Abstract

Background: Augmented reverse shoulder arthroplasty (RSA) implants restore glenohumeral joint alignment in cases of asymmetric glenoid wear. However, no consensus has been reached on whether the use of metallic augmented RSA baseplates and bone graft reconstruction are equivalent in terms of implant fixation and risk of implant loosening. Therefore, the purpose of this study was to compare two augmented RSA designs by assessing the amount of interfacial micromotion generated under realistic physiological loading.

Methods: Finite element analysis (FEA) models of 9 scapulae with Walch-type B2 or B3 glenoid morphology were virtually implanted with both a metallic augmented baseplate (AUG-RSA) and using the angled bony increased offset RSA procedure (BIO-RSA). Simulation of physiological loading was performed on each of the 18 FEA models. The relative tangential and normal micromotion at the implant-to-glenoid interface was compared in each anatomical quadrant.

Results: The AUG-RSA and angled BIO-RSA showed similar magnitudes of micromotion in most anatomical quadrants of the glenoid. Within the superior quadrant, AUG-RSA displayed a higher magnitude of mean and maximum tangential micromotion (mean: 16.6 ± 2.4 µm, $p<0.000$; max: 35.1 ± 5.3 µm, $p<0.000$). The proportion of the posterior quadrant experiencing greater than 50 microns of micromotion was also statistically greater with AUG-RSA (5.8 ± 2.5 %, $p=0.047$).

Conclusion: Due to its statistically greater micromotions and portions of contact exceeding the accepted 50 micron threshold, the AUG-RSA may be more likely to have inhibited bone on-growth. However, the clinical importance of these differences remains unclear.

Level of evidence: Basic Science Study

Keywords: Reverse shoulder arthroplasty; glenoid erosion; finite element analysis; augmented baseplate; bone grafting

Introduction

Treatment of severe posterior glenoid erosion in patients with rotator cuff insufficiency using Reverse Shoulder Arthroplasty (RSA) continues to be a significant challenge. Multiple techniques are currently used to compensate for posterior erosion with the most prevalent being implant and graft-based augmentation to restore near normal version. However, it remains unclear whether one of these augmentation techniques is superior in terms of fixation stability. Therefore, a biomechanical study directly comparing these surgical options was undertaken to determine if they yield significantly different results.

Although RSA has proven largely successful in restoring function to patients with rotator cuff deficiency[9], patients also exhibiting significant posterior glenoid erosion (e.g. those classified as having Walch-type B2 & B3 glenoids) have suffered from poorer outcomes and higher revision risks due to glenoid baseplate loosening[40]. The risk of implant loosening can be primarily linked to the more limited bone stock to support screw fixation and the challenges with achieving proper implant alignment to minimize loading that challenges fixation. Two augmentation approaches have become predominant to address glenoid erosion. These are the use of fully metallic augmented baseplates and bone grafting in combination with a traditional cylindrical baseplate.

Metallic augmented RSA baseplates (termed AUG-RSA hereafter) come in various forms and use different wedge geometries to compensate for asymmetric wear patterns and re-establish joint geometry. Typical parameters defining these augmentations include full vs half wedge (i.e. a wedge covering the full baseplate diameter vs only half), wedge angle, and baseplate thickness. Alternatively, bone graft augmentation can take the form of allografting or autografting with the latter involving humeral head bone or bone from a secondary site such as the iliac crest[19]. The most widely described and discussed grafting option in the context of RSA is the angled Bony Increased Offset RSA (termed BIO-RSA hereafter) proposed by Boileau et al., which couples autologous humeral head grafting with a standard cylindrical baseplate, thus avoiding the necessity for a more specialized baseplate component[2]. More specifically, in this technique a 10 mm thick, cylindrical humeral head autograft is harvested and shaped into a trapezoidal profile to reconstruct the glenoid erosion.

