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Prediction of Damage Formation in Total Hip Arthroplasty using Finite Element Method

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Total hip arthroplasty (THA) patients sometimes encounter periprosthetic fractures. Sudden and high impact loading during certain activities may contribute to the incident such as sideway falls and bending. In this study, damage formation in femoral bone with a hip prosthesis was predicted using the CT-based nonlinear finite element method. 3D model of femoral shaft was developed from CT-images of a 54 years old patient. The femoral head was then cut off and aligned with hip prosthesis stem to reconstruct THA model. Three different configurations of isometric loadings were considered to demonstrate high and complex impact loading. The applied impact forces were normalized to body weight (BW) and vary from 1BW to 5BW. The results showed that the patterns of predicted bone fractures were different for each configuration. Numbers of element failures were the highest in the lateral bending condition. Indication of failure elements at the bone-implant interfaces suggested possibility of prosthesis loosening and instability.

Key words: *Hip Prosthesis, Damage Formation, Femoral Bone, Finite Element Analysis*

1. Introduction

Total hip arthroplasty (THA) is one of the most recognized treatments for osteoarthritis and rheumatoid arthritis. Improvements of surgical techniques and femoral implant design are continuously developed to promote long term performance and stability. However, THA patients were always at risk of falls due to imbalance, medication side effects and difficulty of avoiding environmental hazards [1]. Presence of artificial hip joint has contributed to the gait impairment and remodeling process of the bones. Bones are adapted to the new mechanical environment and became weaker.

Sideways falls might involve sudden and high impact loading to the hip of a THA patient, which is very dangerous to elder patients. It may also lead to femoral bone fractures, joint failures and other successive injuries [2]. Periprosthetic fractures of the hip were expected for high and complex loading vectors acting upon the femur [3]. In predicting the fracture mechanism of femur, a lot of studies have been conducted by surgeon and researchers to investigate the effects of loading direction [4]. For instance, Pinilla et al. [5] conducted a compression test of cadaveric femora specimen while Keyak et al. [5] demonstrated simulation studies on the influence of load direction using the linear finite element method. As an improvement of computational prediction, Bessho et al [4] established nonlinear finite element method for the respective purpose. However, those studies were only focus on intact femur. In this study, a computational model of femur with THA was develop using CT-based nonlinear finite element method.

The purpose of this study was to investigate the mechanisms of periprosthetic femoral fractures associated with THA. Damage models were introduced into the finite element method in order to predict damage formations in a femoral model with hip prosthesis.

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2. Method

2.1 3D inhomogeneous modeling

3D inhomogeneous model of a left femoral shaft was constructed from computed topography (CT-based) data of 54 years old, male patient. The models were developed and analyzed using a commercial biomechanical software, Mechanical Finder version 6.1. Material properties for each tetrahedron element of the bone model were computed by Hounsfield unit value and presenting different scale of bone densities. Assignment of young modulus and yield strength of the model were calculated based on the theory of Keyak et al [6], as illustrated in Fig.1a.

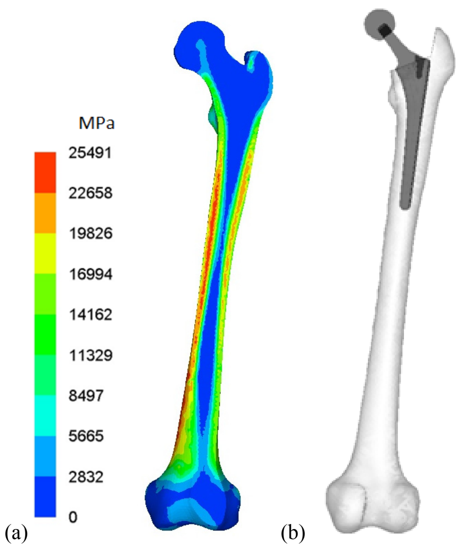

Fig.1 (a) Distribution of young modulus in femoral shaft, (b) 3D model of Total Hip Arthroplasty

2.2 THA modeling

A commercial model of hip implant was imported and aligned in the femoral bone to construct THA model. The femoral ball was cut off and inserted with a prosthesis stem to present artificial ball and socket joint as shown in Fig.1b.

