Stability and Trunnion Wear Potential in Large-diameter Metal-on-Metal Total Hips

A Finite Element Analysis

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Abstract

Background Large-diameter femoral heads for metal-on-metal THA hold theoretical advantages of joint stability and low bearing surface wear. However, recent reports have indicated an unacceptably high rate of wear-associated failure with large-diameter bearings, possibly due in part to increased wear at the trunnion interface. Thus, the deleterious consequences of using large heads may outweigh their theoretical advantages.

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Questions/purposes We investigated (1) to what extent femoral head size influenced stability in THA for several dislocation-prone motions; and the biomechanics of wear at the trunnion interface by considering the relationship between (2) wear potential and head size and (3) wear potential and other factors, including cup orientation, type of hip motion, and assembly/impaction load.

Methods Computational simulations were executed using a previously validated nonlinear contact finite element model. Stability was determined at 36 cup orientations for five distinct dislocation challenges. Wear at the trunnion interface was calculated for three separate cup orientations subjected to gait, stooping, and sit-to-stand motions. Seven head diameters were investigated: 32 to 56 mm, in 4-mm increments.

Results Stability improved with increased diameter, although diminishing benefit was seen for sizes of greater than 40 mm. By contrast, contact stress and computed wear at the trunnion interface all increased unabatedly with increasing head size. Increased impaction forces resulted in only small decreases in trunnion wear generation.

Conclusions These data suggest that the theoretical advantages of large-diameter femoral heads have a limit. Diameters of greater than 40 mm demonstrated only modest improvement in terms of joint stability yet incurred substantial increase in wear potential at the trunnion.

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Clinical Relevance Our model has potential to help investigators and designers of hip implants to better understand the optimization of trunnion design for long-term durability.

Introduction

Concerns regarding wear-associated failure of conventional bearings for THA have provided impetus for renewed interest in metal-on-metal (MOM) bearings, especially for use in younger and more physically active patients. From an engineering standpoint, MOM bearings offer several advantages over conventional implants, including a reduction in bearing surface wear and improved joint stability, both benefits ensuing from the larger head diameters. These assets are reflected in the intermediate-term clinical results of current-generation modest-diameter MOM bearings [30, 58]. However, there is rapidly mounting concern over wear-associated adverse soft tissue reactions after some MOM hip arthroplasties. These adverse local tissue reactions, variably referred to as metallosis [18], aseptic lymphocytic vasculitis-associated lesions [56], pseudotumors [48], and adverse reaction to metal debris [39], have been implicated in unacceptably high short-term failure rates for some MOM devices [5, 9, 19, 38, 39]. The exact mechanism(s) for failure of these devices are incompletely understood. Cup orientation [36, 57], cup geometry [16, 23], and microseparation [40] have all been suggested as contributing factors.

Recently, attention has focused on increased failure rates associated with large-diameter femoral heads used in MOM THA [4, 5, 9, 38, 39]. There is increasing evidence that tissue reaction to wear and corrosion at the head-neck interface (trunnionosis) (Fig. 1), as opposed to reaction to wear at the bearing surface, may play a significant role in failure of large-diameter MOM THAs [5, 28, 38]. Additionally, tissue reactions consistent with metallosis have recently been reported for metal-on-polyethylene THAs [43, 55], suggesting that trunnionosis-type wear is not unique to MOM bearing couples. Trunnion wear increases for larger-diameter heads plausibly might arise because of micromotion accompanying increased offset between the head center and the trunnion interface center of pressure (Fig. 2).

Femoral head size is a critical consideration for MOM bearings. Tribologic theory dictates improved fluid film lubrication, and therefore reduced bearing surface wear, for increased head sizes [52], a relationship that has been well confirmed by wear simulator testing [21]. Impingement avoidance, facilitated by the increased ROM accompanying increased head diameter, is perhaps even more critical for MOM bearings than for conventional implants, due to impingement-associated accelerated wear potential [24].

