Medical Engineering and Physics 000 (2017) 1–8

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

Prediction of damage formation in hip arthroplasties by finite element analysis using computed tomography images

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ARTICLE INFO

Article history:
Received 8 October 2015
Revised 29 August 2016
Accepted 13 March 2017
Available online xxx

Keywords:
Total hip arthroplasty
Resurfacing hip arthroplasty
Femoral bone fractures
Damage formation
CT-based finite element analysis

ABSTRACT

Femoral bone fracture is one of the main causes for the failure of hip arthroplasties (HA). Being subjected to abrupt and high impact forces in daily activities may lead to complex loading configuration such as bending and sideway falls. The objective of this study is to predict the risk of femoral bone fractures in total hip arthroplasty (THA) and resurfacing hip arthroplasty (RHA). A computed tomography (CT) based on finite element analysis was conducted to demonstrate damage formation in a three dimensional model of HAs. The inhomogeneous model of femoral bone was constructed from a 79 year old female patient with hip osteoarthritis complication. Two different femoral components were modeled with titanium alloy and cobalt chromium and inserted into the femoral bones to present THA and RHA models respectively. The analysis included six configurations, which exhibited various loading and boundary conditions, including axial compression, torsion, lateral bending, stance and two types of falling configurations. The applied hip loadings were normalized to body weight (BW) and accumulated from 1 BW to 3 BW. Predictions of damage formation in the femoral models were discussed as the resulting tensile failure as well as the compressive yielding and failure elements. The results indicate that loading directions can forecast the pattern and location of fractures at varying magnitudes of loading. Lateral bending configuration experienced the highest damage formation in both THA and RHA models. Femoral neck and trochanteric regions were in a common location in the RHA model in most configurations, while the predicted fracture locations in THA differed as per the Vancouver classification.

1. Introduction

Total hip arthroplasty (THA) and resurfacing hip arthroplasty (RHA) are common procedures for patients with progressive hip osteoarthritis. Continuous development and improvement of prosthesis engineering design and advanced surgical approaches have enabled the success of the procedures for many decades [1]. However, the risks of femoral fractures in arthroplasty patients still present a challenge for long term performance. The incidence of periprosthetic fractures following THA has increased substantially [2] by more than 25% in the last decade [3]. In RHA, femoral neck fractures are one of the main causes of failure [4] and early postoperative complication [5].

The prediction of loading direction, which is associated to the fracture type, was very challenging. The unique characteristics of femoral bone with its irregular and inhomogeneous structure [6] increase the uncertainties of the procedure. Several studies of injury mechanism have suggested that falling onto the hip is the ultimate reason for femoral fractures, particularly in the elderly population. The greater trochanteric region of the femur was found to absorb most of the impact [7–9]. Experimental investigations of femoral behavior under different isometric and physiological loadings have been continuously conducted in order to provide better clinical information and solutions [10–13]. Furthermore, the advances in computational analysis have enabled proper prediction by considering the muscles reaction force and creating a more accurate representation of the *in vivo* scenario [6]. In THA, several classifications of femoral fractures have been developed over the years in order to describe the fracture locations [14]. For instance, the Vancouver classification is one of the most widely used systems to differentiate the fracture sites. This system considers three important factors associated with the injuries, namely the site of fracture; the stability of the femoral component and the quality of the surrounding bone stock [15].

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http://dx.doi.org/10.1016/j.medengphy.2017.03.006

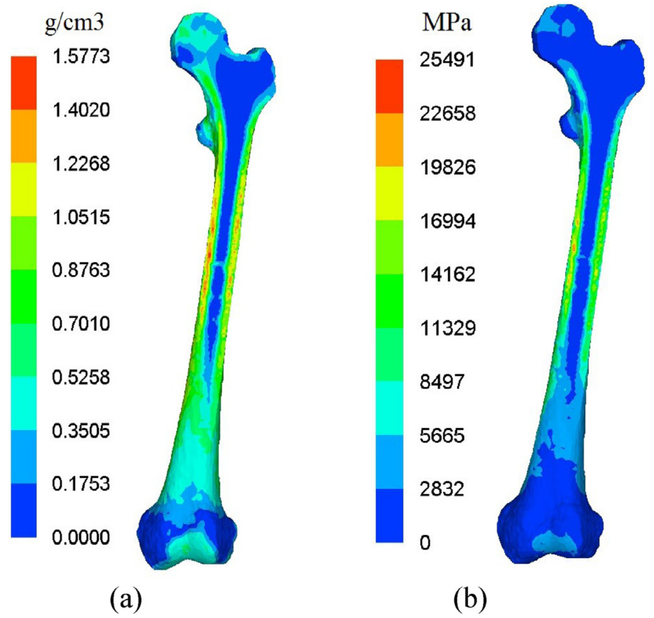

Fig. 1. Distribution of (a) bone mineral density and (b) modulus of elasticity in inhomogeneous femur model.

