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Contact mechanics studies of an ellipsoidal contact bearing surface of metal-on-metal hip prostheses under micro-lateralization

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ABSTRACT

The morphology of the contact bearing surfaces plays an important role in the contact mechanics and potential wear of metal-on-metal (MOM) hip prostheses. An ellipsoidal bearing surface was proposed for MOM hip implants and the corresponding contact mechanics were studied by using the finite element method (FEM) under both standard and micro-lateralization conditions. When under micro-lateralization, the maximum contact pressure decreased from 927.3 MPa to 203.0 MPa, with increased ellipticity ratio medial-laterally. And the contact region was found to shift from the rim of the cup to the inner region compared to the spherical design. Under standard conditions, an increasing trend of the maximum contact pressure for the acetabular component was predicted as the major radius of the ellipsoidal bearing surface was increased. Nevertheless, the maximum contact pressure reached an asymptotic value when the ellipticity ratio was increased to 1.04. Therefore it is critical to optimize the ellipticity ratio in order to reduce the contact pressure under micro-lateralization condition and yet not to cause a markedly increased contact pressure under normal condition. Additionally, the maximum contact pressure in the ellipsoidal bearing surface remained relatively constant with the increased micro-lateralization. It is concluded that an ellipsoidal bearing surface morphology may be a promising alternative by offering better contact mechanisms when micro-lateralization should occur and attributing to minimized wear.

1. Introduction

Hip implants employing hard-on-hard bearing couples have been increasingly introduced recently as alternatives to the majority of current soft-on-hard hip implants using metal-on-polyethylene (UHMWPE). Polyethylene wear particles have been implicated in leading to long-term osteolysis and loosening of hip joints [1–3]. The wear in metal-on-metal (MOM) or ceramic-on-ceramic (COC) hip bearings is greatly reduced compared with that of metal-on-polyethylene ones [4–7]. Especially, the MOM articulation may represent a viable alternative for total hip arthroplasty (THA) in younger, higher demanding patients [8]. However, studies have also demonstrated that wear does take place in MOM and COC hip implants, either tested in hip simulators or retrieved from patients, and the nano-scaled metal debris was associated with adverse local tissue reactions and eventually leading to failure of the implant [9]. Among all wear mechanisms, the superolateral rim is one of the most severely worn regions of acetabular cups from clinical retrieval studies on all types of prostheses [10,11]. Microseparation was reported to be one of the possible causes for superolateral wear [12,13]; however, no general conclusions have been drawn on the superolateral wear mechanisms or a potential effective way to avoid it.

Studies have been carried out aiming to reduce wear, the diameter of the bearing and the radial clearance between the cup and the head have been optimized theoretically and experimentally [14–17]; the wear resistant bearing materials have been developed to minimize wear [18,19]; other factors such as the wall thickness of the cup and structural supports have also been taken into consideration [20,21]. However, the majority of studies were based on current existing designs, which were associated with spherical bearing surfaces, and few studies have been conducted by modifying the spherical shape of the bearing surface to investigate whether a modification of the spherical bearing shape would lead to lower wear.

Surrounding the human hip joints are capsuloligamentous structures and a ligament attaching the femoral head to the acetabulum. During the operation of THR, these supporting structures are transected or removed. This may lead to micro-lateralization between the femoral head and the acetabular cup after THR [22,23],

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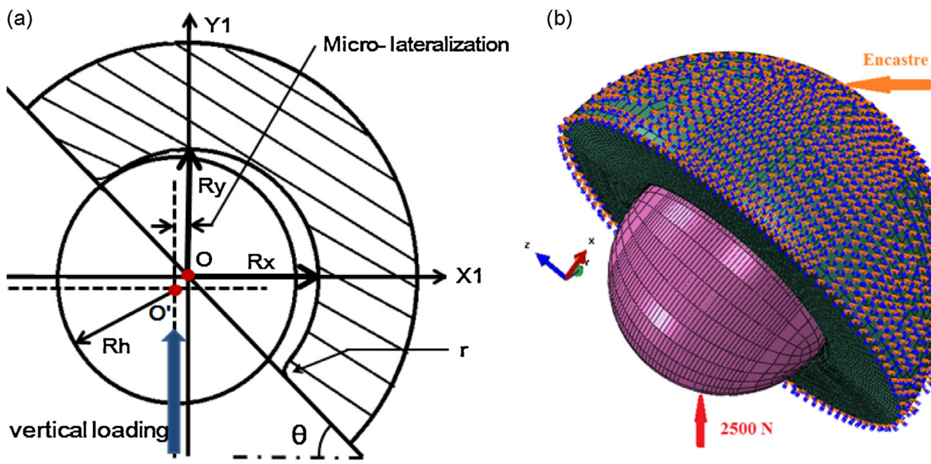

Fig. 1. (a) Schematic diagram for a MOM hip implant with an ellipsoidal acetabular bearing surface against a spherical head under micro-lateralization with 45° of inclination angle, R_x, R_y are radius of the ellipsoidal inner surface of the cup, Rh is the radius of the metal head; (b) the finite element model set-up: 2500 N load was applied vertically through the centre of the head upwards; the head was constrained to move only vertically, and the acetabular cup was fully constrained from the outer surface.

particularly when the head is malpositioned laterally. Fluoroscopic studies have shown the separation of head and cup during the swing phase due to joint laxity.