Fig. 1 An intraoperative image shows an MOM implant trunnion during revision THA from a patient with pain and elevated metallic ions 3 years postoperatively. Visually extensive corrosion (white arrow) was identified along the distal aspect of the trunnion. Gross macroscopic wear was identified on the trunnion surface, especially at the leading and trailing edges (blue arrows). Histology confirmed adverse tissue reaction to metal debris.

This improvement in impingement-free ROM, as well as increased femoral head “jump distance,” has resulted in some surgeons using large-diameter THAs to reduce the incidence of dislocation [49]. However, especially for large head diameters, the exact relationship between head size and joint stability remains unclear. Despite various clinical [3, 15, 42, 53], experimental [3, 10], and computational [17, 51] reports, there is no clear agreement as to whether there exists a practical limit in regard to improved stability with increased head size. Femoral diameter cutoffs have been identified at 28 mm [3], 32 mm [11], and 38 mm [10], beyond which increased head diameter no longer improves stability. Additionally, there is conflicting evidence whether the stability afforded by the use of large heads is [11] or is not [14] maintained when there is cup malpositioning. An important limitation to several of these studies of instability has been the use of simplified joint motions or limited ranges of cup orientations.

In consideration of recent observations related to trunnionosis-associated wear from large-diameter THA heads, we determined whether there was a point beyond which additional gains in stability might begin to be outweighed by increases in wear potential at the trunnion. Using a purpose-developed computational model, we addressed (1) the extent to which large femoral head size influences stability in THA for realistic dislocation-prone motions; and the biomechanics of wear at the trunnion interface by considering the relationship between (2) wear potential and head size and (3) wear potential and other factors, including cup orientation, type of hip motion, and assembly/impaction load.

Fig. 2A–G The finite element model consisted of THA hardware, the proximal femur, and (A) the hemipelvis, and (B) the hip capsule. (C) When appropriately seated on the tapered trunnion of the neck, a moment arm exists between the center of rotation of the head and the

center of pressure on the trunnion. Femoral head diameters used in this study included (A) 32, (B) 36, (C) 40, (D) 44, (E) 48, (F) 52, and (G) 56 mm. The trunnion-bore geometry was identical for all neck-head assemblies.

Materials and Methods

A previously developed [24] and physically validated [25] finite element model of MOM THA was used in this investigation. The computational zoning had been optimized for bearing contact and edge loading [23] by comparison with an analytical Hertzian contact stress solution reported by Sanders and Brannon [50]. The finite element model consisted of bony members (National Library of Medicine Visible Male Project), the hip capsule, and THA hardware (Fig. 2). Manufacturer-provided engineering computer-aided design files of a widely used contemporary THA implant (Summit[®] stem, 36-mm M-spec head, 36- × 56-mm Pinnacle[®] cup; DePuy Orthopaedics, Inc, Warsaw, IN, USA) were preprocessed using TrueGrid[®] (Version 2.3; XYZ Scientific Applications, Inc, Livermore, CA, USA) and Mathcad[®] (Version 14; Parametric Technology Corp, Needham, MA, USA) software. Seven distinct femoral head diameters were generated by projecting the outer surface of the femoral head mesh onto scaled surfaces. The surface geometry of the femoral head bore and surrounding elements remained identical for each. The acetabular shell and liner were also scaled, while

maintaining a constant nominal liner thickness (10 mm) and cup edge fillet radius (approximately 4 mm). The femoral neck, head, and cup liner were modeled as linearly elastic cobalt-chromium (modulus = 210 GPa, Poisson's ratio = 0.3, density = 9.2 gm/cm³) using deformable eight-noded hexahedral elements. The manufacture-specified radial clearance of 0.029 mm was assigned for each simulation. The kinematic frictional coefficient between the femoral head and liner at the bearing surface was assumed to be 0.1 [7], while the coefficient at the trunnion interface between the trunnion and bore was 0.15 [26]. In the interest of computational economy for the stability assessments, the bony anatomy, shell liner, distal neck, and femoral stem were modeled with rigid shell elements. Details for capsular material properties are described elsewhere [25].