Several studies have presented early clinical outcomes for the AUG-RSA and BIO-RSA techniques. With respect to using augmented implants, Kirsch et al., reported no cases of baseplate loosening or radiolucency at an average of 14 months follow-up in a cohort of patients that included B2, B3, and C type glenoids[20]. Similarly, Virk et al., reported radiolucent lines in 5.5% of B2, B3, and C type glenoid patients and no glenoid loosening at a minimum of two years follow-up[39]. With respect to bone grafting techniques such as BIO-RSA, multiple studies have been conducted with conflicting results. Various authors have reported high rates of graft incorporation (>94%), few instances of radiolucency (<2%), and no reported graft resorption[2,3,21,27], while others have reported resorption in up to 25% of cases causing baseplate failure and necessitating revision[5,13,19]. A recent systematic review by Lanham et al. has confirmed these findings for AUG-RSA and BIO-RSA[26]. Only recently has a direct clinical comparison of AUG-RSA and BIO-RSA been reported. Van de Kleut et al. reported on a prospective randomized trial comparing the two techniques over 24 months of follow-up using radio stereometric analysis[22]. These authors reported no differences in implant migration between the techniques and no cases of graft resorption in the case of BIO-RSA. Although this study provides a direct comparison of the techniques, the population in this study was very broad, incorporating patients across the spectrum of A, B, and E type glenoids with only 11 of their 41 patients exhibiting the B2 & B3 morphology that is the most challenging to fixation. As a result, despite its high-quality methodology, this study is not able to clearly determine whether one technique is superior in treating cases of severe erosion.

Primary to the success of both AUG-RSA and BIO-RSA is the ability to overcome the challenges presented by the patient’s limited bone stock to achieve high quality initial fixation that limits micro-motion between the baseplate/graft and reamed glenoid bone. Numerous biomechanical studies using experimental and computational methods have been undertaken to investigate the fixation of non-augmented implants for cases both with and without posterior glenoid erosion [4,7,11,14,15,17,38,41,42]. However, very few biomechanical studies exist that investigate augmented RSA to treat glenoid erosion[10,28,35]. Unfortunately, because these studies used polyurethane foam bone surrogates that do not replicate true bone properties or erosion patterns, they observed implant micromotions of 100-400 microns, which limit the interpretability and value of the findings. Furthermore, no Finite Element modelling studies of augmentation treatments for glenoid erosion have yet been presented in the literature, despite their ability to precisely replicate bone properties and erosion patterns. Given this limited biomechanical literature focused on treating posterior glenoid erosion and the lack of a direct comparison between AUG-RSA and BIO-RSA, the comparative quality of initial fixation between these two techniques remains unclear.

Therefore, the purpose of this study was to directly compare AUG-RSA and BIO-RSA to understand the quality of initial fixation produced by both in precisely matched conditions, which could help to guide clinical practice on the use of these techniques. Our null hypothesis was that there would be no clinically significant difference between the relative micromotion at the scapula-component interface for these two techniques.

Materials and methods

Properly accounting for the specific bone erosion patterns and bone material properties of the Walch-type B2 & B3 glenoid treated using AUG- and BIO-RSA is critical to achieving a high level of fidelity in this study. Therefore, this precluded an experimental approach that used polyurethane foam surrogate models or cadaveric specimen that are unlikely to have Walch-type B2 or B3 arthritic changes. With this in mind, a Finite Element approach was taken that utilized pre-operative CT scans of nine patients with B2 & B3 glenoid erosions who were treated with RSA. This enabled paired models of the AUG-RSA and BIO-RSA to be generated from each patient's CT scan and thus allowed for a direct comparison of their outcomes.

