The effect of stem fit on the radiocapitellar contact mechanics of a metallic axisymmetric radial head hemiarthroplasty: is loose fit better than rigidly fixed?

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Background: Radial head hemiarthroplasty is commonly used to manage comminuted displaced fractures. Regarding implant fixation, current designs vary, with some prostheses aiming to achieve a tight ''fixed'' fit and others using a smooth stem with an over-reamed ''loose'' fit. The purpose of this study was to evaluate the effect of radial head hemiarthroplasty stem fit on radiocapitellar contact using a finite element model that simulated both fixed (size-for-size) and loose (1-, 2-, and 3-mm over-reamed) stem fits. It was hypothesized that a loose stem fit would improve radiocapitellar contact mechanics, with an increased contact area and decreased contact stress, by allowing the implant to find its ''optimal'' position with respect to the capitellum.
Methods: Finite element models of the elbow were produced to compare the effects of stem fit on radiocapitellar contact of a metallic axisymmetric radial head implant. Radiocapitellar contact mechanics (contact area and maximum contact stress) were computed for 0°, 45°, 90°, and 135° of elbow flexion with the forearm in neutral rotation, pronation, and supination.
Results: The data suggest that the loose smooth stem radial head implant may be functioning like a bipolar implant in optimizing radiocapitellar contact. Over-reaming of 3 mm produced a larger amount of stress concentration on the capitellum, suggesting there may be a limit to how loose a smooth stem implant should be implanted.
Conclusions: The loose 1 to 2 mm over-reamed stem provided optimal contact mechanics of the metallic axisymmetric radial head implant compared with the fixed stem.
Level of evidence: Basic Science Study; Computer Modeling
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Keywords: Radial head; hemiarthroplasty; stem fit; contact mechanics; elbow; finite element analysis

Radial head hemiarthroplasty is commonly used to manage comminuted, displaced, unreconstructible radial head fractures, during which a prosthesis is substituted for the excised radial head in an attempt to restore elbow stability and load transfer.[9,15,21] Compared with radial head excision, radial head replacement reduces the forces on the remaining

ulnohumeral joint, potentially lowering the risk of arthritis, which is commonly reported after radial head excision.[2,10] Radial head replacement also serves to improve elbow and forearm stability in patients with concomitant ligament injuries, which occur in up to 75% of patients with comminuted radial head fractures.[2,8,10,19,21]

Despite advances in radial head prosthesis design, the clinical outcomes are variable and joint contact mechanics remain suboptimal.[6,7,12] The substitution of the cartilage surface of the native radial head with a metallic implant with a stiffness multiple orders of magnitude greater than that of the native cartilage may lead to cartilage degeneration and arthritis.[5,14-16] Minimizing peak contact stress and maximizing contact area following radial head hemiarthroplasty may well prevent the degradation of the native cartilaginous surface and improve the long-term outcomes of these devices.[11]

Currently, there is no consensus as to the optimal fixation technique of radial head prostheses in the proximal radius. Implant designs include textured ingrowth stems with a tight "fixed" fit, cemented stems, and smooth stems with either a "size-for-size" or over-reamed "loose" fit. The effect of stem fit on radiocapitellar contact mechanics has not been previously reported, although it has been indicated that rigidly fixing radial head prostheses may increase the risks of revision and complications.[1] It has been suggested that a radial head prosthesis with a smooth loose stem may function somewhat like a bipolar implant, allowing the concave articular surface of the implant to adjust to the relatively spherical capitellum to improve radiocapitellar contact; however, this has not been confirmed.

In view of the foregoing, this study quantified the effect of radial head hemiarthroplasty stem fit using a computational model in a series of cadaveric specimens following virtual radial head replacement. We hypothesized that a loose stem fit would be advantageous in terms of radiocapitellar contact mechanics, with a reduction in radiocapitellar joint incongruence, increased contact area, and decreased contact stress, by virtue of the ability of the loose implant to find its "optimal" position against the native capitellum.

Materials and methods

Model generation

A series of 3-dimensional elbow models were created using computed tomography (CT) data from 10 fresh-frozen cadaveric elbows (average age, 66.1 ± 18.5 years; 6 male and 4 female specimens). A GE Discovery CT750 HD scanner (GE Healthcare, Pewaukee, WI, USA) was used to obtain CT images at 120 kV and 200 mA with a slice thickness of 0.625 mm (voxel dimensions of 0.624 mm, 0.180-0.229 mm, and 0.190-0.229 mm in the axial, coronal, and sagittal directions, respectively).[22] The native elbows underwent CT scanning while intact and were then disarticulated and rescanned in air to establish accurate cartilage geometry for all

specimens.[22] Cartilage was modeled as a nonlinear elastic material, with bone material properties assigned based on CT attenuation.

