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The effect of cup outer sizes on the contact mechanics and cement fixation of cemented total hip replacements

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ABSTRACT

One important loosening mechanism of the cemented total hip arthroplasty is the mechanical overload at the bone-cement interface and consequent failure of the cement fixation. Clinical studies have revealed that the outer diameter of the acetabular component is a key factor in influencing aseptic loosening of the hip arthroplasty. The aim of the present study was to investigate the influence of the cup outer diameter on the contact mechanics and cement fixation of a cemented total hip replacement (THR) with different wear penetration depths and under different cup inclination angles using finite element (FE) method. A three-dimensional FE model was developed based on a typical Charnley hip prosthesis. Two acetabular cup designs with outer diameters of 40 and 43 mm were modelled and the effect of cup outer diameter, penetration depth and cup inclination angle on the contact mechanics and cement fixation stresses in the cemented THR were studied. The results showed that for all penetration depths and cup inclination angles considered, the contact mechanics in terms of peak von Mises stress in the acetabular cup and peak contact pressure at the bearing surface for the two cup designs were similar (within 5%). However, the peak von Mises stress, the peak maximum principal stress and peak shear stress in the cement mantle at the bone-cement interface for the 43 mm diameter cup design were predicted to be lower compared to those for the 40 mm diameter cup design. The differences were predicted to be 15–19%, 15–22% and 18–20% respectively for different cup penetration depths and inclination angles, which compares to the clinical difference of aseptic loosening incidence of about 20% between the two cup designs.

1. Introduction

The Charnley total hip replacement (THR) has been widely used in clinical practice since 1962. The success of this prosthesis has been attributed mainly to its low frictional torque [1,2]. Follow-up studies of Charnley hip replacements have generally shown the arthroplasty to have excellent long-term functional outcome and survivorship. However, like all the other types of artificial hip joints using a metal-on-polyethylene articulation, aseptic loosening of the components, particularly on the acetabular side, has caused majority of the revision and failure of the prostheses [3–6].

The etiology of aseptic loosening of the hip replacement is multifactorial. Osteolytic bone resorption due to the wear particles mainly generated at the articulating surfaces is widely accepted as the main cause [7]. Other mechanisms have also been proposed, including cement damage, bone adaptation, micromotion and high fluid pressure etc. [8]. Particularly, the damage of the cement mantle and subsequent failure of the fixation has been identified as one of possible mechanisms that initiates the loosening and eventual failure of the hip prosthesis [9,10]. The damage of the cement mantle can further produce cement particles, which can invade the articulating surfaces and cause more severe third-body articulating wear. The damage can also provide a pathway for the particulate debris to access the bone-cement interface directly, facilitating the propagation of inflammatory and eventual osteolytic events [11,12].

Evidences from finite element (FE) studies and *in vitro* experiments indicate that the damage of the cement mantle and failure of the fixation is closely associated with the mechanical behaviour within the cement mantle and at the bone-cement interface [13,14]. Coultrup et al. developed a computational cement damage accumulation method to investigate the effect of polyethylene wear rate, cement mantle thickness and porosity on the mechanical failure of the cemented hip replacement [15]. They demonstrated that both cup penetration and decreased cement thickness increased the cement stresses, resulting in a reduction in the cement mantle fatigue life. They also suggested that the mechanical factors in the cement mantle

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make a major contribution to the failure mode of cemented polyethylene cups. Lamvohee et al. investigated the stresses in the cement mantle considering the effect of femoral implant size and bone quality. The FE results indicated that both good quality bone and smaller sized femoral component led to decreased stresses in the cement mantle, resulting in a higher survivorship for the cement [16]. Tong and colleagues conducted a series of FE simulations and *in vitro* experiments to investigate the damage evolution and fatigue failure of the cement mantle in cemented acetabular replacements under different loading conditions. They demonstrated that the failure of the cement fixation initiated in the region where the high stresses were identified from the FE studies [17–21]. All these studies have indicated that high stresses developed in the cement mantle can lead to the damage of the cement mantle and failure of the fixation, which could potentially lead to the loosening of the components and failure of the prostheses.

It is generally believed that the performance of the cemented hip replacement and the mechanical behaviour in the cement mantle near the bone-cement interface is related to many factors such as the head diameter [16,22], penetration depth [15,23], cement thickness [15,16], bone quality [16] and cup outer size [24] etc. Specifically, a clinical study has shown that under similar conditions, the incidence of aseptic loosening for the acetabular cup with outer diameter of 43 mm was smaller than that with outer diameter of 40 mm when penetration depth increases. This was attributed to the lower friction torque with larger outer diameter of the acetabular cup in this study [2]. However, whether other factors, such as the wear in the polyethylene cup and the stresses developed in the cement mantle at the bone-cement interface, will contribute to the different clinical performance of the two prosthesis designs is not recognized. The synergistic effect of the cup outer diameter and cup penetration depth on the contact mechanics of the bearing and stresses of the cement fixation for the cemented hip replacement is not fully understood.

