Contact Mechanics of Modular Metal-on-Polyethylene THR: Finite Element Analysis and Experimental Testing

Xijin Hua\textsuperscript{1}, Zhongmin Jin\textsuperscript{2,1}, Ruth Wilcox\textsuperscript{1}, John Fisher\textsuperscript{1}.
\textsuperscript{1}Institute of Medical and Biological Engineering, School of Mechanical Engineering, University of Leeds, Leeds, United Kingdom, \textsuperscript{2}School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an, China.

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Introduction: Contact mechanics analysis of total hip replacement (THR), particularly under some adverse conditions, is critically important for better understanding the performance and failure mechanism of hip implants from a mechanical point of view [1]. Finite element (FE) models are becoming increasingly useful tools to conduct such investigations [2]. However, the accuracy of the FE model predictions should be demonstrated by comparing with either clinical or experimental observations [3]. This required the contact mechanics of the hip implant to be examined using both FE models and experimental tests for the same sample. Previous studies have showed that the contact mechanics of the modular metal-on-polyethylene (MoP) THR was different from that of non-modular THR [4,5]. However, the contact mechanics of the modular MoP THR, in particular under adverse conditions, have not been comprehensively investigated. The aims of this study were to develop an FE model for a modular MoP THR and to demonstrate the verification of the model by comparing with the experimental test. The verified model will be then used to investigate the contact mechanics of modular MoP THR under standard and adverse conditions in the future study.

Methods: Specimens. Three specimens of polyethylene liner (DePuy Orthopaedics, Inc.) each with different radial clearances and contact conditions were tested. The radii of the inner surface of the liners were measured using a Coordinate Measuring Machine (CMM, Legex 322, Mitutoyo, UK).

Experimental measurement. A station of the Leeds Prosim hip joint simulator (Prosim Limited, Manchester, UK) was used. Each polyethylene liner was locked to a metallic shell via the taper, which was securely mounted to a stainless steel cup holder using Polymethylmethacrylate (PMMA) resin at an angle of 35°. A cobalt chromium (CoCr) femoral head with diameter of 36 mm was mounted on a holder which was attached to the machine (Figure 1a).

Figure 1. The experimental setup for modular THR (a), the FE modelling and boundary conditions for the axisymmetric model (b) and simple model (c).

A pigmented paste (MicroSet, Warwickshire, UK) was applied on the femoral head before loading. Five different loads from 500 N to 2500 N were applied for 2 minutes, which were then moved immediately in order to minimize viscoelastic effects. The contact areas in the liners were imaged and then were calculated using Image-Pro Plus (Media Cybernetics, Inc., MD, USA). For each specimen under a given load, the experiment was repeated three times to obtain an average value.
Finite element modeling. A three-dimensional anatomic modular THR model was created (Figure 1b), which was then simplified to a simple modular THR model (Figure 1c) for purpose of validation and simplifying the experimental set-up. The hemi-pelvic bone in the anatomic modular THR model consisted of a cancellous bone region surrounded by a uniform cortical shell of 1.5 mm thickness. All the materials in both models were modelled as homogeneous, isotropic and liner elastic except the polyethylene liner which was modelled as non-linear elastic-plastic [2]. The elastic modulus and Poisson’s ratio were assumed to be 1 GPa and 0.4 for polyethylene, 116 GPa and 0.25 for titanium, 0.8 GPa and 0.2 for cancellous bone, 17 GPa and 0.3 for cortical bone, 2.5 GPa and 0.254 for cement in both models. The total number of elements for the anatomic model and simple model were approximately 92,000 and 90,000 respectively, including ‘brick’, ‘wedge’, ‘tetrahedral’ and ‘shell’ elements. When the number of the elements was doubled, it yielded less than 5% change in any of the parameters of interest. Contact was modelled on the bearing surface between the femoral head and polyethylene liner, and at the interface between the liner and metal shell, with friction coefficients of 0.083 and 0.15 respectively in both models. For the anatomic model, nodes at the sacro-iliac joint and about the pubic symphysis of the pelvic bone were fully constrained and the bone-implant interface was fully bonded. For the simple model, the nodes at the outside of the cement were fully constrained and the interface between the cement and the metal shell was fully bonded. Three polyethylene liners with three different radii, corresponding to the specimens used in the experimental tests, were reconstructed in both models. Vertical loads from 500 N to 2500 N were applied at the centre of the femoral head and the acetabular cup was positioned at an inclination angle of 35° to reproduce the experimental conditions. The models were solved using ABQUIS (Version 6.9, Dassault Systèmes Simulia Corp., Providence, United States).

Results: For all loading conditions considered, the anatomic model predicted lower maximum von Mises stress of the liner, lower maximum contact stresses and larger contact areas on the articulating surface compared to the simple model, with differences of within 6%, 8% and 12% respectively (Figure 2).

For the three liners with various radii, similar contact area patterns were observed between the experimental measurements and FE predictions from the simple model (Figure 3). The differences of contact areas between the experimental measurements and FE predictions from the simple model were within 2.6%, 7.2% and 12% for the three liners respectively under all loading conditions considered (Figure 3).
Discussion: The verification of a three-dimensional anatomic modular THR model was demonstrated in this study. For purpose of validation and simplifying experimental process, the anatomic model was simplified to a simple model and such simplification was found not to affect the predictions of the contact mechanics of the modular MoP THR markedly. Good agreement of the contact areas were observed between the experimental measurements and FE predictions from the simple model under the same conditions, indicating that the simple model and anatomic FE model was reliable and valid to predict the contact mechanics of modular MoP THR. The FE model developed from this study will be used to investigate the contact mechanics of modular MoP THR under different conditions, especially under adverse conditions in the future study.

Significance: This study demonstrated the experimental measurement to verify a FE model, which is becoming increasingly useful tool to investigate the mechanical behaviour of the THR.

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