insertion on the lesser
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tuberosity. A full thickness superior rotator cuff tear was simulated by releasing the entire supraspinatus and upper portion of the infraspinatus from the greater tuberosity. The specimens were then implanted with the above described custom adjustable RTSA implant positioned in the neutral configuration including $0^\circ$ retroversion relative to the trans-epicondylar axis and with humeral distalization dictated by aligning the superior humeral cup with the superior aspect of the greater tuberosity for all specimens. Following implantation, the three deltoid heads were sutured at their insertion, and the subscapularis and inferior infraspinatus/teres minor musculotendinous junctions were sutured across their width using a running locking stitch. Specimen preparation was then completed as described by Giles et al.,\textsuperscript{12} including fixation of optical trackers to the scapula (Optotrak Certus, NDI, Waterloo, ON, Canada) and insertion of an instrumented intramedullary humeral rod that could provide optical motion tracking and data regarding the loads applied to the rod by the experimenter. These data were recorded using a six degree of freedom load cell (Mini45, ATI-IA; Apex, NC, USA) interposed between the proximal rod, which was inserted into the humeral canal, and the distal rod, which was mated to the testing simulator during passive testing and fitted with brass weights – to simulate the mass of the transected distal arm – during active motion testing. The scapula was cemented to the simulator, and all muscles were connected to computer controlled pneumatic actuators through physiologically accurate lines of action. This simulator produces accurate and repeatable motions along predefined glenohumeral rotation profiles by using a previously validated multi-PID (Proportional-Integral-Differential) control system, which employs real time feedback of the humerus and scapula orientation, to produce independent loads for each muscle group.\textsuperscript{13} The simulator also continuously rotated the scapula to maintain a physiologically accurate glenohumeral-to-scapulothoracic rhythm.
Testing Protocol

Four RTSA configurations with 0 or 10mm of glenosphere lateralization and 0 or 10mm of humeral lateralization were tested in random order. For each configuration, fully unconstrained and simulator-guided muscle driven motions and strength tests were conducted. Fully unconstrained active abduction was simulated from an adducted position (lowest level of abduction without humeral cup impingement) to 90° of humerothoracic abduction at a rate of 1°/s. To ensure proper joint loading was achieved, a physiologic glenohumeral-to-scapulothoracic rhythm of 2:1 was maintained by rotating the scapula using feedback of the instantaneous level of glenohumeral abduction. Additionally, to assess the effect of repairing the rotator cuff, active motion trials were performed with and without (order of testing cuff repair was randomized) subscapularis and infraspinatus/teres minor loading.

Simulator-guided muscle driven active internal and external rotational range of motion (IR/ER ROM) was assessed in full adduction by attaching the distal humeral rod (with weights removed) to a previously described guiding arc that constrained ad-abduction and flexion-extension while leaving axial rotation free to vary. To realistically replicate the pattern of muscle forces present during IR/ER motions, muscle loading ratios were calculated using previously reported pCSA (physiological Cross-Sectional Area) data and EMG signals recorded during IR and ER motions. The resulting ratios were, for internal rotation: 1, 0.16, 0.16, 0, 0, and for external rotation: 0.32, 1, 0, 0.22, 0.3, for the subscapularis, infraspinatus/teres minor, anterior, middle, and posterior deltoid, respectively. Maximum rotational ROM for each motion was recorded after the load of all muscles was increased until the prime mover – the subscapularis for internal rotation and infraspinatus/teres-minor for external rotation – was loaded to 50N. External rotation strength was also assessed by applying the same ramp loading protocol while holding the humerus in neutral
rotation using the simulator’s guiding arc and recording the maximum axial torque measured by
the humeral rod’s load cell.