Model Generation

Implant configurations

Computer-Aided Design (CAD) models of the components required for AUG- and BIO-RSA were reverse engineered from the Aequalis™ Perform™ Reversed (Wright Medical, TN, USA) implant system using the SolidWorks software package (Dassault Systèmes, Vélizy-Villacoublay, France). These components were:

- For the AUG-RSA: an augmented baseplate with a 15-degree full wedge, 29 mm diameter, and a 15 mm long central peg
- For the BIO-RSA: 1) an augmented autologous bone graft with a 15-degree full wedge and 29 mm diameter, 2) a standard baseplate with a 29 mm diameter and a 25 mm long central peg.

Furthermore, the components were assembled into their respective AUG-RSA and angled BIO-RSA assemblies (Fig.1) for later implantation into patient scapula models.

Multiple proposals exist in the literature for screw configurations. In this study the guidelines of Boileau et al. were followed by modeling four peripheral screws, with a configuration of two divergent locking screws located superiorly and inferiorly, and two convergent compression screws located anteriorly and posteriorly[2].

Scapula model generation

The CT scans of the nine patients with confirmed Walch-type B2 or B3 glenoid morphology were imported and segmented in the Mimics software package (Materialise, Leuven, Belgium). After segmentation, a custom Python script based on the method of Pakdel et al., was used to apply Partial Volume Correction to the outer layer of voxels within the scapula segmentation [30]. This ensured that the drop in Hounsfield Unit (HU) intensity of voxels at the boundary between cortical bone and soft tissue, which is inherent to CT scans, was appropriately corrected. This is critical to producing a Finite Element model with accurate bone material properties. The segmentation was then used to generate 3-dimensional surface models of the scapulae and refined using wrapping and smoothing tools.

Virtual surgical implantation

Each of the 9 scapula models were imported into two separate CAD assemblies where each could be virtually implanted with an AUG-RSA and an angled BIO-RSA. The implants were positioned on each scapula by a fellowship trained shoulder specialist (D.S.) following standard clinical guidelines. Specifically, it was ensured that the anterior and posterior screws perforated the cortex of the glenoid vault while the inferior screw engaged the inferior scapular pillar, and the superior screw was directed into the bone of the supraspinous fossa. Furthermore, attention was given to achieving ≥80% backside contact with the glenoid. Contact beyond this threshold was not implemented if it required excessive medial implant positioning, which would mimic over reaming and thus result in the removal of high-quality subchondral bone.

Once appropriate placement was achieved, Boolean subtraction was used to eliminate regions of the scapula that were intersected by the baseplate/bone graft, thus replicating surgical reaming. Moreover, the hole in the scapula replicating the central peg was extended by 1.5 mm to ensure realistic baseplate load transfer. To simulate an accurate representation of a reamed glenoid (i.e. where reaming goes beyond the baseplate diameter), a further 5 mm was removed beyond the radius of the baseplate.

Furthermore, a plane parallel to the lateral surface of the baseplate located just medial to the scapular notch was used to remove the body of the scapula, which was unnecessary for subsequent Finite Element modeling. Additional regions that were known to exhibit zero stress were eliminated, including, sections of the acromion (approximately 20 mm lateral to the lateral face of the baseplate) and the tip of coracoid process (approximately 10 mm lateral to the lateral face of the baseplate). The resultant reamed and trimmed scapula model, implant components, and screws were then exported.

Scapula mesh generation & material property assignment

The scapula and screw models in their assembled (i.e. virtually implanted) positions were imported into the 3-matic software package (Materialise, Leuven, Belgium). A non-manifold assembly was generated that accurately modeled the threaded holes in the scapula resulting from the four fixation screws. The scapula was then meshed with quadratic tetrahedral elements (i.e. C3D10) with a maximum edge length of 1.5 mm and appropriate refinement in the areas of complex geometry (e.g. the threaded screw holes). The resulting scapula volume mesh was then imported into Mimics (Materialise, Leuven, Belgium) for material property assignment.

