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Edge-Loading Severity as a Function of Cup Lip Radius in Metal-on-Metal Total Hips – A Finite Element Analysis

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Abstract

While favorable tribological properties and allowance for larger femoral head sizes have made metal-on-metal bearings an increasingly popular choice for total hip arthroplasty, concerns have mounted regarding adverse reactions to metal wear debris and ions. Metal-on-metal cups differ from conventional polyethylene cups in terms of edge profile design and reductions from full hemisphericity, suggesting differences in loading at or near the cup edge, especially during subluxation events. Finite element analysis was used to investigate the effects of cup orientation and lip edge curvature on damage propensity for edge or near-edge loading during subluxation. Increased cup lip radius (resulting in reduced articular arc) had a detrimental effect upon subluxation-free hip range of motion and upon dislocation resistance. Contact stresses near the cup edge demonstrated complex relationships between edge radius and cup orientation, with peak stresses being influenced by both variables. The tendency for scraping wear at the egress site demonstrated similarly complex dependencies. These data indicate that acetabular cup design is an important determinant of edge and near-edge loading damage propensity.

Keywords

Total hip arthroplasty; finite element; metal-on-metal; subluxation; wear

Introduction

While metal on polyethylene (MoP) constructs are still numerically predominant in installed base of total hip replacements (THRs), concerns with long-term failure due to polyethylene wear have motivated resurgent interest in hard bearings (especially metal-on-metal, MoM) for use in younger, more active patients. As of 2009, it was estimated that MoM bearings accounted for 35% of the THRs implanted annually in the US ¹. While intermediate-term results for MoM bearings for both THR and resurfacing have been promising ²⁻⁴, concerns

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have heightened regarding the deleterious consequences of malpositioned and/or sub-optimally designed implants^{5,6}, especially as regards adverse immunologic or other biologic reactions (e.g. organ toxicity and neoplastic potential) to metallic particle and/or ion challenge in peri-articular tissues⁷⁻⁹. Of particular concern in MoM bearings is the occurrence of edge loading, where near line-contact between the femoral component head and the acetabular cup lip results in a very narrow crescent-shaped region of contact, and therefore highly concentrated stress. This deleterious engagement situation interferes with the precise articulation conditions necessary for fluid-film lubrication of hard bearings¹⁰, resulting in increased friction and accelerated wear¹¹. Cup orientation is the most commonly cited surgical factor influencing edge loading in hard bearings^{5,12-16}. The influences of femoral head size¹⁵⁻¹⁷ and soft tissue laxity in predisposing to “micro-separation”¹⁸⁻²⁰ are also recognized. Recently, however, the role of cup design – specifically, the role of head coverage (the cup’s “articular arc”)^{5,6} and of geometry of the cup edge²¹ – has drawn increased attention for edge loading propensity. To systematically explore those relationships, the present study was designed to test the hypothesis that there is a trade-off, in terms of increased head coverage versus more abrupt curvature sharpness of the cup edge, influencing the adverse mechanical stress concentrations developed during a subluxation event.

Materials and Methods

Finite element (FE) analysis was used to parametrically assess the independent influences of cup edge radius, cup inclination and cup anteversion as factors influencing edge-loading during subluxation. Dependent variables of primary interest were the range of motion, the resistance to dislocation, contact stress on the cup lip, and propensity for debris generation due to scraping. An established^{22,23} FE model of THR impingement/dislocation (Fig. 1) was applied to investigate edge-loading during subluxation. The model consisted of the hip capsule and a widely used contemporary implant (Summit stem, 36mm M-spec head, 36mm×56mm Pinnacle cup, DePuy Orthopaedics, Warsaw, IN). Manufacturer-provided surface geometry CAD files were pre-processed using TrueGrid (v. 2.3 XYZ Scientific Applications, Inc., Livermore, CA). For systematic investigation, the inner surfaces of the manufacturer-provided CAD surfaces were re-parameterized as simple surfaces of revolution, for which the (planar) curves of generation could then be modified to allow for any desired lip radius (and obligate arc of coverage) to be substituted. Seven cup profiles were considered, corresponding to lip radii of 0, 1, 2, 3, 4, 5, or 6mm (Fig. 2). Appropriate mesh zoning densities were determined from mesh sensitivity convergence trials. Mesh zoning of the liner was structured to provide high refinement near the edge of the cup (Fig. 3).