The femoral head was seated (taper-locked) onto the trunnion of the neck by applying an impaction load having an impulse duration of 20 milliseconds. Loads considered ranged from 1 to 17 kN, applied to the reference node of the head in the direction of the neck axis (Fig. 3). Appropriate mesh densities for the trunnion and head bore were determined from a convergence study (Fig. 4), from which a final mesh density of 10 elements/mm³ at the interface

Fig. 3A–C Impactation seating of the trunnion-head interface was performed by (A) simulating a single impulsive (20-millisecond) load to the femoral head in a direction parallel to the axis of the trunnion, (B) resulting in initial contact between the trunnion and head bore.

(C) The head was firmly seated at the end of the impaction impulse. Loads of 5 kN (baseline), 1 kN (low), and 17 kN (high) were considered [22, 33].

was determined to provide compromise between solution precision and computational economy.

Head diameter effects on stability were addressed by considering 36 separate cup orientations: six values of acetabular abduction (anatomic definition [46]) (25°–75°, in 10° increments) and six values of acetabular anteversion (0°–50°, in 10° increments). Five distinct dislocation-prone challenges [47] were used as kinematic and kinetic inputs for the simulations. These involved four separate posterior-dislocation-prone challenges (stooping, squatting, sit-to-stand from a low chair, and sit-to-stand from a normal height) and one anterior-dislocation-prone maneuver (lateral foot pivoting). This ratio of posterior to anterior dislocation challenges is similar to the posterior to anterior incidence observed clinically [20]. Five distinct values of femoral head size were used in this part of the study: 32, 36, 40, 44, and 48 mm, resulting in a total of 900 distinct finite element instability simulations. In all instances, femoral component anteversion was held constant at 10°. The kinematic and loading inputs were applied to a rigid body reference node located at the center of the femoral head. Frictional interaction held the cup liner

within the acetabular cup backing, which in turn was rigidly fixed to the bony bed. Because the primary objective of these first 900 simulations was to investigate joint stability rather than trunnion wear, the entire femoral neck was assumed to be a rigid monobloc to economize computer run time. For each simulation, femoral head subluxation, defined as the magnitude of separation between the center of the femoral head and the articular center of the cup liner, was tracked through the entire input sequence. Subluxation of the femoral head of less than 1 mm was used as an index of stability.

A second series of 65 finite element simulations was undertaken to address the potential for wear debris generation at the trunnion-bore interface. The model development for the trunnion wear series was similar to that for the stability series, with the exception of modeling the femoral neck as deformable cobalt-chromium with eight-noded continuum elements. For this series, three cup orientations (radiographic definition) were considered, including horizontally (25° abduction, 0° anteversion), neutrally (40° abduction, 15° anteversion), and vertically (55° abduction, 30° anteversion) positioned

Fig. 4 A contact analysis convergence study was used to determine the appropriate mesh density used for the trunnion-bore assembly. Peak values of contact stress at the interface were recorded during the head seating analysis step. A nominal mesh density of 10 elements/

mm³ was deemed to provide suitably accurate solutions, consistent with reasonable computational economy. CPU = central processing unit.

cups. Seven distinct femoral head diameters were investigated: from 32 to 56 mm, in 4-mm increments. To investigate the effect of activity movement on trunnion wear potential, three distinct patient motions were considered: gait, stooping, and sit-to-stand from a normal chair height. For each simulation, contact loads and contact stresses occurring at both the bearing surface and trunnion interface were recorded. To investigate the relationship between trunnion wear potential and taper seating load, three distinct impaction loads were considered: a standard value of 5 kN [33], a low value of 1 kN, and a high value [22] of 17 kN. Wear at the trunnion interface was modeled using the Archard relationship [1]: $\dot{w} = p * \dot{s} * k$ where $\dot{w}$ is instantaneous local rate of linear wear, p is local contact pressure, $\dot{s}$ is the local relative interfacial sliding velocity, and k is a tribologically dependent wear factor. For these simulations, a wear factor of $1.13 \times 10^{-8} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ was used [41].