Walch-type B2 & B3 glenoids have highly heterogeneous bone material properties and unique patterns[24]. To accurately model this high variability, the bone material properties of each model were applied based on the Hounsfield Unit (HU) intensity of each individual patient's CT scan. The HU intensity for each scan was internally calibrated using a linear regression technique of in-scan regions-of-interest (ROI) established by Michalski et al.[29]. The calibrated HU values were then used to calculate the apparent bone density for each element using the equation of Pomwenger et al.[32].

$$\rho_{app} = 1.1187 \cdot 10^{-3} \cdot HU$$

Two material types were created to model the bone properties of the scapula. The first, representing trabecular bone, was assigned to any element with an apparent density less than 1.54 g/cm^3, and this range of densities was sub-divided into 100 sub-materials. The second, representing cortical bone, was assigned to any element with apparent density greater than or equal to 1.54 g/cm^3, and this range of densities was sub-divided into 10 material types. The apparent densities assigned to these 110 sub-materials were used to calculate the Young's modulus of each based on established scapula specific relationships (Table I)[25,33,34]. After material property assignment, the resulting model was imported into Abaqus (Dassault Systèmes, Providence, RI, USA).

Finite Element Model Creation

After importing the implant component, bone graft, and screw models into Abaqus, each was meshed with quadratic tetrahedral elements with a maximum edge length of 1.5 mm. Homogeneous material properties were applied to the baseplate and screws, and, for BIO-RSA models, the bone graft. The graft was assigned an apparent density of 0.22 g/cm, consistent with the middle region of the humeral head's trabecular bone[1], with a corresponding Young's modulus of 96 MPa and a Poisson's ratio of 0.3, based on the equations in Table I. The titanium baseplate and screws were assigned a Young's modulus of 113.8 GPa and Poisson's ratio of 0.34. Interaction properties at component interfaces were then defined based on information from the literature (Table II)[16,43].

Boundary and loading conditions

Use of two to four compression screws for RSA fixation is common practice; however, to date, it has not been replicated in FEA studies of RSA [4,8,42]. To improve fidelity, this study did model compression screw preload. The magnitude of preload was based on the experimental results of Terrier *et al.* and Pitocchi *et al*. who both found that anterior & posterior compression screw preload force in standard RSA that averaged ~175 N[31,36]. Due to the glenoid erosion in the present study, the screw engagement length for the anterior and posterior compression screws was shorter than that studied by Terrier or Pitocchi; therefore, the preload force used here was estimated as 150 N by extrapolating Pitocchi et al.'s results for a shorter screw scenario. Given this approximation, a sensitivity analysis, described in the next section, was undertaken to assess the effects of varying pretension magnitude.

A compressive load and a shear load (inferior to superior) of 756 N were applied to the baseplate component to create loading conditions in agreement with those specified in the ASTM F2028-17 standard for testing RSA implants[44]. This loading regimen is also consistent with what has been used in previously reported experimental and FE studies evaluating RSA micromotion[4,8,12,15,38]. The compressive load was applied perpendicular to and across the entire baseplate surface and the shear load was applied parallel to the baseplate surface on its inferior aspect. Simulations were performed in two steps, a preload and loading step. The preload step simultaneously applied pre-tensioning to both compression screws, and subsequently the loading step applied the compressive and shear loads following a linear ramp.

Model quality assessment

To ensure that results did not depend on the number of elements in the model, a convergence analysis was performed. The scapula and implant component meshes were refined from an initial maximum edge length of 3 mm to 0.5 mm in 0.5 mm increments. The component stresses were then evaluated in each of the solved models and the converged model was identified by determining the model with the largest element size for which further element size reduction yielded less than 10% change in stress. The converged model had a maximum edge length of 1.5 mm.

The sensitivity of simulations to compression screw preload magnitude was evaluated by applying preloads of 100, 125, 150, 175, & 200 N, and evaluating the effect on scapula-to-graft micromotion for one scapula treated with BIO-RSA. Across the 100 N range of preload magnitudes, average normal micromotion changed by only 1 micron in the inferior region while being constant elsewhere. For tangential micromotion, changes in average micromotion were more marked in all regions but the largest still amounted to only 4 microns in the anterior region. With these results in mind, the simulations can be considered essentially unaffected by changes in screw preload, and thus the 150 N magnitude was used in all cases.

