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Contact mechanics of modular metal-on-polyethylene total hip replacement under adverse edge loading conditions

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ABSTRACT

Edge loading can negatively impact the biomechanics and long-term performance of hip replacements. Although edge loading has been widely investigated for hard-on-hard articulations, limited work has been conducted for hard-on-soft combinations. The aim of the present study was to investigate edge loading and its effect on the contact mechanics of a modular metal-on-polyethylene (MoP) total hip replacement (THR). A three-dimensional finite element model was developed based on a modular MoP bearing. Different cup inclination angles and head lateral microseparation were modelled and their effect on the contact mechanics of the modular MoP hip replacement were examined. The results showed that lateral microseparation caused loading of the head on the rim of the cup, which produced substantial increases in the maximum von Mises stress in the polyethylene liner and the maximum contact pressure on both the articulating surface and backside surface of the liner. Plastic deformation of the liner was observed under both standard conditions and microseparation conditions, however, the maximum equivalent plastic strain in the liner under microseparation conditions of 2000 μm was predicted to be approximately six times that under standard conditions. The study has indicated that correct positioning the components to avoid edge loading is likely to be important clinically even for hard-on-soft bearings for THR.

1. Introduction

Hip joint replacements have been successfully used in orthopaedics for over fifty years. Whilst clinical studies have shown encouraging long-term clinical performance, failure of these devices can still occur. Specifically, the clinical complications and unexpected failure of hip prostheses linked to edge loading have been reported recently (Langton et al., 2011; Walter et al., 2011; Kwon et al., 2012). This edge loading, defined as the contact of the head on the rim of the liner, has been associated with many factors, including patient activity, prosthesis design, surgical positioning and material combinations (Mellon et al., 2011; Wang et al., 2012; Elkins et al., 2012; Harris, 2012; Underwood et al., 2012). In particular, the primary contribution of the rotational and translational mal-positioning of the components to edge loading has been identified and well summarised (Fisher, 2011; Harris, 2012). Rotational mal-positioning is defined clinically as the steep inclination and excessive anteversion of the acetabular component while translational mal-positioning, also termed as microseparation, is described as the misalignment of the centres of the head and the cup (Nevelos et al., 1999, 2000).

In vitro studies have shown that the introduction of microseparation in a hip joint simulator can successfully reproduce clinically relevant wear rates, wear patterns and wear particle distributions for both metal-on-metal (MoM) and ceramic-on-ceramic (CoC) articulations (Nevelos et al., 2000; Stewart et al., 2001). These outcomes, however, could not be replicated under standard walking conditions with either a normal or a steep cup angle (Williams et al., 2008; Angadji et al., 2009). This indicates that microseparation of the femoral head and the acetabular cup occurs *in vivo* during normal gait, a phenomenon which has also been observed with the aid of fluoroscopy (Dennis et al., 2001; Komistek et al., 2002).

Microseparation usually occurs during the swing phase and is considered to be as a result of muscle weakness, mal-positioning of the acetabular cup or offset deficiency of the femoral head (Ryou et al., 2004). These factors cause the femoral head to be moved laterally relative to the acetabular cup during the swing phase. When a load is applied in the stance phase, the femoral head is moved upward, leading to edge loading, which can have a significant consequence on the wear and biomechanics of the total hip replacements (THRs).

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The effect of edge loading induced by microseparation on the biomechanics and performance of hard-on-hard articulations has been documented (Manaka et al., 2004; Williams et al., 2006; Leslie et al., 2009; Al-Hajjar et al., 2010). In MoM articulations, edge loading can produce accelerated wear of whole joints (Williams et al., 2006; Leslie et al., 2009) and lead to metallosis, abnormal peri-prosthetic soft-tissue reactions such as pseudotumours (Kwon et al., 2012). In CoC combinations, edge loading has been associated with accelerated articulating wear, squeaking, stripe wear on either the head or the cup, and in some situations, the fracture of the components (Nevelos et al., 2001; Stewart et al., 2001; Jarrett et al., 2009; Al-Hajjar et al., 2010). Finite element (FE) studies have also been conducted to examine the stresses in the components due to edge loading and have shown a 3-8 fold increase in the stress of the components in CoC hips compared to that under normal loading conditions (Mak et al., 2002; Sariali et al., 2012). All these studies have provided significant indication that edge loading due to the rotational and translational malposition of the components has a negative impact on the THRs. However, whilst edge loading has been widely investigated for hard-on-hard articulations, fewer studies have been carried out for hard-on-soft combinations, especially with respect to the contact mechanics of modular MoP THR under microseparation conditions. The aim of the present study was therefore to investigate the contact mechanics of a modular MoP THR under edge loading conditions due to the microseparation and rotational malpositioning of the components using FE methods.

2. Materials and methods

A typical commercially available modular MoP total hip system, consisting of metal shell, polyethylene liner and metallic femoral head, was analysed. The nominal diameters of the femoral head and inner surface of the polyethylene liner were 36 mm and 36.6 mm respectively, giving a radial clearance of 0.3 mm between the femoral head and the liner. The outer diameter of the acetabular component was assumed to be 54 mm. A polar fenestration with diameter of 20 mm was considered in the central dome region of the metal shell.

A three-dimensional FE model was created to simulate the position of both the femoral and acetabular components implanted in a hemi-pelvic bone model (Fig. 1). The hemi-pelvic bone model consists of a cancellous bone region surrounded by a uniform cortical shell of 1.5 mm thickness (Udofia et al., 2007). The acetabular subchondral bone was assumed to have been reamed completely prior to implantation.