A total of 965 finite element simulations were thus run using ABAQUS/Explicit Extended Functionality 6.10.EF (Simulia, Providence, RI, USA) as the finite element

solver, executed on a 64-bit Unix operating system with twin dual-quad-core Intel® Xeon® platforms configured with 24 GB of random access memory. Each of the 900 simulations for the THA stability series required approximately 13 processor hours of computer time, whereas each of the 65 simulations for the trunnion wear series required approximately 72 processor hours.

Results

Head Size and Stability

Femoral head subluxation was found to be strongly dependent on both cup orientation and femoral head diameter (Fig. 5). For posterior instability challenges, femoral head subluxation was greatest at low values of cup inclination and low values of cup anteversion. For anterior instability, subluxation was greatest for high values of cup anteversion and for high values of cup inclination. Increasing femoral head diameter had a more pronounced effect on reducing

Fig. 5A–E Femoral head subluxation was tracked during the entire input kinematic sequence for each simulation. Numerical values of subluxation during the stooping, sit-to-stand low, sit-to-stand normal, squatting, and foot pivoting dislocation challenges were averaged for each of the 36 separate cup orientations (rendered here in radiographic orientation) for a femoral stem in 10° of anteversion. (A) For the 32-mm head diameter, average femoral head subluxation was greatest for cups positioned in low values of acetabular anteversion and inclination and for cups positioned in high anteversion. Subluxation was similarly determined for head diameters of (B) 36, (C) 40, (D) 44, and (E) 48 mm.

subluxation for the posterior instability challenges than for the anterior challenge. Instability was preceded by (component-on-component) impingement for most cases, although some situations of foot pivoting with larger heads resulted in spontaneous (slide out [23]) dislocation. Using femoral head subluxation of less than 1 mm as a definition of stability, appreciable improvement in stability occurred when femoral head size was increased from 32 mm to 36 mm (Fig. 6).

Fig. 6 The percentage of orientations yielding a stable articulation (defined as having a maximum femoral head subluxation < 1 mm) was shown to increase as a function of femoral head diameter. The effect of increasing head size was greatest when moving from 32 mm to 36 mm, while there was progressively diminishing improvement in stability with the higher increases of head diameter.

However, further gains in stability with increased head size were less evident. A 10% improvement in stability was observed when femoral head size was increased from 32 mm to 36 mm versus only a 4.7 % improvement when femoral head size was increased from 40 mm to 48 mm.

Head Size and Wear

At the bearing surface, the peak (von Mises) contact stress decreased appreciably when head diameter increased (Fig. 7). By contrast with the bearing surface, peak stresses developed at the trunnion interface (Fig. 8) increased substantially with increased femoral head diameter. Head diameter-dependent trends for (Archard) computed linear wear (Fig. 9) generally followed those for contact stress. Trunnion linear wear demonstrated a predilection to be most severe near the leading and trailing edges of the trunnion, similar to the trunnion wear scars observed during revision (Fig. 1).

Trunnion Wear and Other Surgical Variables

Cup orientation had only a minor influence on stress and wear generation at the trunnion (Figs. 8, 10). However, for horizontally oriented cups, impingement and the resulting subluxation and edge loading caused substantially increased peak stress at the bearing surface (Fig. 7). The individual motion challenge had a more direct effect on trunnion wear potential. Wear was generated at the trunnion due to micromotion (nodal slip) during several distinct phases of the simulated joint motion (Fig. 11). Assembly/

Fig. 7A–C Peak values of surface von Mises (vM) stress occurring at the articular surface were determined for each simulation. (A) For gait, bearing surface stress decreased precipitously when head diameter was increased from 32 mm to 36 mm, for all three cup orientations. Progressively more modest decrements in bearing surface stress with increased head diameter were observed for head sizes of more than 36 mm. Similar relationships were observed for (B) stooping and (C) sit-to-stand for the neutrally and vertically positioned cups. For both of these dislocation challenges, surface stress was greatly increased for horizontally oriented cups, due to impingement, subluxation, and significant edge loading.