**Outcome Variables and Statistical Analyses**

For active abduction, the effects of rotator cuff repair status (yes/no), and humeral and glenosphere
lateralization on resultant joint load, total deltoid muscle force, and joint load angle were assessed.
The force components recorded by the glenosphere load cell were transformed into a coordinate
system aligned with a standard glenoid coordinated system, which was coincident with the
glenosphere center. The resultant joint load was then calculated from these data and the joint
loading angle was found using the superiorly and laterally directed forces such that a 0° angle is
purely compressive, and positive angles are directed superiorly. The total deltoid force outcome
was calculated through the summation of the force on the three deltoid heads at each point in time.
Resultant joint load and total deltoid force data were subsequently expressed as a percentage of
the specimen’s total body weight (%BW). All outcomes for active abduction were evaluated every
7.5° of humerothoracic abduction (5° glenohumeral and 2.5° scapulothoracic) from 15° to 82.5°
as this was the range achieved by all conditions without implant impingement. Each active motion
outcome variable was statistically tested using a 4-way (cuff status, humeral lateralization,
glenosphere lateralization, abduction level) repeated-measures analysis of variance (RM-
ANOVA) with follow-up analyses of interactions where appropriate and Bonferroni-corrected
pairwise comparisons with significance set at \( p < 0.05 \). A power analysis for each outcome variable
indicated that testing of six shoulder specimen would enable a clinically meaningful change of
5%BW to be detected with ≥80% power.
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For active range of motion trials, the reported ROM value was taken as the amount of rotation from the neutral position achieved during maximal muscle loading. Active external rotation strength was recorded as the torque applied to the humeral rod in Newton-Meters (Nm) during maximal muscle loading. For consistency, the ROM and strength outcomes were recorded after holding the maximum muscle loads for 5 seconds. For each of these three outcomes, a 2-way (humeral lateralization, glenosphere lateralization) RM-ANOVA was performed with analyses of interactions where appropriate.
RESULTS:

Active Abduction:

Deltoid Force
Results for total deltoid force indicated that rotator cuff loading (i.e. clinical rotator cuff repair or intact anterior and posterior cuff) did not have a significant main effect (p=0.3) when assessed across all implant configurations and abduction angles; however, in addition to the expected main effect of changing abduction angle (p=0.001), both humeral and glenosphere lateralization significantly affected deltoid force (p<0.021). Specifically, a 10mm increase in humeral lateralization significantly decreased deltoid force (average±SD: 3±2%BW, p=0.016) – although this decrease cannot be considered clinically meaningful – while a 10mm increase in glenosphere lateralization significantly increased deltoid force (8±5%BW, p=0.016). Additionally, there was a significant three-way interaction between cuff status, humeral lateralization, and glenosphere lateralization (p=0.005, Figure 2) such that when there was no humeral lateralization, increasing glenosphere lateralization significantly increased deltoid force without rotator cuff loading (8±5%BW, p=0.012) and this effect was exacerbated when cuff loads were applied (13±8%BW, p=0.010). However, this negative effect on deltoid force was mitigated by humeral lateralization to the extent that deltoid force increases due to glenosphere lateralization were no longer significant (p>0.05).

Resultant Joint Load
In contrast to the effects on total deltoid force, resultant joint load data does indicate that rotator cuff loading has a significant main effect (p=0.002) as does abduction (p<0.001) and glenosphere
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lateralization (p<0.001), but not humeral lateralization (p=0.195). Repairing the rotator cuff resulted in a 12±5%BW (p=0.002) increase in resultant joint load across all implant configurations, while increasing glenosphere lateralization increased joint load by 13±4%BW (p<0.001).

Additionally, cuff status and glenosphere lateralization interacted (Figure 3) such that increasing glenosphere lateralization significantly increases the negative effect of loading the rotator cuff (Unloaded vs Loaded: 0mm=9±3%BW (p=0.001), 10mm=14±7%BW (p=0.005)).

Joint Load Angle

Analysis of the joint load angle data found that abduction (p<0.001), rotator cuff loading (Unloaded vs Loaded: 40±14° vs 34±13°, p<0.001), and humeral lateralization (0 vs 10mm: 40±13° vs 33±14°, p<0.001; Figure 4) all have significant main effects such that load angle becomes more compressive as these factors increase but glenosphere lateralization had no effect (0 vs 10mm: 37±14° vs 37±13°, p=0.83). Both cuff status and glenosphere lateralization significantly interact with abduction angle (p<0.001) such that their effects on joint load angle are reduced as abduction progresses. Conversely, the effect of humeral lateralization was almost completely constant (variation <0.7°) across abduction.

