**The Effect of Humeral Head Positioning and Sizing on Bone Stresses following Total Shoulder Arthroplasty with a Short Humeral Stem**

**ABSTRACT**

**Introduction:**

The use of uncemented humeral stems in total shoulder arthroplasty (TSA) is known to cause stress shielding and result in bone resorption. Shorter length stems with smaller overall dimensions have been shown to decrease stress shielding, however the effect of humeral head sizing and positioning has not yet been investigated. The purpose of this study was to XXX

**Methods:**   
Three dimensional models of 8 male cadaveric humeri (ave age: 68±6 yrs, 8L) were constructed from computed tomography (CT) data. Trabecular and cortical bone were segmented and assigned appropriate properties according to CT attenuation. Bone models were reconstructed with the humeral head…. . Modelling was performed at 45˚ and 75˚ of abduction and the resulting differentials in bone stress versus the intact state and the expected time-zero bone response were determined and compared.

**Results:**

**Discussion**:

**Level of Evidence:** Basic Science Study

**Keywords:** shoulder arthroplasty, humeral head sizing, humeral head positioning, humeral stem, short stem, bone resorption, stress shielding

**INTRODUCTION**

Total shoulder arthroplasty (TSA) is used to restore shoulder function and alleviate pain in patients with glenohumeral arthritis1. During the procedure, the articular surface of the humeral head is removed and the proximal humerus is reamed to allow a humeral stem to be inserted into the resulting canal, and a replacement humeral head component is sized and positioned on the humeral resection plane.

TSA is a relatively successful procedure, however humeral stress shielding following reconstruction occurs clinically and remains a concern with proximal stress shielding reported in 29 to 80% of recipients at mean follow ups ranging from 2 to 3 years5,12,15. Additionally, loosening of the humeral stem with stress shielding listed as probable cause has been reported to occur in as many as 11% of patients, with a further 9% at risk of loosening at 33 month average follow up4.

To address these issues, modifications to humeral short stem design have been introduced including changes to implant surface characteristics and the general reduction in implant size. In a comparison of coated and uncoated surface treatments, the patient cohort who received a coated short stem humeral implant reported no incidences of loosening although 21% did have some stress shielding, compared to the group who received an uncoated implant, 3% of which had some degree of implant loosening with an additional 21% at risk of loosening, and 44% showing indications of stress shielding11. In terms of implant size, both clinical and in-vitro computational studies have shown that smaller sized implants can reduce the risk of stress shielding and result in humeral bone stresses that more closely approximate the intact state when compared to larger-sized implants8,12.

Positioning of short humeral stems has also been shown to have an impact on proximal stress shielding, with stem axis deviation being shown clinically to increase this risk12, and computational work confirming that central stem positioning is advantageous compared to varus or valgus stem angulation resulting in distal stem contact with the medial or lateral cortex [Tavakoli ref].

While the current literature seems to suggest that proximal stress shielding following TSA with a humeral short stem can be affected by short stem design, sizing, and surgical positioning, the effect of humeral head backside contact with the humeral resection plane on humeral bone stresses and expected bone response is not currently fully understood.

In an in-vitro computational model, Synnott et al16 using a generic humeral short stem compared full backside contact of a humeral head sized to cover the full humeral resection plane to one which was left proud with no backside contact. They reported that full backside contact resulted in smaller changes in humeral bone stress compared to intact, and that the non-contact condition resulted in significantly more expected proximal cortical bone resorption due to the lack of load transfer to the cortex at the resection plane.

While previous work suggests that humeral head backside contact with the resection plane may play an important role, particularly in terms of stress shielding in the proximal cortex, the effect of humeral head backside contact when using a size of implant that does not fully cover the humeral resection plane and the impact of uneven backside contact is currently not known. This is important since coverage of the entire resection plane is not always possible clinically, and often a smaller humeral head is positioned in the inferior-medial position on the resection due to anatomy and the preservation of soft tissue. Furthermore, sometimes humeral head backside contact is only achieved either medially or laterally because of resection plane inconsistencies or humeral head misalignment. Additionally, variations in anatomical humeral head geometry can reduce humeral head positioning flexibility by the surgeon resulting in the head being permitted to be moved only medially or laterally depending on the mobility permitted by the implant variation selected.