Biomechanical Outcomes & Statistical Analyses

Results post-processing

Similar to the methods of Conlisk et al., simulation results at the interface between the implant/graft and reamed glenoid were extracted using the COPEN and CSLIP Abaqus variables, which represent the normal and tangential micromotions, respectively[6]. In MATLAB, these results were grouped into superior, inferior, anterior, and posterior quadrants based on a glenoid coordinate system previously defined in Abaqus (Fig. 2). These sub-divided data were then analysed to determine the Root Mean Squared (RMS) and maximum micromotion in each quadrant. To reduce the effect of outlier values when identifying the maximum micromotion for each quadrant, the top 2.5% of micromotion values were averaged together and reported as the maximum. As well, for each quadrant, the percentage of data that exceeded a given micromotion threshold was calculated with two thresholds used: 20 microns, and 50 microns. The 20 and 50 micron thresholds were chosen as they respectively represent conservative and optimistic values for micromotion that begins to limit bone integration and on-growth[18,37].

Statistical analysis

To assess the significance of the results, paired t-tests were performed to compare AUG-RSA to BIO-RSA with statistical significance set to $p < 0.05$. These comparisons were performed for each of the four variables described above and in each anatomical quadrant.

Results

Micromotion

Mean normal micromotion across the 9 subject models in each anatomical quadrant for the AUG-RSA and BIO-RSA techniques were in the range of 2.4 – 12.5 µm and 4.9 – 20.7 µm, respectively (Fig. 3) with no statistically significant comparisons between the two techniques in any quadrant. Mean tangential micromotion for the AUG-RSA and BIO-RSA techniques were in the range of 19.8 – 27.2 µm and 3.2 – 22.9 µm, respectively, with the comparison in the superior quadrant demonstrating statistically greater micromotion resulting from the AUG-RSA (Mean Difference ± Standard Error of Difference: 16.6 ± 2.4 µm, p<0.000).

Maximum normal micromotion (Fig. 4) for the AUG-RSA and BIO-RSA techniques were in the range of 2.8 – 29.7 µm and 5.2 – 49.8 µm, respectively, with the comparison in the superior quadrant demonstrating statistically greater micromotion resulting from the BIO-RSA (9.1 ± 2.8 µm, p=0.012). Maximum tangential micromotion for the AUG-RSA and BIO-RSA techniques were in the range of 44.9 – 60.0 µm and 9.8 – 62.0 µm, respectively, with the comparison in the superior quadrant demonstrating statistically greater micromotion resulting from the AUG-RSA (35.1 ± 5.3 µm, p<0.000).

Bone On-Growth Thresholds

With respect to the percentage of micromotion that surpassed the 20 and 50 microns thresholds thought to effect potential bone on-growth, a number of statistical differences were observed between the techniques. For the 20 micron threshold, the percentage of normal and tangential micromotions in each quadrant that exceeded the threshold for the AUG-RSA and BIO-RSA techniques can be seen in Figure 5. The only statistically significant comparison was found in the superior quadrant for tangential micromotion where AUG-RSA had more micromotion exceeding the threshold (35.5 ± 6.8%, p=0.001). For the 50 micron threshold, the percentage of normal and tangential micromotions exceeding the threshold can be seen in Figure 6. The only statistically significant comparison was found in the posterior quadrant for tangential micromotion where AUG-RSA had more micromotion exceeding the threshold (5.8 ± 2.5 %, p=0.047).