Segmentation from CT data was conducted using Mimics (version 14.12; Materialise, Leuven, Belgium) to acquire bone geometry for each specimen using a minimum segmentation threshold for specimen bone and cartilage of +250 and –500 Hounsfield units, respectively. Bone and cartilage geometries were wrapped and remeshed using a radial basis function (FastRBF; FarField Technology, Christchurch, New Zealand). Subsequently, a quadrilateral mesh was generated on both the bone and cartilage surfaces (Netgen; RWTH Aachen University, Aachen, Germany) applying a maximum element edge length of 0.45 mm, previously justified by a mesh convergence study.[13] By use of a previously described method, custom code was used to mesh the cartilage using a hexahedral mesh.[22] As reported by Schenck et al,[18] on the basis of the average elbow cartilage aggregate modulus of 0.8 MPa and Poisson ratio of 0.07, a bulk modulus of 0.31 MPa and shear modulus of 0.37 MPa were assigned. To mesh the bone geometry, 1-mm linear tetrahedral elements were used with material properties assigned using a Poisson ratio of 0.3 and a density-modulus relationship ($E = 8345p_{app}^{1.5}$).[3] Cobalt chrome material properties ($E = 230$ GPa, $\nu = 0.3$) were assigned to the radial head prosthesis following meshing using 0.25-mm linear tetrahedral elements.