Therefore, the purpose of this study was to quantify the effect of humeral head positioning, either inferior-medial or superior-lateral, on humeral cortical and trabecular bone stresses after TSA with a short stem humeral component. Additionally, we aimed to quantify the effect of humeral head backside contact on humeral cortical and trabecular bone stresses after TSA with a short stem humeral component and an inferior-medial positioned humeral head. We hypothesized that the inferior-medial humeral head position would produce bone stresses closest to the intact state and result in less expected bone resorption in the medial quadrant, and that the superior-lateral position would produce similar results but in the lateral quadrant, directly as a result of their contact with the cortex at these respective locations. Additionally, we hypothesized that for the inferior-medial humeral head position, full backside contact would produce humeral stresses closest to that of the intact bone due to load transfer occurring over the entire backside surface. We also hypothesized that when full backside contact could not be achieved, medial contact would be more preferable compared to lateral contact for the inferior-medial humeral head position tested due to the presence of medial load transfer to the medial cortex for the medial contact condition.

**METHODS**

***Finite Element Simulation and Model Development***

Three dimensional models of eight male left cadaveric humeri (68±6 years average age) were generated from computed tomography (CT) data using MIMICS (Materialise, Leuven, Belgium) software. A combination of automatic threshold-based and manual segmentation methods were used to separate cortical and trabecular bone.

These resulting humeral bone models were then virtually prepared for reconstruction by an orthopaedic surgeon to accept a short stem humeral implant (Exactech Equinoxe® Preserve) that was optimally sized and placed directly in the center of the humeral canal (FIG X).

Three different humeral head conditions were then implemented for each specimen; first, a humeral head that was large enough to cover the entire humeral resection plane was positioned centrally so that cortical contact was achieved circumferentially, and then an undersized humeral head was either positioned inferiorly or superiorly such that cortical contact was achieved in these anatomic locations, and as a result of the head under sizing, no contact occurred on the cortex opposite (FIG X).

Both cortical and trabecular bone was meshed with quadratic tetrahedral elements having a 2 mm maximum edge length, as deemed appropriate by a mesh convergence analysis8.

Cortical bone was given a modulus of elasticity of E = 20 GPa and Poisson’s ratio of ν = 0.32,13. Trabecular bone was given a spatially varying modulus of elasticity using a density-modulus relationship of where E is the elastic modulus and is the apparent bone density1,3,9,10,14,17 and a Poisson’s ratio of ν = 0.3. The implant was also meshed with quadratic tetrahedral elements with a maximum edge length of 2 mm and was given material properties of titanium having a modulus of elasticity of E = 110 GPa and a Poisson’s ratio of ν = 0.3. The three surface characteristics of the stem were assigned appropriately: plasma spray (most proximal, µ = 0.88), grit blast (middle, µ = 0.63), and polished (most distal, µ = 0.40), and the humeral head backside surface was given polished frictional characteristics (µ = 0.40)6,7 (FIG X).

A fixed boundary condition was applied at the distal end of the humerus which was sectioned at the mid-diaphysis. Joint reaction forces representing 45˚ and 75˚ of abduction were applied towards the center of the humeral head on the articular surface, with a magnitude of 440 N for 45˚ and 740 N for 75˚ based on in-vivo telemetrized TSA dataassuming a 50th-percentile male with a body weight of 88.3 kg5.

***Outcome Variables and Statistical Analysis***

To permit statistical analysis, the humerus was divided into four anatomical quadrants (medial, lateral, anterior, posterior) and eight slices of 5 mm thick each, which were parallel to the humeral resection plane for both cortical and trabecular bone.

The volume-weighted percent change in bone stress for each humeral head position versus intact was calculated using the resulting difference for each of the six stress components (σ11, σ22, σ33, σ12, σ13, σ 23). The resulting values were then inserted into the von Mises equation, yielding a scalar representation of the change in bone stress from pre- to post-reconstruction to serve as an indication of the overall change in bone stress as a result of both tensile and compressive stresses although does not include the direction (positive or negative) of the change.

The volume-weighted change in strain energy density (ΔSED) for each element from the intact to the reconstructed state was also determined, and the expected time-zero bone response (resorb, no change, or remodel) for each element was then estimated using a threshold value of 55% change in strain energy density (ΔSED). A decrease in SED of more than 55% would result in an element being classified as having bone resorption potential and an increase of more than 55% would result in bone remodeling potential18.

