Medical Engineering & Physics 36 (2014) 1449–1454

Contents lists available at ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Influence of clearance on the time-dependent performance of the hip following hemiarthroplasty: A finite element study with biphasic acetabular cartilage properties

Junyan Li[a,*], Xijin Hua[a], Zhongmin Jin[a,b], John Fisher[a], Ruth K. Wilcox[a]

[a] Institute of Medical and Biological Engineering, School of Mechanical Engineering, University of Leeds, UK
[b] School of Mechanical Engineering, Xi'an Jiaotong University, China

ARTICLE INFO

Article history:
Received 8 March 2014
Received in revised form 13 May 2014
Accepted 31 May 2014

Keywords:
Hip
Hemiarthroplasty
Contact mechanics
Articular cartilage
Biphasic
Finite element

ABSTRACT

Hip hemiarthroplasty is a common treatment for femoral neck fracture. However, the acetabular cartilage may degenerate after hemiarthroplasty leading to postoperative failure and the need for revision surgery. The clearance between the acetabular cartilage and head of the prosthesis is one of the potential reasons for this failure. In this study, the influence of joint clearance on the biomechanical function of a generic hip model in hemiarthroplasty was investigated using biphasic numerical simulation. Both a prolonged loading period of 4000 s and dynamic gait load of 10 cycles were considered. It was found that a larger clearance led to a higher stress level, a faster reduction in load supported by the fluid and a faster cartilage consolidation process. Additionally, the mechanical performance of the acetabular cartilage in the natural model was similar to that in the hemiarthroplasty model with no clearance but different from the hemiarthroplasty models with clearances of 0.5 mm and larger. The results demonstrated that a larger clearance in hip hemiarthroplasty is more harmful to the acetabular cartilage and prosthesis heads with more available dimensions (i.e. smaller increments in diameter) could be manufactured for surgeons to achieve a lower clearance, and reduced contact stress in hemiarthroplasty surgeries.

1. Introduction

Hip hemiarthroplasty, a surgical procedure in which the femoral head is replaced by a metallic prosthesis, is a common treatment option for joint degradation that only affects the femoral head (e.g. femoral neck fracture). Although it is less destructive, less costly and requires shorter surgical time than a total hip replacement procedure, the acetabular cartilage, when articulating with a metallic head component, may degenerate, resulting in pain, immobility and the need of a revision surgery [1–3]. Therefore maintaining the well-being of the acetabular cartilage in hip hemiarthroplasty is important for the long-term performance of the joint.

Selection of the femoral component size is crucial for hip hemiarthroplasty, as it is directly linked with acetabular function and degeneration [3,4]. Empirically, surgeons initially use a head template of various dimensions to determine the size of the acetabulum and then adopt the largest prosthesis that is smaller than the template to achieve the smallest clearance between the prosthesis and acetabulum. However, artificial heads are most frequently available with 2 mm increments in diameter, which still leads to a mismatch in curvatures. A small head with larger clearance can lead to reduced joint conformity, lower stability, increased stresses and a faster cartilage consolidation process, while a large head may increase the periacetabular stresses and the coefficient of friction [4–6]. The interaction between the femoral component size and joint performance is, as yet, poorly defined. A greater understanding of this relationship could provide insight into whether the current surgical options are adequate and provide guidelines on what dimension of the prosthesis to adopt in order to improve the outcome of hip hemiarthroplasty surgery.

Mechanical factors have long been recognised as the primary contributor to cartilage damage. The function and degeneration of cartilage is closely linked with its biphasic (i.e. fluid–solid) nature, because the fluid phase is able to support most of the compressive load applied to the tissue and it also provides an excellent lubrication environment [7–9]. Particularly for the natural hip joint which is highly conforming, the fluid can provide over 90% load support for a prolonged period, as found recently by the authors using a novel

---

[*] Corresponding author at: Institute of Medical and Biological Engineering, School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK.
Tel.: +44 0113 343 7471; fax: +44 0113 242 4611.
E-mail addresses: ljyjerry@gmail.com, menjlic@leeds.ac.uk (J. Li).

