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The contact mechanics and occurrence of edge loading in modular metal-on-polyethylene total hip replacement during daily activities

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ABSTRACT

The occurrence of edge loading in hip joint replacement has been associated with many factors such as prosthetic design, component malposition and activities of daily living. The present study aimed to quantify the occurrence of edge loading/contact at the articulating surface and to evaluate the effect of cup angles and edge loading on the contact mechanics of a modular metal-on-polyethylene (MoP) total hip replacement (THR) during different daily activities. A three-dimensional finite element model was developed based on a modular MoP bearing system. Different cup inclination and anteversion angles were modelled and six daily activities were considered. The results showed that edge loading was predicted during normal walking, ascending and descending stairs activities under steep cup inclination conditions (≥55°) while no edge loading was observed during standing up, sitting down and knee bending activities. The duration of edge loading increased with increased cup inclination angles and was affected by the cup anteversion angles. Edge loading caused elevated contact pressure at the articulating surface and substantially increased equivalent plastic strain of the polyethylene liner. The present study suggested that correct positioning the component to avoid edge loading that may occur during daily activities is important for MoP THR in clinical practice.

1. Introduction

Despite the successful outcomes and encouraging long-term clinical performance of hip joint replacement, the clinical complications and unexpected failure of the prostheses linked to edge loading are causing concerns [1–5]. The edge loading, usually described as the contact of the femoral head on the edge of the acetabular component, was observed in many retrieval components and usually identified as the condition under which the maximum depth of penetration of the wear scar occurs at the rim of the cup or the wear scar has a distinct boundary in retrieval studies [6–8]. In numerical studies, true edge loading was specified and defined as the condition where the contact patch between the acetabular and femoral components extends over the rim of the cup [9,10].

Edge loading can reduce the tribological performance and may cause unexpected clinical problems [3,6,11–14]. In metal-on-metal (MoM) hip replacement, edge loading can produce accelerated local and overall articulation wear [15,16] and lead to metallosis, adverse peri-prosthetic tissue reactions such as pseudotumours [2,6,17]. In ceramic-on-ceramic (CoC) articulations, edge loading has been associated with accelerated articulation wear, stripe wear on either the femoral or acetabular component, and in some situation, squeaking and fracture of components [11,18–20]. For metal-on-polyethylene (MoP) and ceramic-on-polyethylene (CoP) combinations, although *in vitro* experimental studies indicated that edge loading induced by steep cup inclination and lateral microseparation did not increase the wear of prostheses compared to that without edge loading [21,22], finite element (FE) studies have shown that substantial increase in the stresses and plastic strain of polyethylene component were predicted for the hip prosthesis under edge loading conditions [13], which may contribute to subsequent fatigue and fracture. Therefore, persistent and sustained efforts to reduce or prevent edge loading should be still made for hard-on-soft articulations.

It has been recognized that the occurrence of edge loading on the hip joint replacement is related to many factors such as prosthetic design [10,23], malposition of components [9,14,16], impingement and dislocation [24,25], and patient activities [17,26]. Particularly, the malposition of the components has been recognized as an important factor causing the poor outcome of hip joint replacement. Although a golden "safe zone" with cup inclination of 40±10° and anteversion of 15±10° was recommended and

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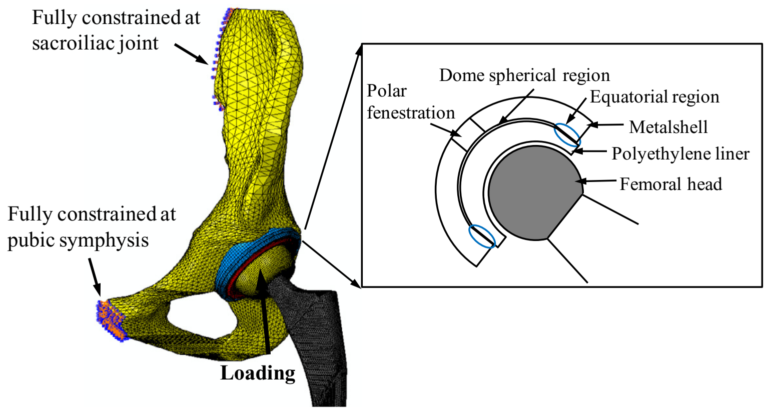

Fig. 1. The FE modelling and boundary conditions, and cross-section of the modular MoP THR showing the detailed structure and features.