A four-way (humeral head position, abduction angle, slice depth, quadrant) repeated measure analysis of variance (RM-ANOVA) with a significance level of α = 0.05 was conducted to assess the change in bone stress and the expected bone response for each implant position investigated. A post-hoc power analysis showed that a power of 0.8 or greater was achieved for all outcome variables.

**RESULTS**

***Changes in Bone Stress***

Pooling all quadrants, slice depths, and abduction angles, both the valgus and varus positions resulted in larger changes in bone stress from the intact state than the standard central position, for both cortical and trabecular bone. For cortical bone, the standard position (STD) altered bone stress by 28.9±5.5%, whereas the valgus (VAL) and varus (VAR) positions altered bone stress by 36.4±8.8% (P = 0.03) and 33.1±8.4% (P = 0.17), respectively (Figure 2). Similar trends were observed for trabecular bone stress changes relative to the intact state, where the standard position (STD) altered bone stress by 86.3±27.9%, and the valgus (VAL) and varus (VAR) positions altered bone stress by 88.1±48.3% (P = 0.9) and 90.2±51.1% (P = 0.81), respectively (Figure 2).

Significant changes in cortical bone stress compared to intact were observed in all quadrants at depths of 5 mm or greater beneath the resection plane (Figure 3).

*Change in Cortical Bone Stress:*

For cortical bone, in the posterior quadrant at depths greater than 5 mm, the valgus position altered bone stress more than the standard position (**5-10 mm**: 45° P=0.033, 75° P=0.019; **10-15 mm**: 45° P=0.014, 75° P=0.01; **15-20 mm**: 45° P=0.016, 75° P=0.012; **20-25 mm:** 45° P=0.005, 75° P=0.005; **25-30 mm:** 45° P=0.005, 75° P=0.004; **30-35 mm:** 45° P=0.008, 75° P=0.006; **35-40 mm:** 45° P=0.002, 75° P=0.003) (Figure 3). Likewise, within the lateral quadrant, at slice depths between 5-40 mm, the valgus position altered cortical bone stress more than the standard position (**5-10 mm**: 45° P=0.029, 75° P=0.027; **10-15 mm**: 45° P=0.007, 75° P=0.007; **15-20 mm**: 45° P=0.003, 75° P=0.005; **20-25 mm:** 45° P=0.009, 75° P=0.011; **25-30 mm:** 45° P=0.035, 75° P=0.025; **30-35 mm:** 45° P=0.008, 75° P=0.002; **35-40 mm:** 45° P=0.017, 75° P=0.004) (Figure 3). In the medial quadrant at slice depths between 20-40 mm the valgus position altered cortical bone stresses more than standard position (**20-25 mm:** 45° P=0.075, 75° P=0.045; **25-30 mm:** 45° P=0.032, 75° P=0.044; **30-35 mm:** 45° P=0.021, 75° P=0.023; **35-40 mm:** 45° P=0.003, 75° P=0.003) (Figure 3). In the anterior quadrant at slice depths of 25-40mm beneath the resection plane, the valgus position changed cortical bone stress more than standard position (**25-30 mm:** 45° P=0.021, 75° P=0.013; **30-35 mm:** 45° P=0.02, 75° P=0.006; **35-40 mm:** 45° P=0.018, 75° P=0.007) (Figure 3).

*Change in Trabecular Bone Stress:*

In the posterior quadrant at the 20-25 mm slice depth, the valgus position altered bone stress more than the standard position (**20-25 mm:** 45° P=0.052, 75° P=0.047) (Figure 3). Within the lateral quadrant at the slice depth of 0-5 mm, the valgus position altered trabecular bone stress less than the standard position (**0-5 mm:** 45° P=0.007, 75° P=0.009), however this trend changed for the slice depths from 10-40 mm with no statistical significance between the two alignments (**10-15 mm**: 45° P=0.454, 75° P=0.443; **15-20 mm**: 45° P=0.167, 75° P=0.139; **20-25 mm:** 45° P=0.15, 75° P=0.135; **25-30 mm:** 45° P=0.213, 75° P=0.19; **30-35 mm:** 45° P=0.285, 75° P=0.269; **35-40 mm:** 45° P=0.215, 75° P=0.215) (Figure 3). In the medial quadrant, the slice depths between 30-40 mm beneath the resection plane were the only locations where the valgus position altered trabecular bone stress significantly less than the standard position (**30-35 mm:** 45° P=0.038, 75° P=0.021; **35-40 mm:** 45° P=0.022, 75° P=0.017) (Figure 3). In the anterior quadrant, at the slice of 0-5 mm, the varus position changed trabecular bone stress more than the standard position (**0-5 mm:** 45° P=0.14, 75° P=0.012) (Figure 3).