Active Internal-External Rotation:

Range of Motion & Strength

A two-way RM-ANOVA for active internal rotation found that neither implant variable had a significant main effect (p>0.05) but humeral and glenosphere lateralization did produce a significant cross-over interaction (p=0.002; Figure 5). Specifically, with 0mm of glenosphere lateralization, increasing humeral lateralization by 10mm significantly increased range of motion
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(7±5°, p=0.019). However, with 10mm of glenosphere lateralization, the lateralized humeral configuration produced less internal rotation compared to the neutral (i.e. 0mm) humeral configuration (5±7°), but this difference was not significant (p=0.092).

Similar analysis of the active external rotation data found that it was significantly increased by both humeral (10±6°, p=0.008) and glenosphere lateralization (10±9°, p=0.033) (Figure 5).

A two-way RM-ANOVA for active external rotation strength found that neither humeral lateralization (p=0.99) or glenosphere lateralization (p=0.61) produced a significant main effect.
DISCUSSION:

Although RTSA is primarily indicated as a treatment for rotator cuff tear arthropathy or massive cuff tears, in many cases, portions of the degenerated infraspinatus and subscapularis are amenable to repair despite having decreased contractile capabilities. Previous studies, focusing on the effects of cuff repair on RTSA stability/dislocation and internal-external rotation range of motion\(^5\)\(^-\)\(^7\),\(^{10,21,23,24}\), have disagreed on whether these tissues should be repaired when possible. This study is unique as it focuses on the kinetic effects of rotator cuff repair and how this is affected by RTSA configuration. We have found that rotator cuff repair increases the demands on the deltoid during abduction and this in turn increases joint loading. This effect is further exacerbated by glenosphere lateralization. Conversely, humeral lateralization reduced the deltoid muscle’s required force, which mitigated the increases in joint loading caused by rotator cuff repair. Furthermore, humeral lateralization produced a more compressive joint load, which effectively stabilizes the joint, but did so without increasing joint load magnitude.

Effects on Active Abduction

As expected, repair and loading of the rotator cuff significantly (p=0.001) shifted the joint loading angle towards compression (~6°). Additionally, results indicate that increasing humeral lateralization from neutral to 10mm produces a similar compressive shift in joint angle of 7° irrespective of cuff repair status, but if combined with cuff repair, the loading angle can be shifted ~13° towards compression. Shifting of the joint load towards greater compression is desirable as it is less challenging to glenosphere baseplate fixation, which is especially important to the promotion of osseous integration in the early post-operative phase. These data also suggest that both cuff repair and humeral lateralization are effective at stabilizing an RTSA by producing a more compressive overall joint load, which increases concavity compression. However, while
rotator cuff repair produces this affect through larger muscle and joint loading, humeral lateralization causes the deltoïd to wrap around the greater tuberosity to a greater extent and this redirects its tension through the humeral head and articulation thus resulting in a more compressively directed joint load without introducing additional force into the joint (Figure 6). Therefore, with respect to joint load angle which affects functional stability and implant fixation, repair of the rotator cuff and use of humeral lateralization are equally effective; however, these factors must be viewed in light of the manner in which they produce these effects and their other impacts on RTSA biomechanics.

As previously reported, these data demonstrate that glenosphere lateralization significantly increases joint loads (14%BW) as a result of decreasing the deltoïd’s mechanical advantage\textsuperscript{14,18,19}. Rotator cuff repair was also found to significantly increase joint load magnitude (12%BW). Additionally, the interaction between these two factors meant that if the rotator cuff was repaired, and the glenosphere was lateralized – for instance to avoid scapular notching – the joint load increased by approximately 29%. The sensitivity of humeral polyethylene liners to increases in load has not be clearly defined in the literature, an increase of this magnitude may lead to increased wear\textsuperscript{3}.