The global mechanics of the impingement/subluxation FE model had previously been physically validated using a cadaver preparation²³. However, because the present focus of interest was upon contact stress concentrations near the cup edge during subluxation, an additional useful metric for model validation was the ability to approximate severe stress concentrations for a geometrically similar situation where gold-standard data were available. A Hertzian analytical solution for general elliptical contact²⁴, for which sphere-on-torus (head-on-radiused rim lip) contact represents a special case, provides that standard. Good

agreement was achieved for all six variants of non-zero cup edge radius (Fig. 4), with a mean relative error of 8.8%. Owing to the higher mesh resolution at the radiused cup edge for cups with a smaller value of edge radius, contact solutions were slightly more accurate for lower values of r .

Cup inclination (abduction) effects were investigated by considering eleven distinct orientations, with tilt (radiographic definition²⁵) varying between 20° and 70°, in 5° increments. For these eleven inclination variants, the cup was held in a constant 10° of anteversion. Similarly, cup version was also investigated by generating ten additional orientations, with (radiographic) cup version between -6.5° and 25°, in 3.15° increments, at a constant 40° of inclination. For all FE simulations, the femoral stem was oriented in 10° of anteversion. The MoM bearing components were modeled as linearly elastic (CoCr, elastic modulus $E = 210\text{GPa}$, Poisson's ratio $\nu = 0.3$, density $\rho = 9.2\text{ gm/cc}$), with radial clearance δ of 0.029 mm, and with a friction coefficient μ of 0.1²⁶. The hip capsule, the major contributor to dislocation resistance, was modeled as an anisotropic fiber-dominated hyperelastic material, details for which are described elsewhere^{22, 23}.

The edge loading challenge investigated was a trunk leaning maneuver, such as when tying shoes²⁷. The motion and loading inputs were determined from kinematic and inverse dynamic data from human-subject optoelectronic motion capture²⁸, and were applied as boundary conditions to the center of the femoral head. The simulation began with the hip in full extension, and progressed (unless dislocation occurred) to approximately 103° of flexion, 22° of adduction and 7° of internal rotation.

The femoral head displacement and rotation and the moment resisting dislocation were tracked throughout the entire motion sequence. To avoid disparate situations with very different component appositions due to full or nearly-full dislocation, all comparisons were limited to poses having 2.0 mm or less of femoral head subluxation. Work done to displace the femoral head²³ was utilized as a comparative metric of resistance to dislocation. Additionally, the contact stress (von Mises), contact pressure, and local relative slippages of head vs. cup nodes were registered. Estimates for scraping wear²² were also computed, using an Archard-Lancaster formulation: $\dot{w} = p \cdot \dot{s} \cdot k$, where $\dot{w}$ is instantaneous local rate of wear, p is local contact pressure, $\dot{s}$ is the local relative sliding velocity, k and is a wear factor indicative of abrasiveness at the contact site²⁹.

A total of 147 separate cases were run, using Abaqus/Explicit 6.9.3. as the FE solver. Each individual simulation required approximately 30 processor-hours of computer time, on a dual quad-core Intel® Xeon platform configured with 24 GB of RAM, running under a 64-bit Linux operating system.

Results

The angular range of motion (ROM) showed strong dependencies upon both cup orientation and lip geometry (Figs. 5-6). For any given lip radius, as cup inclination increased, ROM increased (Fig. 5). This effect was most pronounced at larger lip radii. At 6 mm of lip radius, each 5° increase of inclination resulted in approximately 1° of increased ROM; for 0 mm lip

radius, each 5° inclination increase resulted in only 0.03° of ROM improvement. Similarly, for any given cup orientation, as lip radius increased, ROM decreased. Decreases of 1.65° and 0.02° per mm increase in lip radius were observed for cups with 20° and 70° of inclination, respectively. Similar relationships were observed between anteversion, lip radius and ROM (Fig. 6). However, ROM reductions from increased cup lip radius became negligible for cups with at least 10° of anteversion.