accepted by most surgeons [27], a large variation in the cup orientation was observed in clinical practice [28,29]. The adverse effect of malposition of acetabular component on the performance and outcome of the hip joint replacement was also reported [29,30]. Schmalzried et al. conducted a study to investigate the relationship between the design, position and wear of acetabular component and the development of pelvic osteolysis [30]. They demonstrated that the osteolysis of the ilium was associated with a lateral opening of the acetabular component of more than 50°. Kennedy et al. reviewed two groups of total hip arthroplasties with mean inclination angles of 61.9° and 49.7° and concluded that although the postoperative Mayo clinical hip score was similar for the two groups, the group with a mean inclination of 61.9° had higher rate of recurrent dislocation, osteolysis, wear asymmetry and acetabular component migration, compared to the group with a mean inclination of 49.7° [29]. Therefore, the malposition of components on edge loading and performance of hip joint replacement should be examined.

The important contribution of daily activity patterns on the occurrence of edge loading has been demonstrated in a number of previous studies [17,26,31]. Mellon et al. investigated the effect of function activities (*i.e.* level walking and stair descent) and cup orientation on the edge loading and contact stress of MoM hip resurfacing using FE method and a combination of the computed tomography (CT) and three-dimensional lower limb motion capture data [26]. They suggested that steep cup inclination can cause edge loading and that individual's activity patter can compensate or even override the influence of steep cup inclination and prevent edge loading. Using the same method, Kwon et al. quantified the duration and magnitude of *in vivo* edge loading during functional activities (*i.e.* level walking, stair climbing and rising from a chair) in MoM hip resurfacing arthroplasty with and without pseudotumours [17]. They indicated that edge loading in MoM hip resurfacing with pseudotumours (which was associated with higher inclination and anteversion angles) occurred with significantly longer duration and greater magnitude of force compared to that without pseudotumours during daily activities. A study conducted by von Arkel et al. showed that the prevalence of posterior edge loading can be reduced by introducing abduction to activities that require deep flexion such as rising from a chair and stooping [31]. These studies have demonstrated the important contribution of patient's daily activities on the edge loading in total hip replacement (THR). However, these studies were based on *in vivo* evaluation and therefore the edge loading was roughly evaluated by using either the distance or angle between the hip contact force vector and acetabular cup edge vector. In this case, the magnitude of loading and deformation of the component were not considered in these studies.

The aims of the present study were, firstly, to determine whether edge loading occurred, the duration of edge loading occurrence and the specific instances over which edge loading occurred during different daily activities under different cup orientation conditions, and secondly, to investigate the effect of cup orientations and edge loading on the contact mechanics of a modular MoP THR during different daily activities using FE method.

2. Materials and methods

A typical modular MoP total hip system, consisting of metallic acetabular shell, polyethylene liner and metallic femoral head, was analysed. The inside of the acetabular shell is comprised two distinct regions: the central dome region and the locking mechanism. The central dome region covers approximately 140° of the interior of the shell, providing backside support to the liner. Peripheral to the dome is the locking mechanism, which extends to the face of the acetabular shell. The polyethylene liner is mechanically locked with the acetabular shell *via* the locking mechanism, forming two areas between the acetabular shell and polyethylene liner: the dome spherical region and equatorial region, as shown in Fig. 1.

The nominal diameters of the femoral head and inner surface of polyethylene liner were 36 mm and 36.6 mm respectively, giving a radial clearance of 0.3 mm between the femoral head and polyethylene liner. The radii of the central dome region of the acetabular shell and outer surface of the polyethylene liner were 24.14 mm and 24 mm respectively, giving a gap of 0.14 mm between the acetabular shell and polyethylene liner at the central dome region (dome spherical region). The outer diameter of the acetabular shell was 56 mm. A polar fenestration with radius of 10 mm was considered in the central dome region of the acetabular shell.

A three-dimensional FE model was developed to simulate the implantation of the modular MoP total hip system into a hemi-pelvic bone model (Fig. 1). The hemi-pelvic bone model consisted of a cancellous bone region surrounded by a uniform cortical shell with thickness of 1.5 mm [32]. 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 behaviour with the plastic stress-stain constitutive relationship showing in Fig. 2 [33,34]. The femoral head was modelled as a rigid body as the elastic modulus of the metallic femoral head is about 200 times that for polyethylene liner. The mechanical properties for the materials are presented in Table 1. The FE model comprised approximately