Finite element modeling

Finite element analysis was performed using Abaqus (version 6.14; Simulia, Providence, RI, USA). A tie constraint was used to bond the backside of the cartilage and subchondral bone of the dissimilar meshes of the native humerus. By use of a rigid body tie, the proximal humerus was connected to an individual guiding node to which boundary conditions were applied, constraining the humerus in all degrees of freedom. A commonly used axisymmetric implant shape (Evolve; Wright Medical Group, Memphis, TN, USA) was chosen for this study, with implant sizing for each specimen being conducted by an upper-extremity fellowship-trained orthopedic surgeon. The radial head implant was virtually positioned by an expert surgeon such that the long axis of the implant stem aligned with the native radial head axis. Fixation was varied from a fixed fit with respect to the radius, which disallowed motion, to a loose fit with a 1-, 2-, or 3-mm over-reamed (diametral clearance) stem fit. The 1-, 2-, and 3-mm over-reamed stem fits corresponded to a maximum allowable angulation of 2.3°, 4.6°, and 6.9°, respectively, based on a 25-mm stem length, which is standard for the implant studied (Fig. 1).[4] The fixed scenario mimicked a press-fit or cemented implant, whereby no rotation was permitted. The distal end of the ulna was then constrained in all degrees of freedom, after which a 100-N compressive load was applied to the radius, which articulated it with the humerus and ulna.[17,20] For the fixed stem fit, the radial head implant was not permitted to rotate out of plane; however, for each of the loose stem fits, the implant was permitted to rotate out of plane up to the maximum angle specified earlier for each fit. Surface-to-surface discretization was defined between the radial head implant and capitellar surface to establish penalty-based contact. A nonlinear modeling approach was used whereby assumptions regarding elements, loads, boundary conditions, and material stiffness were considered. As reported by Willing et al,[22] this modeling technique was found to
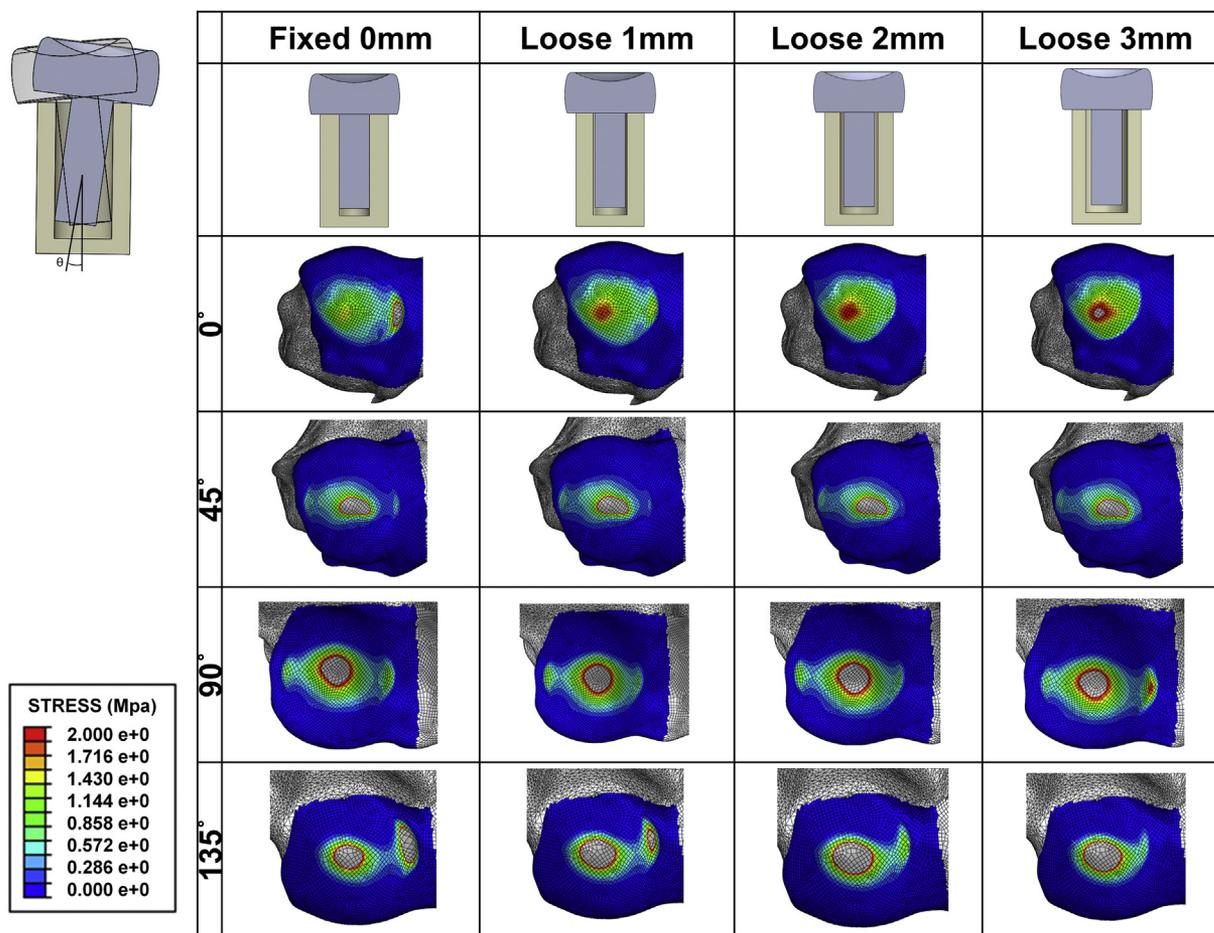
Figure 1   Capitellar contact stress maps and implant fit for 0-mm (fixed) stem fixation and 1-, 2-, and 3-mm (loose, *left* to *right*) over-reamed stem fixation.

yield contact areas within 10% of those acquired experimentally using a cadaveric elbow and a joint casting method.

## Study parameters and statistical analysis

Comparisons between fixed, 1-mm, 2-mm, and 3-mm radial head implant stem fits were made regarding changes in radiocapitellar contact area and maximum contact stress relative to the native intact state (Fig. 2). Radiocapitellar contact mechanics (contact stress and contact area) were computed for 0°, 45°, 90°, and 135° of elbow flexion with the forearm in neutral rotation. For each flexion or extension angle and implant fixation (fixed, 1 mm, 2 mm, and 3 mm), the outcome variables were normalized to the corresponding intact state, with comparison performed using a 2-way (flexion angle and stem fit) repeated-measures analysis of variance with the level of significance defined as $P < .05$.

Results

As the stem fit was loosened from fixed, the radial head was observed to angulate in the varus and valgus directions dependent on flexion angle, driven predominantly by impingement. At 0° of flexion, as the stem fit was loosened,

the radial head implant tilted into valgus, driven by contact in the trochlear groove, visible as the gray region of high contact stress (gray region indicating contact stress > 2 MPa) (Fig. 1). At this flexion angle, the 3-mm loose fit generated a new region of high contact stress at the center of the articular contact, visible as the gray region near the center of the capitellar surface. A similar result was observed at 45° and 135° of flexion, where increased loose stem fit moved the contact from the trochlear groove laterally into the center of the articulation or to the most lateral edge of contact. Finally, at 90°, the radial head tilted into varus once the loose fit reached 3 mm, resulting in regions of elevated contact stress in the trochlear groove (Fig. 3).