All the materials in the FE model were modelled as homogenous, isotropic and linear elastic except the polyethylene liner which was modelled as non-linear elastic-plastic with the plastic stress-stain constitutive relationship showing in Fig. 2 (Liu, 2005). The mechanical properties for the materials are presented in Table 1 (Udofia et al., 2007; Hua et al., 2012). The femoral component was assumed to be rigid because the elastic modulus of the metallic femoral component is at least two orders of magnitude greater than that of the polyethylene material. The total number of elements for the FE model was approximately 92, 000, predominantly consisting of eight-node brick elements, six-node wedge elements, four-node tetrahedral elements and three-node shell elements. The sensitivity of the results to the mesh was carried out in the cases of standard conditions and 1500 μm microseparation conditions under cup inclination angle of 65°, and results showed that when the number of the elements was doubled, the change in any of the parameters of interest was within 5%.

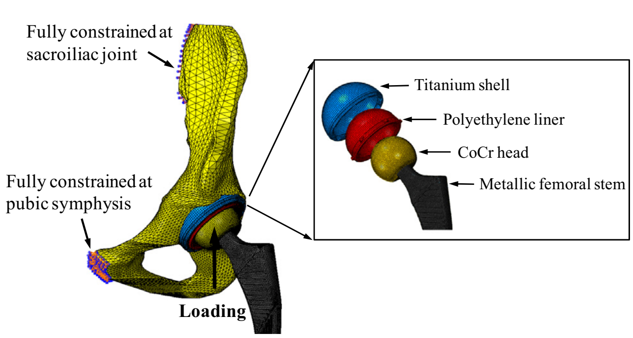

Fig. 1. The boundary conditions and components of the finite element model.

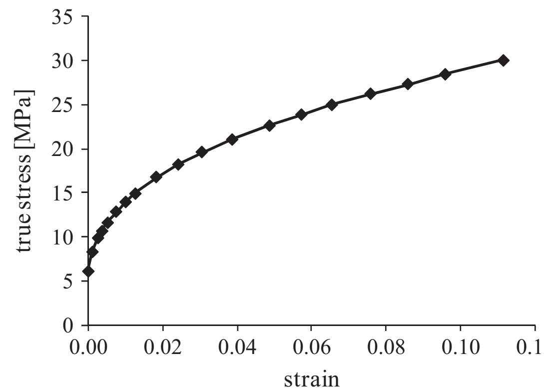

Fig. 2. The plastic stress-strain relation for the polyethylene liner (Liu, 2005).

Table 1
The material properties for the components in the present study (Udofia et al., 2007; Hua et al., 2012).

Components	Materials	Young's modulus (GPa)	Poisson's ratio
Polyethylene liner	UHMWPE	1	0.4
Metal shell	Titanium	116	0.25
Cortical shell	Cortical bone	17	0.3
Cancellous bone	Cancellous bone	0.8	0.2

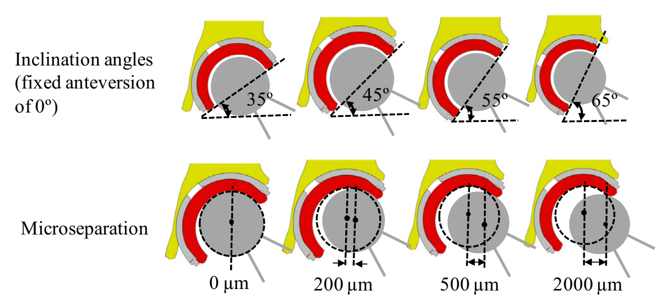

Fig. 3. The definition of cup inclination angles and head lateral microseparation distances in the FE model, four cup inclination angles and 12 microseparation distances were considered in the present study. Only four microseparation distances are shown in this figure.

A sliding contact formulation was used both on the articulating surface and at the metal shell/liner interface, with friction coefficients of 0.083 and 0.15 respectively (Ramero et al., 2007; Amirouche et al., 2008). The nodes situated at the sacroiliac joint and about the pubic symphysis were fully constrained to simulate the sacral and pubic support of the pelvic bone. The interface between the bone and the implant was fully bonded to simulate a situation where the porous sintered coating and in-grown bone were well bonded (Fig. 1). The rotation of the femoral head was fully constrained while the translation was restrained to ensure that the femoral head was only allowed to move along the loading directions. The FE analysis was performed using ABAQUS software package (Version 6.9, Dassault Systèmes Simulia Corp., Providence, United States). The validation of the FE model was presented in detail in a previous study (Hua et al., 2013), which has shown good agreements of contact areas (within 12%) between the FE predictions and the experimental measurements using Leeds Prosim hip joint simulator.

Different loads with magnitude of 2500 N and different directions of 10° medially, 0° (vertical) and 10° laterally were applied through the centre of the femoral head. Four cup inclination angles, varying between 35° and 65° in 10° increments, and 12 lateral microseparation distances of 0 μm, 60 μm, 100 μm, 150 μm, 200 μm, 300 μm, 400 μm, 500 μm, 800 μm, 1000 μm, 1500 μm and 2000 μm were considered in the present study. The definition of the cup inclination angles and head lateral microseparation is shown in Fig. 3.

3. Results

Edge loading appeared for lower values of microseparation of the head as the cup inclination angles increased (Fig. 4, Table 2). There was no substantial elevation in the stresses and plastic