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Finite Element Analysis of the Contact Mechanics of Ceramic-on-Ceramic Hip Resurfacing Prostheses

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Abstract

Ceramics are good alternative to metal as bearing couple materials because of their better wear resistance. A Finite Element (FE) study was performed to investigate the contact mechanics and stress distribution of Ceramic-on-Ceramic (COC) hip resurfacing prostheses. It was focused in particular on a parametric study to examine the effects of radial clearance, loading, alumina coating on the implants, bone quality, and fixation of cup-bone interface. It was found that a reduction in the radial clearance had the most significant effect on the predicted contact pressure distribution among all of the parameters considered in this study. It was determined that there was a significant influence of non-metallic materials, such as the bone underneath the bearing components, on the predicted contact mechanics. Stress shielding within the bone tissue was found to be a major concern when regarding the use of ceramic as an alternative to metallic resurfacing prostheses. Therefore, using alumina implants with a metal backing was found to be the best design for ceramic resurfacing prostheses in this study. The loading, bone quality, and acetabular cup fixation conditions were found to have only minor effects on the predicted contact pressure distribution along the bearing surfaces.

Keywords: contact mechanics, hip, resurfacing, ceramic, finite element analysis

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1 Introduction

Hip resurfacing arthroplasty can be described as a bone-conserving procedure because only the diseased or damaged surfaces of the acetabulum and femoral head are replaced; thus, most of the bone stock is preserved, particularly on the femoral side. This limited amount of resection preserves the bone for reconstructive procedures that may be necessary in the future. Additionally, the increased stability and range of motion are particularly attractive for more active patients. Hip resurfacing arthroplasty has therefore been recommended for younger and more active patients[1–3]. The implants used in resurfacing arthroplasty have varied in the material, design, sizing, fixation, surface finish, and instrumentation.

Early resurfacing designs received poor feedbacks related to the combination of bearing materials. A metal femoral head was used against a polyethylene cup in these early hip resurfacing systems. With these prostheses, there were problems of polyethylene-wear- induced osteolysis and implant loosening associated with conventional metal-on-polyethylene Total Hip Replacements (THR)[4,5]. Improvements in metal- machining technology and new surface treatments as well as technical advances in the operating theatre have brought about a resurgence of interest in the concept. Short-to-medium term clinical reports on metal-on-metal hip resurfacing replacements have been promising[1,2,6]. However, there remain a number of long-term concerns. For example, the use of large metal-on-metal bearing components has raised concerns about host hypersensitivity to metal ion deposits[5,7,8], which could cause biological complications and implant loosening. The selection of implant materials for bearing surfaces is partly guided by the need to minimize debris generation[9]. Ceramics are good alternative to metal as bearing couple materials because of their better wear resistance[9,10]. Ceramic has commonly been used for the femoral head in THR; however, it has not often been used in hip resurfacing[11,12]. Therefore, an investigation of the possibility of using ceramic materials for resur-

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facing prostheses is meaningful. Although there are some concerns about the design limitations and the fracture of brittle ceramic implants, new alumina composites (alumina matrix composite and hot isostatic pressed alumina) provide better design facilities because of increased fracture toughness and bending strength[13].

To the best of our knowledge, there have been no studies investigating the contact mechanics of ceramic-on-ceramic hip resurfacing prostheses. The effects of design parameters, such as radial clearance, bone quality, coefficient of friction, and the cup-bone interface on the contact mechanics at the bearing surfaces could be important for the clinical performance and long-term survival of the prosthesis[14–18]. These factors could adversely affect the lubrication of the prosthesis thereby leading to increased wear and ultimately resulting in loosening of the prosthetic components. In this study, it is anticipated that the effect of these design parameters and the patient's bone characteristics on the contact mechanics at the bearing surfaces of COC hip resurfacing replacements will be important to understand the tribological performance of these implants.

2 Materials and method

A three-dimensional anatomic model of a hip joint was created from Computed Tomography (CT) scans of a left hip joint by a similar method as earlier studies[19,20]. To investigate the idea of ceramic-on-ceramic contact, an alumina ceramic hip resurfacing prosthesis was implanted (45° of abduction and 10° anteversion) in the original three-dimensional pelvic and femoral bone models in I-DEAS (Version 11). The hip resurfacing prosthesis was modeled with the same geometry as the commercially available 50 mm diameter resurfacing implants (DUROM™, Zimmer). The anatomic FE model of the resurfacing of the hip joint was then meshed in I-DEAS (Version 11, Eds, USA) and solved in ABAQUS (Version 6.9, Simulia, USA) as shown in Fig. 1. A total of 58,073 nodes and 52,542 8-node brick and 6-node wedge elements were used to mesh the three-dimensional anatomic FE model.

The outer surface of the acetabular cup in the conceptual model was assumed to be porous and was introduced as a press-fit component. The femoral component was described by a large head and a short tapered central stem for the purposes of alignment, initial stability, and acting as a bridge for the head-neck junction[1], and it was fixed to bone using polymethylmethacrylate (PMMA) cement. Therefore, the implant-bone, implant-cement, and cement-bone interfaces were assumed to be fully bonded to simulate full bone ingrowth and perfect cement fixation[21,22]. However, the cup-bone interface was also directed to have unbounded contact by applying a large coefficient of friction of 0.6[23]. The nominal radial clearance between the femoral head and acetabular cup was set to be 0.075 mm for this study. The contact between the articulating surfaces of both the femoral head and acetabular cup was assumed to be frictionless, and various coefficients of friction up to 0.6 were analyzed to investigate the resulting effect on the contact mechanics of COC hip resurfacing. The prosthesis was implanted in bone, which consisted of a cancellous region surrounded by a uniform cortical bone layer 1.5 mm thick[22,25]. The femoral component was fixed into the femoral head by means of PMMA bone cement. The cement thickness on the femoral side ranged between 1 mm and 1.5 mm[2,4,23]. All the materials considered in the current study were assumed to be linearly elastic and isotropic. The material properties of all of these components are given in Table 1.

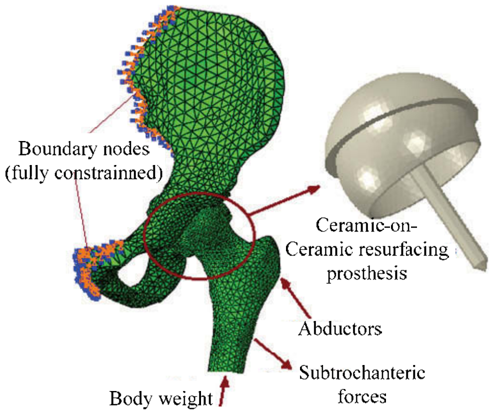

Fig. 1 Three-dimensional anatomic finite-element model of ceramic-on-ceramic hip resurfacing replacement showing the boundary conditions.

Table 1 Mechanical properties of a hip resurfacing prosthesis and the underlying non-metallic materials[24–26]

Material	Elastic modulus, E (GPa)	Poisson's ratio, v
Alumina[24]	380	0.26
Co-Cr-Mo	210	0.3
Ti6Al4V	110	0.3
Cortical bone[25]	17	0.3
Cancellous bone[25]	0.8	0.2
PMMA cement[26]	2.27	0.23