For all elbows and flexion angles investigated, the fixed stem fit radial head generated a mean contact area of 165.17 $\pm$ 28.45 mm^2. As the stem fit was progressively loosened, the contact area successively decreased for the 1-, 2-, and 3-mm stem fits, producing mean contact areas of 161.81 $\pm$ 30.11 mm^2, 152.83 $\pm$ 26.57 mm^2, and 139.90 $\pm$ 24.53 mm^2, respectively, for all angles of flexion investigated. Although no significant difference was detected between the fixed and 1-mm stem fits ($P \geq .181$), both the 2- and 3-mm over-reamed fits decreased the contact area, on average
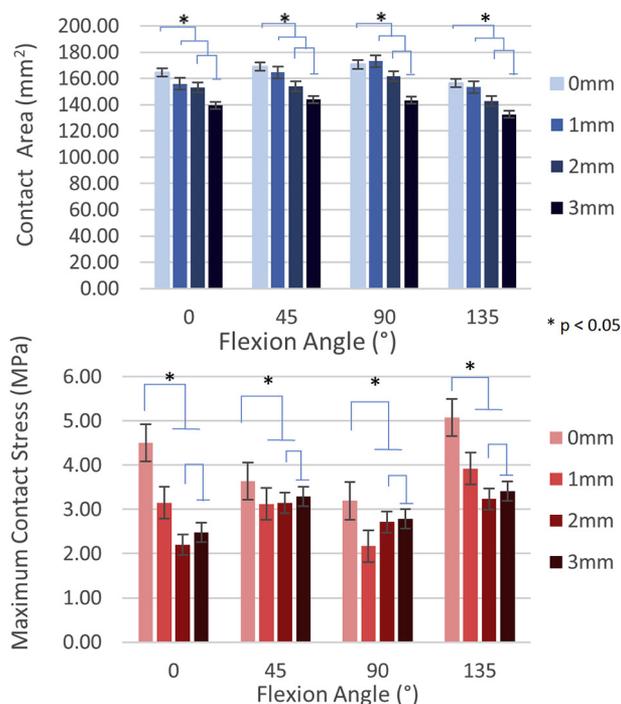
Figure 2 Mean (+/- 1 standard deviation) contact area (*top*) and maximum contact stress (*bottom*) for 0-mm (fixed) stem fixation and 1-, 2-, and 3-mm (loose, *left* to *right*) stem fixation (N = 10).

by 12.34 ± 6.17 mm^2 ($P < .001$) and 25.27 ± 12.637 mm^2 ($P < .001$), respectively, relative to the fixed stem fit (Fig. 2). In addition, increasing the looseness of the stem fit from 1 mm to 2 mm and 3 mm decreased the contact area by 8.98 ± 4.49 mm^2 ($P < .001$) and 21.91 ± 10.95 mm^2 ($P < .001$), respectively.

The fixed stem fit produced higher maximum radiocapitellar articular contact stress compared with the 1-, 2-, and 3-mm over-reamed stem fits for all angles of flexion, with peak contact stress of 4.10 ± 3.74 MPa for the fixed fit and 3.02 ± 2.35 MPa, 2.82 ± 2.17 MPa, and 3.00 ± 2.15 MPa for the 1-, 2-, and 3-mm fits, respectively (Fig. 2). On average, loosening the stem fit from fixed to 1-, 2-, and 3-mm over-reamed decreased maximum contact stress by 1.09 ± 2.74 MPa ($P < .017$), 1.28 ± 3.12 MPa ($P < .013$), and 1.10 ± 3.15 MPa ($P < .033$), respectively. No significant difference was detected between the 1- and 2-mm stem fits ($P \geq .41$) or between the 1- and 3-mm stem fits ($P \geq .94$). However, when the stem fit was increased from 2 to 3 mm, there was a small but significant increase in maximum contact stress of 0.21 ± 0.015 MPa ($P < .028$, Fig. 2). In addition, for each of the loose stem fits, for all flexion angles, the total angulation was equal to the maximum permitted value of stem tilt in the radial neck.