Head displacement work also sensitively depended upon cup design and orientation (Figs. 7-8). In general, displacement work increased for increased cup inclination, for increased cup anteversion, and for decreased lip radius. For cups at 20° of inclination (Fig. 7), each 1 mm of incremental increase in lip radius resulted in a 0.30 J decrease of displacement work. This stability reduction diminished as tilt increased: cups at 40°, 50°, 60° and 70° of tilt demonstrated per-mm displacement work decreases of 0.23, 0.17, 0.13 and 0.08 J, respectively. This effect was similar for cups at varying degrees of anteversion (Fig. 8), with per-mm decreases of 0.38, 0.28, and 0.05 J for cups in -3°, 3° and 9° of anteversion. However, there was only minimal dependency of displacement work on lip radius for cups anteverted to 9° or more.

More than half the permutations of cup orientation and lip radius (Fig. 9) had peak von Mises stresses that exceeded the yield strength of wrought CoCr alloy³⁰. A few situations of cup version also exceeded the material yield strength, but this happened only for cups positioned in less than 12° of anteversion (Fig. 10). Computed scraping wear (Fig. 11) tended to demonstrate similar dependency upon lip radius and cup inclination as was observed for peak stresses. The geometry and computed scraping wear was consistent with head damage patterns seen in posteriorly dislocated femoral head retrievals (Fig. 12).

Discussion

Precisely engineered elastohydrodynamic lubrication conditions in MoM bearings afford excellent wear properties during normal conformative articulation. However, these conditions probably no longer exist during edge loading. Rather, there is greatly accelerated bearing surface wear, and possible scraping wear from head engagement with the cup lip. The effect of cup orientation on bearing surface wear of hard bearings has been extensively investigated. Although most clinical retrieval and simulator studies have identified increased bearing surface wear for high inclination^{5, 12-14}, some have not^{16, 31}. Similarly, controversy exists regarding acetabular anteversion effects, with both increased^{15, 16} and decreased¹¹ wear having been measured. This inconsistency may be due in part the substantial differences of articular arcs among cup designs⁶. Additionally, predilection to different challenge activities by individual patients might also explain some of the high variability in orientation-vs.-wear relationships.

Edge loading is associated with soft tissue laxity and with ensuing micro-separation during gait¹⁸⁻²⁰. For gait-associated micro-separation, the most severe stresses occur near the superiolateral rim of the cup²⁰, an effect that tends to be worsened by increased cup inclination¹⁸. By distinction, the present study addresses more severe (albeit less frequently occurring) posterior lip edge loading arising from high hip flexion^{11, 32} associated with

leaning-type maneuvers. Leaning can progress to frank posterior dislocation for certain combinations of cup design and orientation even without impingement, either of neck-on-liner/shell or of bone-on-bone³³.

Corroborated by Hertzian contact analysis²⁴ it is intuitive that a reduction in contact stress with increased lip radius occurs for micro-separation loading conditions^{20, 21}. However, the present data suggest that micro-separation perhaps should not be viewed as an entirely “independent” variable for MoM wear simulations. Rather, design-dependent differences in cup lip geometry unavoidably influence subluxation dynamics, and therefore micro-separation severity, at the whole-construct level.

Computed contact stresses and edge scraping wear demonstrated complex relationships with lip geometry and cup orientation (Figs 9-11). Four separate factors interact to influence lip stress concentrations: (1) the subluxation resistance afforded by cup orientation; (2) the subluxation resistance afforded by lip geometry; (3) the onset of edge loading, *influenced in turn by cup orientation and geometry*, and (4) nominal head-cup engagement due to articulation arc span. For any given cup lip radius, increasing inclination (Fig 7) and increasing anteversion (Fig. 8) increased the work required to subluxate the head. Conversely, for any given cup orientation, increased lip radius involved decreased subluxation work. Consider for example a cup with 35° inclination (Fig 9): At a lip radius of 0 mm, edge loading was minimal due to maximal cup coverage of the head (i.e., no subluxation, Fig. 5). As the lip radius was increased to 3 mm, the articular arc necessarily decreased, and contact stress was necessarily elevated due to the associated subluxation and edge loading. For lip radii greater than 3 mm, however, although edge contact occurred earlier, edge loading intensity was reduced due to the lower subluxation resistance, and therefore contact stress was reduced. This same relationship held true for scraping wear (Fig. 11).