Micro-lateralization between the femoral head and the acetabular cup has been considered as one of the main reasons causing the rim wear [24]. The contact mechanics in ceramic-on-ceramic hip implants was investigated under micro-lateralization condition and the edge contact occurred between the superolateral rim of acetabular cup and the femoral head [25]. The predicted contact pressure was markedly increased when the rim contact occurred [25]. The wear of MOM hip implants under micro-separation was also investigated by Walter et al. via hip simulator testing and a marked increase in wear was observed [26]. Clinically relevant wear rates, patterns and mechanisms for alumina-alumina hip prostheses have been reproduced [27–29]. Micro-lateralization may be a critical determinant for the wear of hip implants. Therefore, it is necessary to consider micro-lateralization into the design and optimization of the bearing surfaces of hard-on-hard hip prostheses.

An alphararbola bearing surface has been investigated in comparison to the traditional spherical design for both contact mechanics and lubrication studies [30], which was an attempt to modify the shape of bearing surface to minimize the wear. It has been found that the contact pressure was decreased while the lubricant film thickness increased, compared with a conventional spherical bearing surface design. But few studies have been put into the effect of micro-lateralization on these designs. The aim of this study was to propose a novel aspherical bearing surface for the cup and investigate the contact mechanics behavior under micro-lateralization.

2. Model and method

This study focused on an MOM hip implant. The acetabular bearing surface proposed in this study was an ellipsoidal shape. Similar to the “alphararbola” surface defined in Meng’s study [30], the “ellipsoidal” surface in present study implies the oblate ellipsoid with the radius of the equator equal to each other but longer than the radius of the pole. As shown in Fig. 1, R_x and R_y represented the major and minor radius of the ellipsoidal inner surface of the acetabular cup. The major axis R_x was oriented in the medial-lateral direction and parallel to the coronal axis. The minor axis R_y was perpendicular to the major axis and parallel to the sagittal axis. In this study, R_y was fixed as 14 mm, and R_x varied from 14 mm to 16 mm. The outer surface of the cup was spherical with a radius of 26 mm. The cup was positioned with an anatomical inclination angle (θ) of 45°. Radius of curvature for the edge of the cup r is equal to 2 mm. Femoral head with a radius of 13.95 mm was used in this study, which gave a minor clearance of 0.05 mm. The ellipticity ratio was defined as the ratio of the major to minor axis radius, whose value was varied from 1 to 1.14 in this study. Micro-lateralization was modeled with the value varied from 0 to 0.25 mm. The standard condition was also considered as the case of zero micro-lateralization for comparison reason.

Both the femoral head and the acetabular cup were assumed to be CoCr alloy. The corresponding elastic modulus and Poisson’s ratio were chosen as 220 GPa and 0.3 respectively. All the materials were assumed to be homogeneous and linear elastic. Three-dimensional finite element models including the acetabular cup and the femoral head were built and solved in ABAQUS 6.7-1. A mesh sensitivity and convergence analysis was completed under the standard condition to ensure the accuracy of the model. The element size of 1 mm was employed in the model except in the contact region where the element size was reduced to 0.5 mm locally. The finite element model was comprised of a total of approximately 138,800 eight-node brick elements (C3D8R). The effect of the mesh sensitivity for a specific spherical bearing surface with a cup radius of 14 mm under a specific micro-lateralization of 0.25 mm was also considered by reducing the minimum element size to 0.25 mm and 0.1 mm. Such a condition represented the worst case scenario in terms of the mesh sensitivity required. For validation purposes, a micro-lateralization value of 0.005 mm was initially employed, which was designed to represent conditions of the spherical design.

The interface between the cup and the head was defined as a pair of contact surfaces, with the head bearing surface chosen as the master surface and the cup as the slave surface. Friction between the bearing surfaces was neglected to simulate a well-lubricated condition. In order to avoid the initial penetration of the surfaces, the option of “Adjust = 0” was adopted. The cup was fixed through the outer surface. The femoral head were constrained to move only along the loading direction. A fixed load of 2500 N (±10%) was applied through the centre of the femoral head, as shown in Fig. 1.

3. Results

Fig. 2 shows the predicted contour plots of the contact pressure distribution as a function of different acetabular major radii under 0.25 mm micro-lateralization. The corresponding maximum contact pressure is shown in Fig. 3. The contact region was predicted