impaction seating of the head onto the trunnion resulted in slip aligned with the long axis of the trunnion (Fig. 11, i). Increased frictional torque at the bearing surface during the motion resulted in rotational micromotion about the neck axis, while increased joint forces produced slip again predominantly parallel to the neck in the direction of the load. Therefore, a wide variation in trunnion stress (Fig. 8) and wear (Fig. 10) was observed during a single gait, stooping, or sit-to-stand cycle. For gait (Fig. 8A), increasing the head diameter from 32 mm to 40 mm increased peak stress on the trunnion by only approximately 3.5%. Further increasing head size to 44 mm increased peak trunnion stress by 9.5% relative to 32 mm. Even more notably, increasing head size to 48, 52, and 56 mm resulted in stress increases (compared to 32 mm) of 24%, 40% and 51%, respectively. Similar trends were observed for the sit-to-stand simulations (Fig. 8B). For stooping (Fig. 8C), a comparable dependency of trunnion stress on femoral head size was observed for neutrally and vertically oriented cups. For horizontally oriented cups, the decreased trunnion stress compared to the two other cup orientations was due to frank dislocation occurring for the lower values of head size (32–40 mm) before attainment of peak joint contact loads. For head sizes larger than 40 mm, subluxation and eccentric loading of the head caused higher stresses to develop at the trunnion than those occurring for neutral or vertical cup orientations. The magnitude of impaction load used to seat the femoral head substantially influenced trunnion contact pressure (Fig. 12) and trunnion micromotion (Fig. 13). As would be expected intuitively, increased impaction force resulted in increased trunnion stress and therefore more trunnion interfacial frictional stress to resist micromotion. However, wear depends on both contact stress (increased for stronger impaction) and micromotion (decreased for stronger impaction). Therefore, the overall effect of increased impaction force on trunnion interface wear was much less pronounced than on either contact stress or micromotion alone and indeed was almost negligible (Fig. 14). This was very different from the effect of increasing head diameter, where both trunnion contact stress and trunnion micromotion unremittingly increased, thereby greatly increasing computed interface wear.

Discussion

While the theoretical advantages of large-diameter MOM THA bearings seem attractive, their actual clinical utility

Fig. 8A–C Peak values of von Mises (vM) stress occurring at the trunnion were determined for each simulation. (A) For gait, trunnion stress was found to increase with increased femoral head diameter for all three cup orientations. The influence of head diameter on trunnion stress was progressively more pronounced for higher head diameters. A similar dependency of head diameter on trunnion stress was also observed for (B) sit-to-stand and (C) stooping. Stooping simulations with horizontally positioned cups at lower values of head diameter resulted in frank dislocation before maximum joint contact stresses could be developed, resulting in lower values of trunnion stress. For stooping, stresses at higher values of head diameter were found to approach or exceed the yield stress of cobalt-chromium (broken horizontal line), indicating potential for plastic yield on the trunnion for larger-head diameters.

remains an open question. Using a finite element formation coupled with physiologically realistic input motions and loads, this study was designed to address the interplay between THA stability and the propensity for increased trunnion interface wear as head sizes vary in MOM THA.