Discussion

A better understanding of the effects of radial head implant stem fit on radiocapitellar contact mechanics, with specific emphasis on over-reamed loose-fit fixation, may lead to improved clinical techniques, implant designs, and clinical outcomes. An interesting finding was that, as the stem fit was loosened, the total articular contact area decreased, which was contrary to our hypothesis. Although the contact area decreased, the corresponding maximum contact stress for the loose stem implants decreased because of a change in radial head angulation. In general, a decrease in contact area is associated with an increase in contact stress; however, in this case, the angulation of the implant was thought to be largely driven by impingement of the radial head in the trochlear groove. The resulting radial head angulation of the loose stem design alleviated these impingements, but this came at the cost of reduced contact area by virtue of the fact that the impingement resulted in radial head rotation to a less congruent position with the capitellum—particularly with implants with greater stem clearance.

The results of this study show that for the axisymmetric metallic radial head implant investigated, a fixed stem fit produced higher maximum articular contact stresses than all loose stem fits tested (1, 2, and 3 mm). This higher maximum contact stress produced by the fixed stem fit is thought to be the result of stress concentrations at local incongruities present between the radial head implant and the native capitellum during loading owing to the implant's inability to angulate to alleviate these regions of high contact stress. This was particularly apparent in the trochlear groove, where at 0°, 45° and 135° of flexion, the loose-fit radial head implants angulated in the valgus direction in response to impingement. However, at the largest loose-fit clearance, the implant appeared to have rotated so far in valgus that the contact stress in the center of the capitellum was elevated greater than that of the smaller clearance fits, particularly at 0° of flexion. At 90° of flexion, the opposite was observed, whereby the implant rotated in the varus direction reducing maximum contact stress for the 1- and 2-mm fits; however, the 3-mm fit permitted too much varus rotation, resulting in impingement in the trochlear groove.

An interesting finding was that, for all loose stem fits investigated, under 100 N of applied loading, all the radial head implants assumed a final angular position that was at—or very close to—the maximum angulation permitted by the respective loose fit (1 mm, 2.3°; 2 mm, 4.6°; and 3 mm, 6.9°). This is hypothesized to be the reason the 3-mm over-reamed stem fit had higher maximum contact stress than both the 1- and 2-mm stem fits. The extra angulation afforded by over-sizing the radial canal permitted too much freedom of motion, allowing the implant to rotate into a suboptimal orientation under the applied forearm load. These data seem to indicate that there was an optimal range for loose stem fits; excessive stem over-reaming should likely be avoided with this smooth stem implant design.

The radiocapitellar articular contact area was similar between the fixed stem fit and the 1-mm over-reamed stem but decreased with the 2- and 3-mm over-reamed fits. The contact area shifted from the lateral portion of the capitellar
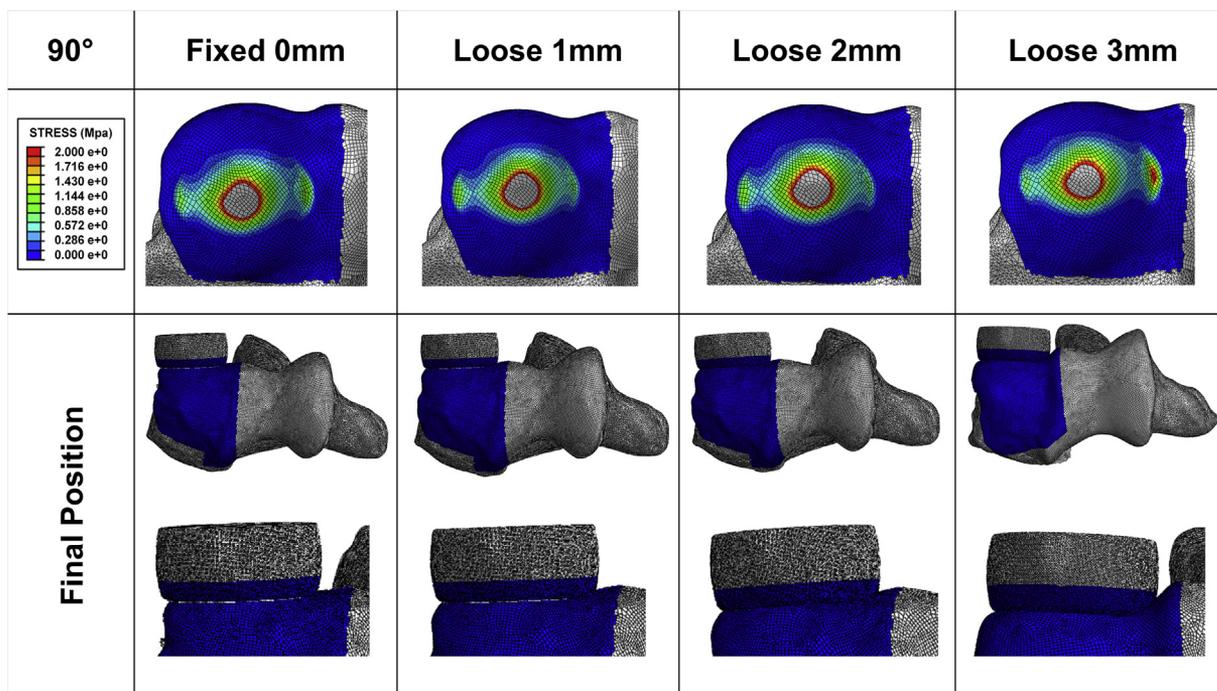
Figure 3 Capitellar contact stress maps and corresponding final implant positions at 90° of flexion for 0-mm (fixed) stem fixation and 1-, 2-, and 3-mm (loose, *left* to *right*) over-reamed stem fixation.