Although repairing the cuff caused a significant increase in joint load magnitude, this outcome alone does not clearly elucidate the cuff’s role in abduction following RTSA, as this increase may be attributable to the added rotator cuff loading, or, alternatively, could be an indicator that the cuff acts as an adductor thus increasing the required deltoid force and thus the overall joint load. This distinction can be made by looking at deltoid muscle force. Specifically, when assessing the average effect across all RTSA configurations, these data suggest that the cuff is not an adductor as there are no significant increases in deltoid force when the cuff is repaired. However, there is a
significant interaction between cuff repair status, humeral and glenosphere lateralization such that increases in deltoid force due to cuff repair (i.e. the slope of the lines in Figure 2) were exacerbated when glenosphere lateralization was increased (~5%BW) irrespective of the level of humeral lateralization. This demonstrates that glenosphere lateralization (through implant or bony means – as in the BIO-RSA which uses a bone graft to achieve lateralization) causes the rotator cuff to act as an adductor and antagonist to the deltoid. Therefore, the combination of these factors should be employed with caution due to the ~13%BW increase in the deltoid force required to produce motion.

Interestingly, the three-factor interaction in the deltoid force data also indicates that when the glenosphere is lateralized, although humeral lateralization did not alter cuff repair’s effect of increasing deltoid force, it did decrease the magnitude of deltoid load nearly equally for both cuff repair states (~5%BW). This consistent decrease in deltoid force caused by adjusting humeral lateralization indicates that it increases the deltoid mechanical advantage, thus decreasing the deltoid’s required force, but it does not markedly change the antagonistic adduction effect of the rotator cuff. Therefore, whereas the concurrent use of rotator cuff repair and glenosphere lateralization should be considered cautiously, the addition of humeral lateralization in cases where the glenosphere is lateralized can improve function and reduce deltoid fatigue irrespective of rotator cuff repair status.

Effects on Internal-External Rotation

Evaluation of internal rotation range of motion using physiologically accurate muscle loading ratios found that neither implant variable significantly affected motion but that they interacted with one another in a cross-over pattern caused by changing combinations of impingement and soft
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tissue restraint. Specifically, IR could be increased by lateralizing the glenosphere (~7°) as a result of decreased contact with the anterior glenoid and coracoid, or by lateralizing the humerus (~10°) due to increases in the cuff’s IR moment arms. However, IR is reduced compared to these two configurations (by ~2° and ~5°, respectively), when both parameters are lateralized, due to overstuffing of the joint and over tensioning of the posterior soft tissues. As such, over tensioning of the posterior soft tissues in the horizontal plane results in a posterior tether to internal rotation. In the case of external rotation range of motion, both humeral and glenosphere lateralization produced significant and equivalent increases (10°, respectively). These increases can be explained similarly to those initially seen with internal rotation; however, in this case, rotation was not limited by over tensioning of the anterior soft tissues when both lateralizations were applied as was the case with internal rotation. Therefore, these results help to confirm the clinical findings of Boileau et al. that BIO-RSA can increase motion by decreasing impingement⁴, but also supports the value of humeral lateralization in increasing motion by improving the rotator cuff’s mechanical advantage. However, it has been shown that these improvements in internal rotation can be partially negated by combined lateralization. As such, it is important to specifically assess IR range of motion when using lateralized glenospheres or a BIO-RSA and to appropriately manage the soft tissues. If IR is restricted with lateralization, it may be prudent to release contracted posterior capsular tissues.

External rotation strength is critically important to performing activities of daily living and thus was of interest in this protocol; however, neither implant variable assessed in this study showed any effect on strength. Despite not effecting external rotation strength in the tested neutral position, it is possible that humeral lateralization increases external rotation strength with the arm in externally rotated orientations by causing the greater tuberosity and cuff insertion to lay more
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eccentric relative to the cuff’s line of action, which should increase its mechanical advantage and thus strength. However, further investigations are required to test this hypothesis.