Discussion

Directly comparing the clinical and biomechanical efficacy of the increasingly popular AUG-RSA and BIO-RSA techniques for treating posterior glenoid erosion is critical to understanding whether one technique produces superior results. To date, only one clinical study by van de Kleut et al. and one biomechanical study by Stroud et al. has undertaken this type of direct comparison[23,35]. Unfortunately, in both cases a number of factors have significantly limited the interpretability of the results in specifically addressing the efficacy of these two techniques for use with significant glenoid erosion. Specifically, although van de Kleut's study used advanced Radio Stereometric methods, the aggregation of data across the full spectrum of glenoid conditions (e.g. non-eroded, superior eroded, and posterior eroded) and the limited number of patients in their cohort with posterior erosion, precludes a conclusion being drawn about the two techniques' efficacy in treating Walch-type B2 & B3 glenoid erosion. Regarding Stroud's study, although it compared BIO-RSA to various AUG-RSA implants, because of its use of polyurethane foam without a cortical shell and not modeling glenoid erosion, the results are likely to not accurately reflect the two techniques' performance. The results of the current study are able to shed further light on the comparative biomechanics of these two techniques and help to determine whether they are equivalent.

A number of important findings can be drawn from the results of conducting paired simulations of the AUG-RSA and BIO-RSA techniques in models of 9 patients with B2 & B3 glenoid erosion. BIO-RSA exhibited greater normal micromotion than AUG-RSA in the superior quadrant in terms of mean, maximum, and % of data over the 20 and 50 micron thresholds. However, this difference was only statistically significant with respect to maximum micromotion (11.9±9.4 µm vs 2.8±2.5 µm), and even in this case the BIO-RSA's micromotion fell well below the 20 micron threshold, which is thought to act as a conservative value for micromotions that negatively affecting bony on-growth.

With respect to tangential micromotions, they are consistently greater than normal in all quadrants for both techniques except for BIO-RSA in the superior quadrant where normal micromotion is marginally greater. This is consistent with expected mechanical behaviour as the constructs are more able to resist normal micromotion due to the compressive load application and compression screw preloading. Comparing the techniques, AUG-RSA produced statistically significantly more tangential micromotion both in the mean and maximum metrics, with the mean just exceeding the conservative 20 micron threshold and the maximum across all subjects approaching the optimistic 50 micron threshold. Furthermore, AUG-RSA resulted in approximately 1/3rd of the superior quadrant exceeding the 20 micron threshold and 1/10th exceeding the 50 micron threshold. Given the proportion of micromotion exceeding the above thresholds, these results raise questions about the potential for bony on-growth in the superior quadrant with the AUG-RSA; however, the potential clinical implications of this may be mitigated by the fact that the superior quadrant is primarily subjected to compression and thus bone on-growth may not be as important as for a quadrant that experiences distractive motions.

AUG-RSA also yielded tangential micromotions in the posterior quadrant such that a statistically larger portion of the quadrant exceeded the 50 micron threshold as compared to the BIO-RSA results (11.8±13.2% vs 6.0±8.8%). This difference could be due to a combination of the significantly higher rigidity of the augmented metallic implant and the poor screw fixation due to the limited bone stock in this region. This finding suggests that bony on-growth may be inhibited in portions of the posterior quadrant when using the AUG-RSA; however, because only 12% of the posterior quadrant exceeded the threshold on average across the 9 subjects, this may not be clinically significant.

No other statistically significant differences were observed, but the proportion of tangential micromotion exceeding the 20 micro threshold was greater than 20% for the anterior, inferior, and posterior quadrants for AUG-RSA with anterior reaching 45%, while for BIO-RSA, the anterior and posterior quadrants also exceed the threshold in 20% of values. Therefore, a major portion (45%) of the anterior quadrant may experience inhibited on-growth as judged by the conservative 20 micron threshold, but the size of this region is not statistically larger than the 25% observed with the BIO-RSA.