For all but the lowest values of lip radius, the best-case cup orientation fell outside the accepted “safe zone” for dislocation avoidance³⁴ (Fig. 13). That is to say, avoidance of dislocation and avoidance of near-edge stress concentration are divergent goals. Larger lip radii tended to avoid high edge-loading stresses, but their reduced articular coverage was detrimental to stability. Similar observations have been recently made regarding MoM resurfacing prostheses^{5, 6, 15}, where “cover appeared to be the most important factor explaining wear”⁵.

This study has several limitations. First, only a single challenge maneuver was considered. There potentially are an indeterminate number of patient-specific challenge maneuvers, and data presently are lacking as to how many and what type of such events occur. However, by eliminating potentially confounding influences of impingement on subluxation mechanics, the particular challenge here considered was useful in isolating the effect of cup design and orientation on near-edge loading. Second, while the present study investigated a total of 147 distinct variants of cup design and orientation, only a single-sized (36mm) implant was considered. Since the increased jumping distance afforded by large heads³⁵ helps protect against dislocation³⁶, it would be expected that larger heads would influence the tendency for scraping wear. The effect of head size on posterior edge-loading wear is an inviting

subject for future studies. Finally, in numerous cases, the peak computed von Mises stresses approached or exceeded the yield strength of CoCr alloy. This implies onset of plastic deformation. While the details of such deformation could potentially have been explored through the use of an elasto-plastic material model for CoCr, doing so would have come at the expense of greatly more complexity of the analysis and with no clear basis for validation of that aspect of the model. Rather, it seems reasonable and sufficient to take the stance that onset of material yield is categorically an adverse occurrence, regardless of the details of how much plastic strain occurs.

In conclusion, the present data demonstrate complex relationships between cup lip geometry, cup orientation and edge loading-associated scraping wear. Under subluxation conditions, radiused cup edges can unintentionally lead to elevated contact pressures, higher risk of material yield, and/or potentially more severe scraping wear. And, importantly, even small changes in bearing surface design can dramatically influence these THR performance parameters.

Acknowledgments

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References

1. Bozic KJ, Kurtz S, Lau E, et al. The epidemiology of bearing surface usage in total hip arthroplasty in the United States. *J Bone Joint Surg Am.* 2009; 91:1614–1620. [PubMed: 19571083]
2. Girard J, Bocquet D, Autissier G, et al. Metal-on-metal hip arthroplasty in patients thirty years of age or younger. *J Bone Joint Surg Am.* 2010; 92:2419–2426. [PubMed: 20962192]
3. Zywiell MG, Sayeed SA, Johnson AJ, Schmalzried TP, Mont MA. Survival of hard-on-hard bearings in total hip arthroplasty: A systematic review. *Clin Orthop Relat Res.* Epub ahead of print.
4. Amstutz HC, Grigoris P. Metal on metal bearings in hip arthroplasty. *Clin Orthop Relat Res.* 1996; (329 Suppl):S11–34. [PubMed: 8769320]
5. De Haan R, Pattyn C, Gill HS, et al. Correlation between inclination of the acetabular component and metal ion levels in metal-on-metal hip resurfacing replacement. *J Bone Joint Surg Br.* 2008; 90:1291–1297. [PubMed: 18827237]
6. Griffin WL, Nanson CJ, Springer BD, Davies MA, Fehring TK. Reduced articular surface of one-piece cups: A cause of runaway wear and early failure. *Clin Orthop Relat Res.* 2010; 468:2328–2332. [PubMed: 20480405]
7. Hosman AH, van der Mei HC, Bulstra SK, Busscher HJ, Neut D. Effects of metal-on-metal wear on the host immune system and infection in hip arthroplasty. *Acta Orthop.* 2010; 81:526–534. [PubMed: 20860450]
8. Silva M, Heisel C, Schmalzried TP. Metal-on-metal total hip replacement. *Clin Orthop Relat Res.* 2005; 430:53–61.
9. Pandit H, Glyn-Jones S, McLardy-Smith P, et al. Pseudotumours associated with metal-on-metal hip resurfacings. *J Bone Joint Surg Br.* 2008; 90:847–851. [PubMed: 18591590]
10. Udofia IJ, Yew A, Jin ZM. Contact mechanics analysis of metal-on-metal hip resurfacing prostheses. *Proc Inst Mech Eng H.* 2004; 218:293–305. [PubMed: 15532995]
11. Lusty PJ, Watson A, Tuke MA, et al. Wear and acetabular component orientation in third generation alumina-on-alumina ceramic bearings: An analysis of 33 retrievals. *J Bone Joint Surg Br.* 2007; 89:1158–1164. [PubMed: 17905951]