***Time-Zero Estimated Bone Response***

Following reconstruction, for both cortical and trabecular bone in all quadrants, there existed volumes of bone that exhibited resorbing potential for all three positions investigated. Overall, the valgus position produced the largest volume of bone with resorbing potential compared to the standard and varus positions in all quadrants and slice depths except in the medial quadrant within the most proximal slice (Figure 4).

*Cortical Bone Response:*

In the posterior quadrant, valgus implant positioning resulted in significantly more bone volume having resorbing potential compared to the standard position from 5-15 mm beneath the resection plane (**5-10 mm**: 45° P=0.062, 75° P=0.019; **10-15 mm**: 45° P=0.032, 75 P=0.006) (Figure 4). Similarly, in the lateral quadrant valgus implant positioning resulted in significantly more bone volume having resorbing potential compared to the standard position from 0-30 mm beneath the resection plane (**0-5 mm**: 45° P=0.034, 75° P=0.031; **5-10 mm**: 45° P=0.024, 75° P=0.039; **10-15 mm**: 45° P=0.034, 75° P=0.019; **15-20 mm**: 45° P=0.008, 75° P=0.016; **20-25 mm:** 45° P=0.002, 75° P<0.001; **25-30 mm:** 45° P=0.024, 75° P=0.04) (Figure 4). In the medial quadrant, valgus implant positioning resulted in significantly less bone volume having resorbing potential compared to the standard position from 0-10 mm beneath the resection plane (**0-5 mm**: 45° P=0.096, 75° P=0.043; **5-10 mm**: 45° P=0.043, 75° P=0.024) and significantly more bone volume with resorbing potential compared to the standard position from 15-20 mm beneath the resection plane (**15-20 mm**: 45° P=0.008, 75° P=0.011). Also in the medial quadrant, varus implant positioning resulted in significantly more bone volume with resorbing potential compared to the standard position from 0-10 mm beneath the resection plane (**0-5 mm**: 45° P=0.038, 75° P=0.114; **5-10 mm**: 45° P=0.05, 75° P=0.29) (Figure 4). Looking at the trend in the anterior quadrant, valgus implant positioning resulted in significantly more bone volume with resorbing potential compared to the standard position from 0-10 mm beneath the resection plane (**0-5 mm**: 45° P=0.049, 75° P=0.04; **5-10 mm**: 45° P=0.002, 75° P=0.005) (Figure 4).

*Trabecular Bone Response:*

Similar trends were observed in the trabecular bone, with the valgus position producing the greatest volumes of bone with resorbing potential compared to the standard position. In the posterior quadrant, valgus implant positioning resulted in significantly more bone volume having resorbing potential compared to the standard position from 0-20 mm beneath the resection plane (**0-5 mm:** 45° P=0.019, 75° P=0.001;  **5-10 mm**: 45° P=0.007, 75° P=0.004; **10-15 mm**: 45° P=0.009, 75° P=0.001; **15-20 mm**: 45° P=0.018, 75° P=0.042) (Figure 4). Likewise, in the lateral quadrant, valgus positioned implants resulted in significantly more bone volume with resorbing potential when compared to the standard position at slice depths from 0-25 mm beneath the resection plane (**0-5 mm:** 45° P=0.005, 75° P=0.011;  **5-10 mm**: 45° P=0.01, 75° P=0.004; **10-15 mm**: 45° P=0.014, 75° P=0.012; **15-20 mm**: 45° P=0.026, 75° P=0.026; **20-25 mm**: 45° P=0.052, 75° P=0.042) (Figure 4). Additionally, in the lateral quadrant, varus positioning of the implant resulted in significantly more bone volume with resorbing potential compared to the standard position from 25-30 mm beneath the resection plane (**25-30 mm**: 45° P=0.135, 75° P=0.005) (Figure 4). Similarly, in the medial quadrant, valgus implant positioning resulted in significantly more bone volume having resorbing potential compared to the standard position from 10-20 mm and 30-40 mm beneath the resection plane (**10-15 mm**: 45° P=0.057, 75° P=0.037; **15-20 mm**: 45° P=0.06, 75° P=0.044; **30-35 mm**:45° P=0.015, 75° P=0.013; **35-40 mm**: 45° P=0.008, 75° P=0.009 ) (Figure 4).