This investigation is subject to a number of limitations. First, wear at the trunnion interface *in vivo* is a complex process involving both mechanical and electrochemical (ie, corrosive) processes [29]. The present investigation focused entirely on mechanical (fretting) wear, which while significant, seemingly would be exacerbated by adverse electrochemical effects, given the mechanical coupling of fretting and corrosion. Additionally, at present, information is minimal regarding the micromechanics of wear debris generation at the trunnion interface. Actual *k* factors for trunnion interface wear have yet to be measured. The particular value used in this study corresponded to that for bedding-in wear at the bearing surface of MOM implants determined from hip simulator studies [41] and almost certainly constitutes an underestimate. Furthermore, the present study focused on mechanical wear potential only at the trunnion. Additionally, to the authors' knowledge, the span in femoral head size used in this series (32–56 mm) is greater than that for any currently available single-taper modular system. While useful for exploring underlying biomechanical relationships, our results are contingent on the premise of the trunnion interface, liner thickness, and liner edge profile remaining identical for all head sizes. In particular, very large femoral heads often require a metal sleeve adapter to fit the neck trunnion (taper-within-taper). This additional interface surface would tend to lead to a further increase in wear generation, an occurrence that has been recently corroborated clinically [28]. Additionally, while 900 distinct simulations were run to assess for implant stability, the inclusion of only a single value of femoral anteversion and the investigation of only five dislocation-prone motions represented only a fraction of all possible permutations of orientation, head size, and joint motion. Finally, we investigated only a single trunnion geometry

from a single manufacturer. While most head-neck interfaces in contemporary MOM THAs adhere to a nominal 12/14 taper geometry, slight proprietary deviations exist among different manufacturers. The sensitivity of trunnion

Fig. 9A–B Micromotion of the trunnion relative to the head bore results in the generation of linear wear on the interface surfaces. Total cumulative linear wear for (A) gait at the end of the motion cycle was approximately $\frac{1}{2}$ of that occurring for (B) sit-to-stand. For all motions, linear wear increased with increased femoral head diameter.

interface wear debris generation to subtle design differences is an inviting issue for further study.

The utilization of large heads in modular THA is an archetypical example of the “choices and compromises” [34] inherent in design of successful orthopaedic implants. It is well recognized that increasing head diameter reduces impingement, improves stability, and enhances the elastohydrodynamics of joint lubrication. However, it is unclear whether a practical head size limit exists as regards improved overall construct performance, given the

potentially adverse effects at the trunnion interface. We determined whether such a limit could be identified for large-diameter MOM bearings. Instability continues to be a major clinical concern in THA [6], with impingement avoidance being a particularly significant consideration for MOM bearings. Our data indicate diminishing further improvement of intrinsic joint stability for head diameters of approximately 40 mm or more (Fig. 6). However, stress at the trunnion interface (Fig. 8) continued to increase unabatedly for head diameters larger than 40 mm for

Fig. 10A–C Volumetric wear at the trunnion demonstrated strong dependence on head size for (A) gait, (B) stooping, and (C) sit-to-stand. This dependency of head size was most pronounced at higher values of head diameter.

normal-function scenarios where impingement-associated edge loading did not occur. Correspondingly, a tendency for increased wear at the trunnion interface continued, similarly unabated, for head sizes larger than 40 mm. A substantial attraction of the present finite element formulation is the ability to simulate accelerated wear at the trunnion interface resulting from macro- or microscopic damage to the trunnion. This is yet another inviting topic for further investigation.

In contrast to the stability benefit seen with the use of larger femoral heads, the role of head size on trunnion wear is not as clear. Historically, clinical issues arising from wear at the trunnion interface were a well-recognized concern [29, 44, 54], even before the present era of large-sized heads. Various factors affecting wear had been empirically identified, including implantation time [29, 32], alloy composition (especially galvanic corrosion effects) [12, 13, 32], joint load magnitude [31], numbers of loading cycles [29], moment arm [8, 32], and frictional torque at the bearing surface [27]. However, many of these factors were related to design inadequacies and/or inappropriate manufacturing tolerances of earlier-generation devices [35]. Indications of relatively low corrosion at the trunnion-head interface [37] and excellent intermediate-term survival [58] for (modest-diameter) modern MOM implants suggest that the trunnion interface is not necessarily the weakest link for all MOM implants. However, the emerging clinical picture for large-diameter modular THA is not so clear. Given the recent reports of high rates of trunnionosis-associated failure [5, 28, 38] with large-diameter implants, the use of large-diameter MOM implants warrants further biomechanical and clinical scrutiny, especially in light of disturbingly elevated revision rates for large-diameter THA in the most recent registry data [2].