12. Brodner W, Gröbl A, Jankovsky R, et al. Cup inclination and serum concentration of cobalt and chromium after metal-on-metal total hip arthroplasty. *J Arthroplasty*. 2004; 19:66–70. [PubMed: 15578556]
13. Khan M, Kuiper JH, Richardson J. The exercise-related rise in plasma cobalt levels after metal-on-metal hip resurfacing arthroplasty. *J Bone Joint Surg Br*. 2008; 90:1152–1157. [PubMed: 18757953]
14. Williams S, Leslie I, Isaac G, et al. Tribology and wear of metal-on-metal hip prostheses: Influence of cup angle and head position. *J Bone Joint Surg Am*. 2008; 90(Sup3):111–117.
15. Langton D, Jameson S, Joyce T, et al. Early failure of metal-on-metal bearings in hip resurfacing and large-diameter total hip replacement: A consequence of excess wear. *J Bone Joint Surg Br*. 2010; 92:38–46. [PubMed: 20044676]
16. Bernstein M, Walsh A, Petit A, Zukor DJ, Antoniou J. Femoral head size does not affect ion values in metal-on-metal total hips. *Clin Orthop Relat Res*. Epub ahead of print.
17. Leslie I, Williams S, Brown C, et al. Effect of bearing size on the long-term wear, wear debris, and ion levels of large diameter metal-on-metal hip replacements? An in vitro study. *J Biomed Mater Res B Appl Biomater*. 2008; 87B:163–172.
18. Leslie IJ, Williams S, Isaac G, Ingham E, Fisher J. High cup angle and microseparation increase the wear of hip surface replacements. *Clin Orthop Relat Res*. 2009; 467:2259–2265. [PubMed: 19363640]
19. Al-Hajjar M, Leslie IJ, Tipper J, et al. Effect of cup inclination angle during microseparation and rim loading on the wear of Biolox Delta ceramic-on-ceramic total hip replacement. *J Biomed Mater Res B Appl Biomater*. 2010; 95:263–268. [PubMed: 20860044]
20. Mak MM, Besong AA, Jin ZM, Fisher J. Effect of microseparation on contact mechanics in ceramic-on-ceramic hip joint replacements. *Proc Inst Mech Eng H*. 2002; 216:403–408. [PubMed: 12502004]
21. Mak M, Jin Z, Fisher J, Stewart TD. Influence of acetabular cup rim design on the contact stress during edge loading in ceramic-on-ceramic hip prostheses. *J Arthroplasty*. 2011; 26:131–136. [PubMed: 20149581]
22. Elkins JM, O'Brien MK, Stroud NJ, et al. Hard-on-hard total hip impingement causes extreme contact stress concentrations. *Clin Orthop Relat Res*. 2011; 469:454–463. [PubMed: 20953853]
23. Elkins JM, Stroud NJ, Rudert MJ, et al. The capsule's contribution to total hip construct stability - A finite element analysis. *J Orthop Res*. 2011 Epub ahead of print.
24. Antoine J, Visa C, Sauvey C, Abba G. Approximate analytical model for Hertzian elliptical contact problems. *J Tribology*. 2006; 128:660–664.
25. Murray D. The definition and measurement of acetabular orientation. *J Bone Joint Surg Br*. 1993; 75:228–232. [PubMed: 8444942]
26. Brockett C, Williams S, Jin Z, Isaac G, Fisher J. Friction of total hip replacements with different bearings and loading conditions. *J Biomed Mater Res B Appl Biomater*. 2007; 81:508–515. [PubMed: 17041924]
27. Pedersen DR, Callaghan JJ, Brown TD. Activity-dependence of the “safe zone” for impingement versus dislocation avoidance. *Med Eng Phys*. 2005; 27:323–328. [PubMed: 15823473]
28. Nadzadi ME, Pedersen DR, Yack HJ, Callaghan JJ, Brown TD. Kinematics, kinetics, and finite element analysis of commonplace maneuvers at risk for total hip dislocation. *J Biomech*. 2003; 36:577–591. [PubMed: 12600348]
29. Archard J. Contact and rubbing of flat surfaces. *J Appl Phys*. 1953; 24:981–988.
30. ASTM F-799-95. Standard specification for cobalt-28 chromium-6 molybdenum alloy forgings for surgical implants. American Society for Testing and Materials. 1995; 13.01:230–232.
31. Johansson HR, Johnson AJ, Zywił MG, et al. Does acetabular inclination angle affect survivorship of alumina-ceramic articulations? *Clin Orthop Relat Res*. Epub ahead of print.
32. Walter WL, Insley GM, Walter WK, Tuke MA. Edge loading in third generation alumina ceramic-on-ceramic bearings: Stripe wear. *J Arthroplasty*. 2004; 19:402–413. [PubMed: 15188097]
33. Scifert CF, Noble PC, Brown TD, et al. Experimental and computational simulation of total hip arthroplasty dislocation. *Orthop Clin North Am*. 2001; 32:553–67. vii. [PubMed: 11689369]