Limitations & Future Work

The results of this study should be viewed in light of its limitations. First, as with all in-vitro testing, the use of cadaveric specimens may affect results; specifically, in this study specimens did not exhibit existing rotator cuff tears and thus the testing of lateralized RTSA configurations with simulated rotator cuff repair did not result in the large passive joint forces that could occur clinically due to tendon retraction. However, from a clinical standpoint, over tensioned soft tissues often relax post-operatively and thus this study’s rotator cuff repair model can be considered analogous to this relaxed state. Second, in conditions where rotator cuff repair was simulated, the muscle loads used during testing were guided by previously reported EMG data for healthy patients as none exist post-RTSA. The use of these healthy EMG signals may influence the magnitude of the observed trends but because all conditions were tested with the same EMG patterns, comparisons between implant configurations should still yield meaningful results. Third, the current simulator is not able to simulate all shoulder muscle groups, specifically humerothoracic muscles, thus measurements of active IR-ER rotation could only form a basis for comparison between implant configurations and not to define the precise range of motion. Fourth, the current protocol only assessed external rotation strength in neutral rotation, which did not show an affect; however, further investigations in other orientations may have more comprehensively described the effects of the tested conditions. Finally, we believe that further research is required to elucidate the effects on active abduction of independently repairing the subscapularis and
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332 infraspinatus muscles, which would require simulation of humerothoracic muscles not currently
333 included in this model.
CONCLUSION

Rotator cuff repair in the setting of RTSA produces an antagonistic effect that increases the deltoid muscle’s work during elevation and this effect is exacerbated by increased glenosphere lateralization. The combination of these rotator cuff forces and the increased demands on the deltoid muscle significantly increases joint loads. The long-term effects of these changes remain unknown but their magnitude is likely to be clinically meaningful. Humeral lateralization, however, produces increased deltoid wrapping that results in improved joint compression and stability – without the added muscle and joint loading associated with rotator cuff repair – and increases the deltoid’s mechanical advantage which reduces the deltoid force required for elevation. Therefore, humeral lateralization could be used in conjunction with rotator cuff repair to maximize joint stability, or in its place to produce a similar stabilizing effect while decreasing the demands on the deltoid and avoiding complications associated with rotator cuff repair.
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FIGURE & TABLE LEGENDS

**Figure 1** - Computer rendering of the custom instrumented RTSA composed of a glenosphere fixation baseplate (i), a six degree of freedom load cell (ii), glenosphere lateralization spacer (iii), custom 38mm glenosphere with hollow to accommodate ii & iii and a corresponding humeral cup (Depuy) (iv), humeral head-neck angle component (v), and baseplate and fixation stem which facilitates humeral lateralization (vi).

**Figure 2** - Effects of rotator cuff repair status, HLat, & GLat on deltoid force (mean±SD). Note that p-values indicate the effect of GLat with and without loading on the rotator cuff.

**Figure 3** - Effects of rotator cuff repair status and GLat on joint load (mean±SD) across abduction. Note that shaded areas represent ±1 Standard Error of the Mean and p-values are for effect of rotator cuff repair status averaged across abduction.

**Figure 4** – Effects of rotator cuff repair status and HLat on joint loading angle (mean±SD). Included p-values indicate the significant difference between the two levels of each factor averaged across the levels of the other factor. Note that a 0° joint load corresponds to pure compression and positive values are superiorly directed.

**Figure 5** – Effect of HLat and GLat on internal and external rotation range of motion (mean±SD). Note that * and † indicate the significant difference (p=0.008 & p=0.033) between the two levels of the humeral and glenosphere lateralization factors averaged across the levels of the other factor for external rotation range of motion.

**Figure 6** – Illustration of the deltoid’s compressive effect on the glenohumeral joint for RTSA configurations with (right) and without (left) humeral lateralization. Note that the white arrows represent the deltoid muscle force direction acting at the level at which the tissue contacts the greater tuberosity and the black arrows represent the force imparted on the humeral head. This
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The imparted force is related to the component of the muscle forces perpendicular to the tangent of the greater tuberosity’s surface at the point of contact. Also note the increase in deltoid moment arm caused by humeral lateralization (i.e. left vs right pane).