Bonnevialle et al. recently studied various RSA designs for non-eroded conditions and found micromotions ranging from 42 to 129 μm[4]. Although focused on a different clinical condition, the current results are in fair agreement (tangential micromotion: 10 to 104 μm), which supports the validity of the current findings. The slightly smaller micromotions in this study may be attributable to the accurate modeling of screw thread geometry and inclusion of compression screw preload, neither of which were included in Bonnevialle's simulations. Friedman et al. studied AUG-RSA fixation for the treatment of glenoid erosion using 4th generation composite foam bone surrogates and found tangential micromotions of 116.8 ± 47.1 μm under similarly directed but lower magnitude loads[10]. Micromotions in the current study are in line with those of Friedman et al. but fall on the low end of the values reported, which can be attributed to the foam bone surrogates used in the previous study not accurately modeling the bone properties and distribution of an eroded glenoid, which are captured in this study.

There are a number of limitations inherent in this study. First, in order to accurately model the true glenoid erosion conditions, this study created simulations based on CT-scans of patients with Walch-type B2 & B3 glenoid erosion, and as such it was not possible to undertake an experimental validation directly. However, as noted in the previous paragraph, the results presented here are in agreement with a previously published RSA Finite Element study and a previous experimental investigation. Second, this study only investigated the micromotion immediately after surgery and not the effects of repeated cyclic loading; however, bone on-growth is primarily dictated by cycle-to-cycle micromotion not long-term migration and thus this study can still provide important insights. Furthermore, the study of Friedman et al. found that micromotion did not significantly change before and after subjecting the AUG-RSA to 10,000 cycles of loading, which indicates that the results presented here are likely to be a fair representation of micromotion throughout an extended period of cyclic loading[10]. Third, understanding the potential for graft resorption is important factor, but was not studied here. The strongest computational assessment of resorption involves homologous regional comparison of strain energy density in the bone of interest pre- and post-intervention; however, this is not possible in grafting procedures where no bone is present pre-intervention.

Conclusion

This is the first biomechanical comparison of AUG-RSA and BIO-RSA for the treatment of posterior glenoid erosion. In addition, the Finite Element simulations conducted in this study incorporated a number of advancements that improved the fidelity of the results. Findings indicate that AUG-RSA produced significantly greater micromotions, and in some quadrants a significantly greater proportion exceeded the accepted 50 micron threshold for promotion of bone on-growth. This suggests that AUG-RSA may be more likely to have inhibited bone on-growth compared to BIO-RSA; however, it is unclear if the magnitude of differences is clinically important.

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Table Legends

Table I: Scapula-specific relationships for Young's modulus and Poisson ratio.

Table II: Abaqus interaction properties used in both AUG-RSA and angled BIO-RSA.

Figure Legends

Figure 1: Augmented RSA configurations. (Left) AUG-RSA assembly, with scapula, posterior augmented baseplate, compression and locking screws. (Right) BIO-RSA assembly, with scapula, wedge-shaped bone graft, cylindrical baseplate, compression and locking screws. Note: the displayed screw lengths are illustrative only and not reflective of the lengths used for each patient. As well, these images are drawn from the virtual implantation in CAD and thus the detailed threaded holes in the scapula are not shown as they are created in a later step.

Figure 2: Anatomical quadrant divisions of the glenoid. Illustration of the quadrants used to sub-divide the simulation results.

Figure 3: Average micromotions. This plot illustrates the RMS normal and tangential micromotions across each quadrant for the two techniques.

Figure 4: Maximum micromotions. This plot illustrates the maximum normal and tangential micromotions in each quadrant for the two techniques.

Figure 5: Percentage beyond 20 micron threshold. This plot illustrates the percentage of normal and tangential micromotion data in each quadrant for the two techniques that surpass the 20 micron threshold that is conservatively thought to inhibit bone on-growth.

Figure 6: Percentage beyond 50 micron threshold. This plot illustrates the percentage of normal and tangential micromotion data in each quadrant for the two techniques that surpass the 50 micron threshold that is optimistically thought to inhibit bone on-growth.