In the anterior quadrant, valgus implant positioning produced significantly more bone volume with resorbing potential compared to the standard position from 0-5 mm beneath the resection plane (**0-5 mm:** 45° P=0.07, 75° P=0.045), which was also the same trend for varus implant positioning resulting in significantly more of its bone volume with resorbing potential compared to the standard position from 20-25 mm and 30-35mm below the resection plane (**20-25 mm**: 45° P=0.018, 75° P=0.023; **30-35 mm**: 45° P=0.101, 75° P=0.048 ) (Figure 4).

**DISCUSSION**

***Changes in Bone Stress***

The volume-weighted absolute average change in bone stress, Δσ, delivers an estimate for the magnitude of bone stress that was altered within the volume-of-interest relative to the intact state. Since the outcome measure is an absolute differential, it does not provide information on whether the stress value was overall higher or lower within the reconstructed bone; it simply reflects the total magnitude of change from the intact state. An ideal scenario is one in which the reconstructed state mimics the stress of the intact state and any alteration in the bone stress outcome measure is likely less favorable.

Changes in cortical bone stress generally decreased moving distally for all three implant positions, likely due to the increasing load transfer from the implant to the surrounding cortical bone; returning the stress state of the bone to its natural form. Varus and valgus implant alignment seemed to have the largest impact on changes in cortical bone stress in the posterior and lateral quadrants. Valgus alignment produced significantly larger changes in bone stress compared to the standard and varus implant alignment at depths greater than 5 mm below the humeral cut plane. There were also many slice depths in these quadrants, particularly in the range of 5-25 mm beneath the humeral cut plane where the valgus aligned implant altered cortical bone stress more than the varus aligned implant. In the medial quadrant, valgus alignment had the greatest impact on cortical bone stress in the most distal slices, likely a direct result of distal contact of the humeral stem with the medial cortex endosteum.

Similar trends were observed within trabecular bone where valgus implant alignment produced larger departures in bone stress from the intact state compared to the standard position, with the exception of the most distal slices in the medial quadrant, where interestingly the standard position produced significantly larger changes in bone stress compared to the varus position. It is also interesting to note that although the varus aligned implant produced larger departures in bone stress than the standard implant position, significant differences between these two implant positions were only detected in trabecular bone at 75º of abduction in the most proximal slice.

***Time-Zero Expected Bone Response***

Valgus implant alignment produced more potential for cortical bone resorption than the standard position in the lateral quadrant from 0-30 mm, and in the anterior quadrant from 0-10 mm beneath the humeral cut plane at time-zero. This was also found in the posterior and medial quadrants from 10-20 mm beneath the humeral cut plane. This may be due to distal contact of the valgus aligned stems with the medial cortex causing direct load transfer distally that unloads the proximal aspect of the humerus. Similar results were observed in trabecular bone, where the valgus implant alignment produced more expected bone resorption than the standard position in most of the slices between 0-25 mm beneath the humeral cut plane in the posterior and lateral quadrants, and a variety of slices in the medial and anterior quadrants.

The only locations where valgus alignment produced less expected bone resorption than the standard and varus positions were in the two most proximal slices of the medial quadrant. This trend reversal could be a result of the interaction of the points of load transfer of the valgus and varus aligned stems (Figure 5). The distal aspect of the valgus positioned stem is stabilized by contact with the medial cortex endosteum which prevented movement of the stem in the direction of adduction forming a ‘bottle opener’ effect. This may be exacerbated by the absence of humeral head contact with the lateral cortex, resulting in the implant being supported by the less stiff trabecular bone, thereby reducing load transfer laterally. Medial contact forces between the backside of the humeral head and the resection plane may have been elevated to counteract the moment produced by the distal stem contact resulting in less medial bone resorption directly beneath the humeral resection plane.