As indicated in the present study, other factors undoubtedly affect the generation of trunnion wear in THA. An obvious example relates to the motion at the hip. As demonstrated computationally (Figs. 9, 10), the wear generated at the trunnion during gait was less than 1/2 of that seen with the other motions. However, it has been shown [45] that up to 7000 individual gait cycles are undertaken per day by patients with THA, compared to only 70 sequences of sitting/standing. Thus, the wear generated during gait is expected to dominate the cumulative damage at the trunnion over the service life of the implant. Additionally, while cup orientation was shown to substantially affect the stresses generated at the bearing surface (Fig. 7B–C), there were only minor deviations in the predicted trunnion wear for the different cup positions, suggesting that the biomechanical

Fig. 11 Relative nodal slippage (micromotion) during the input assembly/motion simulations at six distinct instances (i to vi) is shown. Direction of nodal slip is indicated by arrows of vectors assigned to selected nodes on the trunnion interface. (i) Trunnion assembly during impaction resulted in vertical slip of interface nodes. (ii) After the impaction load, elastic recoil in the trunnion-bore interface resulted in relaxation of the assembly and slip in the opposite direction. (iii) During the motion sequence, node slip was

minimal during low values of joint contact load and bearing surface frictional torque. (iv) For intermediate values of both bearing surface frictional torque and joint contact force, net slipping was primarily rotational. (v) Further increasing both bearing surface frictional torque and joint contact loads resulted in a mixed rotational/translation slip. (vi) At peak values of joint contact load, slip was primarily parallel to the axis of the trunnion-bore.

factors resulting in trunnion wear, namely bearing surface torque and loading moment arms, are more strongly influenced by femoral head size than by surgical orientation. Furthermore, additional choices and compromises undoubtedly apply also to design of the trunnion. While it has been well established that increased trunnion diameter significantly reduces wear potential at this interface [32], implant manufacturers place high

emphasis on keeping neck diameters low to maintain favorable head to neck ratios. From a biomechanical viewpoint, it is plausible that a point of diminishing returns similarly exists between reduced taper diameter and improved impingement/stability. Quantification of the choices and compromises of using larger trunnions is another attractive avenue for further parametric investigation.

Fig. 12 The finite element simulation consisted of three distinct phases (i to iii). (i) The femoral head was impacted onto the trunnion, resulting in the rapid development of contact pressure at the interface. (ii) After the impulse loading, the trunnion-bore interface underwent elastic recoil until static equilibrium was reached. (iii) Then, the motion cycle (gait in this illustration) was run. While the use of higher impaction loads resulted in substantially greater initial contact pressure, all three simulations converged toward similar values of pressure during the duty cycle simulation. The illustration shown is for neutrally positioned cups with 56-mm femoral head diameters.

Fig. 13 Increased interface motion, measured in terms of instantaneous slip distance between nodes at the interface, was seen for the gait simulation with a low (1-kN) impaction load, compared with normal (5-kN) or increased (17-kN) loads for 56-mm head diameters in neutral cup positions.

In summary, our results corroborate recent clinical evidence that large-diameter heads for MOM THA have a tendency to cause deleterious wear generation at the trunnion-bore interface. While construct stability was shown to increase with larger-diameter femoral heads, this effect was diminished for the largest-diameter femoral heads investigated. Additionally, the wear potential at the trunnion increased substantially for head diameters larger than 40 mm and for malpositioned cups that underwent impingement. The tendency for trunnion wear could be only weakly influenced by higher assembly/impaction loading on the neck. The model has potential to help investigators and designers of hip implants to better

Fig. 14 Increasing the value of impaction force decreased the volumetric wear occurring at the trunnion interface during the gait cycle for 56-mm head diameters in neutral cup positions. This relationship exhibited exponential decay (inverse power law regression).

understand the optimization of trunnion design for long-term durability.

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