34. Lewinnek GE, Lewis JL, Tarr R, Compere CL, Zimmerman JR. Dislocations after total hip-replacement arthroplasties. *J Bone Joint Surg Am.* 1978; 60:217–220. [PubMed: 641088]
35. Sariali E, Lazennec JY, Khiami F, Catonne Y. Mathematical evaluation of jumping distance in total hip arthroplasty: Influence of abduction angle, femoral head offset, and head diameter. *Acta Orthop.* 2009; 80:277–282. [PubMed: 19421906]
36. Berry DJ, von Knoch M, Schleck CD, Harmsen WS. Effect of femoral head diameter and operative approach on risk of dislocation after primary total hip arthroplasty. *J Bone Joint Surg Am.* 2005; 87:2456–2463. [PubMed: 16264121]

Fig 1.

Anterior-to-posterior view of the THR finite element model of edge loading at approximately 80° flexion. The model consisted of a 36mm MoM implant (stem, head, liner and shell) as well as the hip capsule and the acetabular and femoral bony beds. The kinematics of the leaning motion challenge resulted in posteriorly-directed head slide-out subluxation/dislocation. For visual clarity, the bony beds and the anterior region of the hip capsule have been rendered transparent.

Fig 2.

The articular coverage arc (α) of the liner is a function of the cup lip radius (r). For an edge radius of 2 mm (r_1 , left cup edge), the corresponding articular arc (α_1) was approximately 168°. When increasing the edge radius to 6 mm (r_2), the articular arc (α_2) decreased to 153.5°. The articular arcs corresponding to the additional lip radii considered were as tabulated.

Fig 3.

Contact pressures (MPa) are shown for the six non-zero cup radii used in the validation series. Contact simulations were highly sensitive to mesh resolution near the engagement site. Therefore, mesh zoning resolution, which was determined from mesh sensitivity convergence studies, was approximately equal for the entire egress contact region (shown here as the outlined elements near the edge of the cup).