surface to a more even distribution with increased contact on the medial portion of the capitellum (Fig. 1). Although a decrease in contact area was seen with the 2- and 3-mm stem fits, providing a 1- or 2-mm loose stem fit produced a decrease in maximum articular contact stress and reduced local regions of stress concentrations relative to the fixed stem fit. These data suggest that a compromise between contact area and maximum contact stress may be needed when deciding how much over-reaming is optimal.

This study shows that loose stem fits in radial head hemiarthroplasty have the potential to reduce maximum articular contact stress for all flexion angles investigated. Comparing all loose stem fits, we found that the 2-mm over-reamed fit provided the greatest decrease in maximum contact stress, although this was accompanied by a decrease in radiocapitellar contact area. Although a reduction in radiocapitellar articular contact area may be a negative consequence, the decrease in maximum contact stress associated with the loose stem fits likely outweighs the reduction in contact area, as preventing local stress concentrations may help preserve the native cartilage and improve long-term patient outcomes. In addition, as suggested by Agyeman et al,[1] loose fitting may result in reduced risks of revision and complications.

Radiographic lucencies are known to commonly occur around smooth stem radial head arthroplasty implants and may reflect adjustment of the implant to better track with the capitellum.[20] This adjustment of implant position may be directed by the annular ligament or from the interaction of the concave articular surface of the radial head with the relatively spherical capitellum. Progression of lucencies around smooth stem implants is not typically seen over time and is not correlated with patient symptoms.[9,17] These data suggest that a loose smooth stem radial head implant may in fact be functioning in some respects as a bipolar implant, permitting angulation and rotation of the implant relative to the radius, which may improve radiocapitellar contact.

The strengths of this study include the repeated assessment of each specimen and the associated response to each stem fit investigated compared with the native state. Accurate bone and cartilage geometry was also applied using repeated CT data acquisition both while intact and in air for the study population of 10 elbows. Region-specific bone material properties were also simulated based on CT attenuation.

Limitations of this work include the assumptions associated with finite element analysis including the material models applied to the bone and cartilage, as well as the contact algorithms selected in the modeling process. Although these errors were present in all models and because all outcome variables are compared with the intact state, we are confident in the comparisons presented in this work. Furthermore, only 1 smooth stem metallic axisymmetric implant design was studied; further work should extend this to other implant shapes and materials. Finally, the use of computer simulation requires several assumptions, although previous work has shown that these assumptions result in less than 10% error for contact area.[22] A tribology study that assesses the wear rate of the cartilage using cadaveric specimens with varying laxities of radial head implants would be a fitting next step for this work.

Conclusion

The loose over-reamed stem provided improved contact mechanics compared with the fixed stem. The 1-mm over-reamed stem reduced maximum contact stress without significantly affecting contact area. Over-reaming of 2 mm provided the greatest decrease in maximum contact stress, albeit with a significant reduction in contact area. Over-reaming of 3 mm produced a larger amount of stress concentration on the capitellum, suggesting there may be a limit to how loose a smooth stem implant should be implanted. A fixed axisymmetric metallic radial head implant was shown to be less effective in distributing these regions of high contact stress and resultantly had the highest maximum cartilage stress. Over-reaming a smooth stem axisymmetric radial head implant by 1 to 2 mm provided improved elbow contact mechanics and may help to preserve the remaining native capitellar cartilage.

Disclaimer

Graham J.W. King is a consultant for Wright Medical Technologies and as such receives royalties for implant development related to the subject of this article. Wright Medical Technologies had no input into this research project in any manner.

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