Improvement in the engineering design and material selection in RHA has increased bone preservation and reduced incidence of dislocation [16,17]. However, complications of femoral neck fractures remain and the incidence is higher in several independent series [18,19]. In addition to poor surgical techniques and biological factors, biomechanical factors such as having nothing in the femoral neck, neck lengthening and malalignment of the femoral component contribute to fracture risks [20].

As a consequence, the aim of the present study is to analyze the effects of different types of femoral components, namely THA and RHA, in predicting the risk of femoral fractures using finite element (FE) analysis. Different loading configurations were considered in the analysis to simulate isometric loading modes and sideway fall. The fracture risk was discussed in the resulting damage formation element of the inhomogeneous bone model. To the best of our knowledge, this approach has not yet been applied to HA model to evaluate the possibility of bone fractures.

2. Materials & method

The geometry of the femoral bone was developed from a CT based image of a 79-year-old living female with hip osteoarthritis in the left joint. The data was provided by Kyushu University Hospital, Japan. The CT images were compiled and stacked into commercial biomedical software Mechanical Finder 6.1 (Research Center of Computational Mechanics Inc, Tokyo) to construct a three dimensional (3D) model using FE analysis. The total number of elements for the femoral bone in THA and RHA were 146,414 and 166,414 respectively. For femoral components, prosthesis and femoral ball were assigned with 23,349 elements while resurfacing implant had 37,484 elements. Automated mesh size of 2 mm was considered with tetrahedron elements for all models. In generating an inhomogeneous model, each element of the bone model was generated based on the basis of the linear relationship between ‘apparent density’ and gray value of the data in Hounsfield unit (HU). Material properties for the bone elements were computed based on the basis of the study by Keyak et al. [21,22] to present the variation of bone mineral density and young’s modulus for the femoral bone (Fig. 1). The high values of Young modulus in outer part present cortical bones, while lower values indicate cancellous bones. The model was also assumed to be an isotropic material.

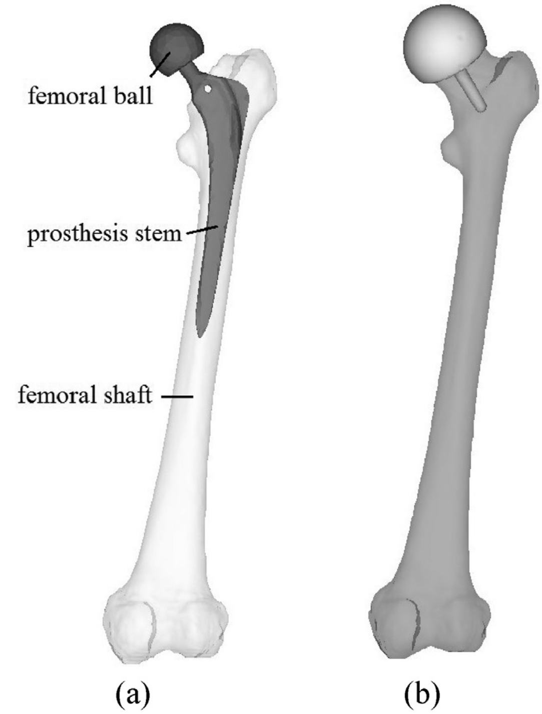

Fig. 2. 3D model of (a) total hip arthroplasty and (b) resurfacing hip arthroplasty.

Table 1
Mechanical properties of hip arthroplasties.

Properties	Titanium alloy	Alumina	Cobalt chromium
Elastic modulus (GPa)	114	370	230
Poisson ratio	0.34	0.22	0.30
Critical stress (GPa)	0.88	0.40	0.94
Yield stress (GPa)	0.97	3.00	2.70
Density (g/cm^3)	4.43	3.96	8.28

2.1. FE model of HAs

HA models were constructed by replacing the hip joint with different femoral component models. The 3D models of femoral components or implants were imported into the biomedical software to develop the THA and RHA models. The THA model was developed by replacing the hip joint with Titanium Alloy prosthesis stem and Alumina femoral ball. The femoral head was cut off and the prosthesis stem was aligned properly into the femoral canal. The difference in the RHA model is that the femoral head was resurfaced by implanting the Cobalt Chromium prosthesis pin. Descriptions of both models are illustrated in Fig. 2, while the mechanical properties of the femoral components [23] are summarized in Table 1. The connection between the implant and the bone is assumed to be perfectly bonded at the interface.

2.2. Loading and boundary conditions

In this study, we examined different configurations to demonstrate the various loading directions and boundary conditions. Three types of isometric loadings were axial compression configuration (ACC), torsion configuration (TC) and lateral bending configuration (LBC). The consideration of loading was adapted from the well-established and validated testing protocol for periprosthetic femoral shaft fixation [24–28]. In addition, the characteristic