Fig 4.

Validation of the FE simulations was conducted by comparing the computed contact pressures for edge-loading with corresponding Hertzian exact solutions for Hertzian elliptical (sphere-on-torus, upper right background image) contact. The specific cases used were a cup in 40° of inclination and 10° of anteversion (left background image), at six values of cup lip radius. (The condition of 0 mm cup lip radius did not meet the predicate analytical solution conditions for elliptical contact.) The mean error in peak stress was 8.8%.

Fig 5. Subluxation-free range of motion (ROM) for 77 permutations of cup lip radius and cup inclination. In general, ROM was reduced for increased values of cup lip radius and decreased cup inclination. The changes in ROM due to lip radius change were most profound for the more horizontally oriented cups. Contact pressure contours for the 5-mm lip radius cases are shown in the lower insets.

Fig 6.

Subluxation-free range of motion (ROM) for 77 permutations of cup lip radius and cup anteversion. Similar to the inclination series (Fig. 5), ROM was decreased for both increased values of cup lip radius and decreased cup anteversion. However, ROM at higher anteversion angles was less sensitive to cup lip radius. Contact pressure contours for the 5-mm lip radius cases are shown in the lower insets.

Fig 7.

Subluxation resistance work for 77 permutations of cup lip radius and cup inclination. Resistance energy was greatest for cups with the smallest lip radius at higher cup orientations. The effect of cup lip radius was most pronounced at more horizontal orientations, where increasing the cup edge radius from 0mm (3.3 J) to 6mm (1.4 J) for a cup in 20° of inclination resulted in a 60% reduction in dislocation resistance energy.

Fig 8. Subluxation resistance work for 77 permutations of cup lip radius and cup anteversion. In general, dislocation resistance increased for decreased values of cup lip radius and increased cup anteversion. However, cup edge design demonstrated little effect for cups anteverted at least 15°.

Fig 9.

Computed peak values of surface (contact) von Mises stress versus cup lip radius for the eleven cup inclinations. For the higher cup inclinations (60°, 65° and 70°), polynomial regression trends (broken lines) demonstrate a distinct intermediate cup radius (~1.7 – 2.6 mm) for which peak contact pressure is predicted to be minimal. By contrast, trends for lower cup inclinations (20°-40°) all demonstrate a distinct radius for which peak contact stress is maximized. Intermediate cup inclinations (45°, 50° and 55°) demonstrate lip radii having both local minima and maxima of peak contact stress. Many of the permutations of cup lip radius and cup inclination demonstrated surface stresses in excess of the yield strength of wrought Co-Cr alloy (827 MPa, horizontal solid line), indicating a likelihood of permanent material deformation at the cup edge.

Fig 10.

Peak surface von Mises surface stress versus cup version, for the seven cup lip radii. Variations in surface stress were greatest for lower values of cup anteversion, but demonstrated minimal variation for cups in 9° or more of anteversion. Many permutations of cup lip radius and cup orientation demonstrated surface stresses in excess of the yield strength of wrought Co-Cr alloy (horizontal solid line), indicating high likelihood of permanent deformation at the cup edge.

Fig 11.

Computed values of volumetric scraping wear versus cup chamfer radius for various cup inclinations at 6° of anteversion. Scraping wear tended to decrease with increasing lip radius, especially for radii above 2mm, but there were several instances of heightened scraping for conditions of low inclination and small lip radius.

Fig 12. Scraping wear scar computed on the femoral head for a 40° inclined, 6° anteverted cup with a 3 mm radius. A similar damage feature is apparent on a femoral component head (similar trunnion taper axis orientation) from an implant that was revised at 2 months due to dislocation.

Fig 13.

As a function of lip radius, values for inclination angle (left axis, circle symbols) and anteversion (right axis, square symbols) having the minimal peak surface stress. For cups with a lip radius greater than 1 mm, these “best-case” cup orientations lie outside the generally accepted “safe zone” for THR implantation.