http://dx.doi.org/10.1016/j.medengphy.2014.05.014

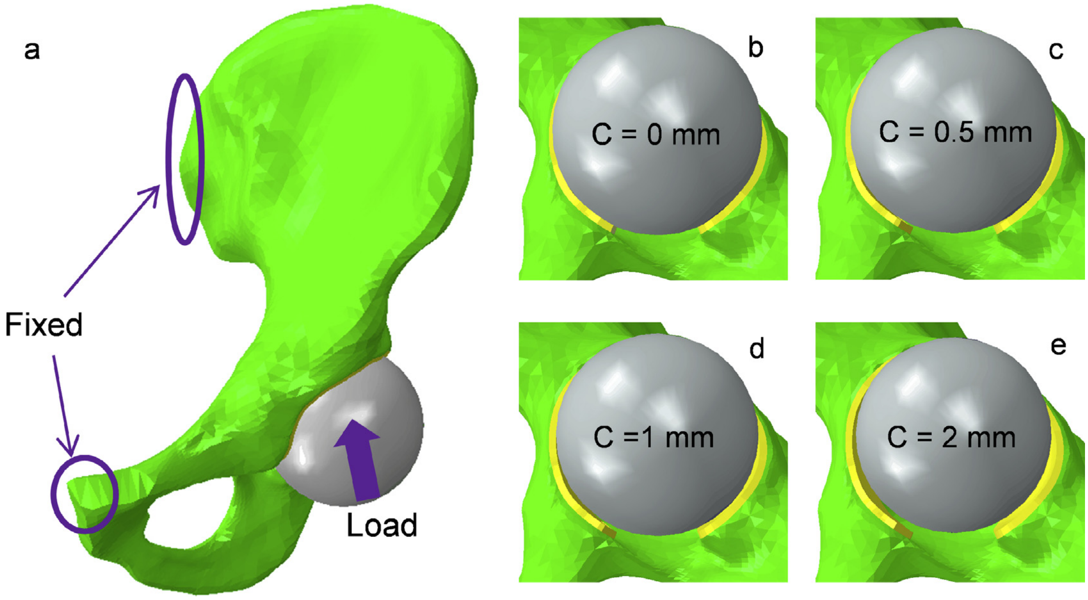

Fig. 1. The three dimensional hip model in hemiarthroplasty (a) and the metal heads with four different dimensions articulating against with the acetabular cartilage (b–e) (C: clearance).

biphasic computational model [10,34]. It is therefore necessary to consider the cartilage as a biphasic structure to obtain a greater understanding of the function and degeneration mechanisms of the hip joint following hemiarthroplasty.

The time-dependent tribological performance of the hip following hemiarthroplasty has been measured experimentally by Lizhang et al. [4], which is most likely associated with the fluid in the cartilage, supporting the importance of a biphasic investigation. However, the fluid pressure distribution within the hip cannot be determined through current experimental techniques, and a computational approach serves as the only method by which the biphasic behaviour of the joint can be fully investigated. Using a biphasic finite element (FE) simulation, Pawaskar et al. [11] evaluated the mechanical response of a hemiarthroplasty hip model for a variety of activities over short periods. However, the effect of different head sizes (joint clearances) and a prolonged loading period on the biphasic behaviour of hip in hemiarthroplasty has not been investigated, due to the limitations of that biphasic model. The aim of this study was therefore to use a biphasic FE model to evaluate the influence of joint clearance on the biphasic performance of the hip joint following hemiarthroplasty during a prolonged physiological loading period and under a dynamic load representing the gait cycle.

2. Methods

The hip hemiarthroplasty FE model used in this study was composed of a pelvis with the acetabular cartilage in articulation with a metallic prosthetic head component (Fig. 1). The labrum was not considered in this study, since it is commonly incomplete after hip hemiarthroplasty surgery. Details of model construction for the pelvis and acetabular cartilage were described in a previous study [10]. Briefly, the acetabular cartilage was assumed to be spherical (radius = 28 mm) with a uniform thickness of 2 mm to create a generic geometry for the acetabulum. The bone was represented by around 91,600 tetrahedral elements and the cartilage was meshed with 8400 hexahedral elements. A sensitivity study on the number of elements was conducted to ensure the model was insensitive to a denser mesh. The cartilage and bone were bound together through sharing the same nodes on their interface. The cartilage was assumed to be biphasic, whereby the solid phase was represented as neo-Hookean material (aggregate Young's modulus $E = 1.2$ MPa, Poisson's ratio $\nu = 0.045$) with a constant permeability ($K = 0.0009\ \mathrm{mm}^4/\mathrm{N\,s}$) [12]. The bone was modelled as impermeable and linearly elastic with Young's modulus of 17,000 MPa and Poisson's ratio of 0.3 [13]. The cortical bone and trabecular bone were not modelled separately because they were found to have little influence on the model predictions of interest for this study [10].

The metallic head component was represented by a rigid and impermeable sphere. To evaluate the influence of head size on the model predictions, four different radial clearances (0 mm, 0.5 mm, 1 mm and 2 mm) were evaluated by varying the size of the head (Fig. 1). The contact between articulating surfaces was assumed to be frictionless due to the low friction coefficient [14,15]. The fluid flow on the articulating surfaces was defined as contact-dependent so that fluid exudation was prevented on the cartilage surface that was in contact with the impermeable head but allowed for open surfaces. The pelvis was fixed at the sacroiliac and pubis symphysis joints. Loads were applied to the centre of the metallic head which was fixed in rotational degrees of freedom but allowed to move translationally for self-alignment. Rotation of the head was not considered because of its spherical geometry and the frictionless assumption of the articulating surfaces. Two common kinds of loads were considered: (1) a static load of approximately 2130 N based on the average data for one leg stance, ramped over 0.6 s and then held constant for 4000 s; (2) a time-dependent dynamic load during 10 cycles of gait – this load varied in magnitude and direction through each cycle to represent walking at normal speed (1.1 m/s) [16]. Additionally, the natural whole joint model with a radial clearance of 0.5 mm as described in a previous study [10] was considered for comparison.

The modelling procedure has been previously validated by comparing the model predictions to experimental tests, and good agreement in contact mechanics was achieved [17,35]. FE analyses were conducted using the open-source solver FEBio (version 1.5.0; Musculoskeletal Research Laboratories, Salt Lake City, UT, USA; URL: mrl.sci.utah.edu/software/febio) [18] owing to its good convergence capability in the simulation of biphasic materials in contact [10]. Contact stress, contact area, fluid pressure and fluid support ratio (the load supported by the fluid pressure over the total load) were recorded.