The aims of the present study were therefore to investigate how the cup outer diameters influence the contact mechanics of the bearing and the mechanical behaviour of the cement mantle in the cemented hip replacement with different penetration depths and under different cup inclination angles, and by doing this, to explore whether the contact mechanics and cement mechanical behaviour are the contributed factors causing the different performance of the two sized arthroplasties (with cup outer diameters of 40 and 43 mm) observed clinically.

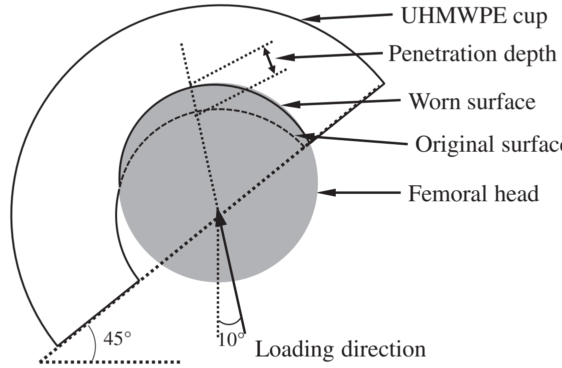

Fig. 1. A schematic cross-section showing the generation of the wear penetration in the acetabular cup. Firstly, the femoral head was offset in the direction of the load application by a distance of the penetration depth simulated. The material of the cup overlapped with the femoral head was then removed to get the desired penetration depth.

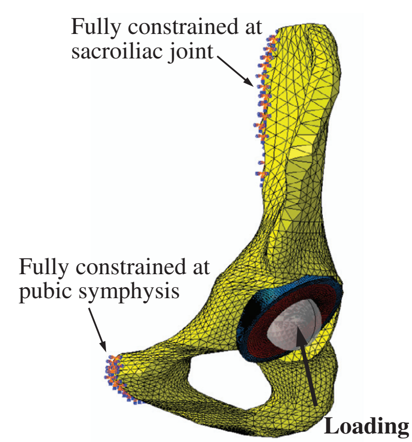

Fig. 2. The boundary conditions and loading conditions for the three-dimensional FE model. The load was applied to the centre of the femoral head with a direction of 10° medially.

Table 1
The material properties for the components in the present model [25,36].

Components	Materials	Young's modulus (GPa)	Poisson's ratio
UHMWPE cup	UHMWPE	1	0.4
Bone cement	PMMA	2.5	0.254
Cortical bone	Cortical bone	17	0.3
Cancellous bone	Cancellous bone	0.8	0.2

2. Materials and methods

A typical Charnley hip system, consisting of a hemispherical ultra-high molecular weight polyethylene (UHMWPE) cup and a stainless femoral head was analysed. The nominal diameters of the femoral head and inner surface of the cup were 22.225 and 22.59 mm, respectively [25]. Two acetabular cups with outer diameters of 40 and 43 mm, which represent two typical Charnley designs in clinical practice [2], were modelled. The thickness of the polymethylmethacrylate (PMMA) bone cement was assumed to be 2 mm, as previous studies suggested that the thickness of the cement mantle should be not less than 2 mm for the 22.225 sized arthroplasty [16,26]. The geometries of the acetabular cup and cement layer were assumed to be hemispherical, as shown in Figs. 1 and 2. Different penetration depths of 1, 2 and 4 mm on the acetabular cup and different cup inclination angles of 45°, 55° and 65° were considered. Penetration was simulated by intersecting the cup using the femoral head in the direction of resultant load. Firstly, the femoral head was offset in the direction of the load by a distance of the desired penetration depth. The material of the cup overlapped with the femoral head was then removed to get the worn cup. The cup inclination angle was defined as the angle between the plane of the face of the acetabular cup and the anatomical transverse plane. The reconstruction of the penetration and cup inclination angles are illustrated in Fig. 1.

A three-dimensional FE model was developed to simulate the positions of both the femoral head and acetabular cup implanted in a hemi-pelvic bone model (Fig. 2). The hemi-pelvic bone model consisted of a cancellous bone region surrounded by a uniform cortical shell. 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 linearly elastic except the UHMWPE cup which was modelled as a non-linear elastic-plastic material with the plastic stress-strain constitutive relationship shown in Fig. 3 [27]. The other material properties used in this study are given in Table 1. The femoral component was assumed to be rigid because the elastic modulus of this metallic component is at least two orders of magnitude greater than that of the UHMWPE material. The cortical shell and cancellous bone in the pelvis were simulated using three-node shell elements and four-node tetrahedral elements respectively while the