The varus aligned stem is initially stabilized by contact with the lateral cortex and, in contrast to valgus stem positioning, the distal stem can move freely in the medial direction. The lateral contact between the resection plane and the backside of the humeral head would normally counteract the applied joint reaction force. Since there was no lateral cortical contact, the humeral head subsided slightly into the trabecular bone and resulted in displacement of the distal stem away from the lateral cortex endosteum medially. This may explain why significant differences between the varus and standard positions were not typically observed.

The results of this work agree with the findings of Peduzzi et al12, who investigated stress shielding in 183 patients following TSA with Aequalis Ascend Flex short stems at 2 year follow up. Although they reported good mid-term results with no complications related to the stem, proximal bony adaptations were observed in 80.3% of patients. They also found that varus and valgus stem axis deviations increased the risk of bony adaptation, suggesting that implant positioning may also contribute to stress shielding in humeral short stem components. It is important to note that the stem design in their study included a different metaphyseal geometry, which may have affected the implant-bone load transfer patterns.

The presence of bone resorption potential in all implant positions investigated also agrees with clinical studies that have reported stress shielding in a large proportion of patients. In a study of 73 patients who had received uncemented short stem humeral components with a minimum 2 year follow up, Casagrande et al4 found that 71% of shoulders had signs of radiolucency and 8.7% were “at risk” of loosening before a minimum 3-year mark for follow up. The causes for humeral loosening and bone resorption were not clear in this study; however, lack of bony on-growth and stress shielding are mentioned as possible causes. Although Schnetzke et al15 reported good clinical outcomes and implant fixation in 82 patients that underwent TSA, they also reported that 13.6% of shoulders had stress shielding and resorption taking place at the medial cortex of the humeral calcar.

The present study has several strengths. Our analysis allowed for direct element-to-element comparison of bone stress and changes in strain energy density between the intact and the reconstructed states, enabling us to detect alterations in the distinct anatomical segments of the humerus bone. Joint loads were applied representing two distinct abduction angles, in which telemetrized shoulder implant data representative of certain daily tasks was utilized to represent clinically relevant cases. Eight humeri were virtually repeatedly reconstructed with three different stem positions, allowing for the comparison of bone stress between each implant position, something which would have not been achievable using in-vitro cadaveric testing due to the destructive nature of implantation. This allowed for repeated statistical assessments over the population of humeri investigated, which would not have been possible if a single bone model was employed.

This study also has several limitations. Assumptions made in assigning bone material properties, model boundary conditions, and expected bone response are necessary for computational modelling; and while they may induce error, it is important to note this error is constant throughout all models, and hence the comparison of results following the alteration of implant position are likely to be a direct result of this change in modelling parameter alone. Furthermore, the estimates obtained for expected bone response according to change in strain energy density alterations, are obtained immediately following humeral reconstruction, and therefore may not be indicative of long-term bone remodeling since the model is not iterative and does not account for the long-term bone remodeling process. Lastly, the incomplete coverage between the back side of the head and the resection plane might have altered bone-implant load transfer and amplified the differences measured between the three stem positions. Future investigations should consider varying degrees of humeral head backside contact to assess its impact on humeral bone stress following shoulder arthroplasty.

**CONCLUSIONS**

The results of this study show that the preferred positioning for a short stem humeral implant is a centered, standard implant position without any distal cortical contact. However, if distal contact must occur, valgus malposition may be worse than varus malposition in terms of changes in bone stress from the intact state, the expected time-zero bone response and subsequent stress-shielding.

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**FIGURE LEGENDS**

Figure 1: (A) Valgus (left), standard (middle), and varus (right) stem positions investigated, and (B) stem and head contact conditions.

Figure 2: Mean (±1 STD) von Mises of the change in cortical bone (left) and trabecular bone stress (right) for valgus (left), standard (middle), and varus (right) implant positions.

Figure 3: Mean (±1 STD) von Mises of the change in cortical bone stress (top) and trabecular bone stress (bottom) for the varus (inset top), standard (inset middle), and valgus (inset bottom) implant positions by anatomic quadrant (inset left to right) and slice depth (inset top to bottom).

Figure 4: Estimated time-zero bone response of cortical (top) and trabecular bone (bottom) for the varus (inset top), standard (inset middle), and valgus (inset bottom) implant positions by anatomic quadrant (inset left to right) and slice depth (inset top to bottom).

Figure 5: Points of contact for load transfer for the valgus (left) and varus (right) implant positions (forces responding to implant-bone load transfer represented by arrows) under the applied joint reaction force (shown in red).