Material of the prosthesis stem is modeled as titanium alloy while femoral ball as alumina. The respective properties were summarized in Table 1 [7]. Interconnection between both implants and bone was assumed to be perfectly bonded at the interface.

2.3 Loading and Boundary Conditions

Three types of loading and boundary conditions were considered in the analysis to demonstrate different configurations, namely

Table 1 Mechanical property of hip prosthesis [7]

Properties	Ti6Al4V	Alumina
Elastic Modulus (GPa)	114	370
Poisson Ratio	0.34	0.22
Critical Stress (GPa)	0.88	0.40
Yield Stress (GPa)	0.97	3.00
Density (g/cm^3)	4.43	3.96

stance (SC) [4], torsion (TC) and lateral bending (BC) [8]. Each configuration exhibits different loading directions at angle α (with reference to the long axis of femur in the frontal plane) and β (with reference to the femoral neck axis in the horizontal plane) [4]. Fig.2 illustrates the loading and boundary conditions for each configuration while Table 2 describes the orientation of loading direction.

Different loading magnitudes which range from 1BW to 5BW are considered to predict the stress behavior and potential of fracture patterns. Finite element analyses combined with damage mechanics models are performed to predict damage formations in both THA model and intact femur [9].

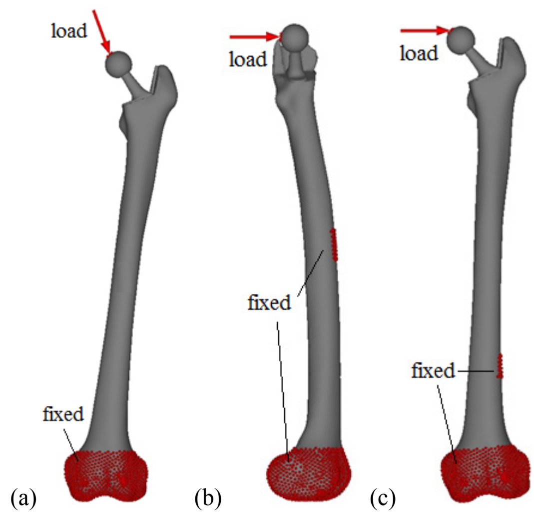

Fig.2 Description of loading and boundary condition for different configurations: (a) stance, (b) torsion and (c) lateral bending

Table 2 Different angle of loading direction

Configuration	α	β
SC [4]	160	0
TC [8]	0	90
BC [8]	90	0

3. Results & Discussion

3.1 Damage accumulation

Prediction of tensile and compressive damages in the models was performed computationally with use of failure and yield criterions. The different fracture models are installed in Mechanical Finder software. The load bearing strain under compression was set to 3000 micron which representing bone loading that leads to bone formation. The tensile strength was set to 80% of the yield strength determined from the CT images [9,10]

Increment of failure and yielding elements by increasing body weight (BW) loading are presented in Fig. 3 for different configurations. Failure elements were differentiated into tensile and compressive criterion. Different findings of isometric loadings were presented in Fig.3a till Fig. 3c for stance, torsion and lateral bending configuration, respectively. Both tensile and compressive failures were predicted to increase rapidly from 3BW to 5BW in SC configuration. However, the magnitude of them was much lower at 1300 of total elements, as compared to TC and BC configurations. Tensile failures were dominant in TC and BC cases as compared to compressive failures. The direction of loading applied to the hip reflects to the findings. Numbers of element failures were high in both cases at smaller BW loading and exceed extremely at 5BW magnitude. The total of failures was predicted about 15,000 and 30,000 elements for TC and BC configurations. Hip loading with lateral bending configurations was predicted to demonstrate the highest of element failures as compared to other configurations.

3.2 Locations of damage formation

Distribution patterns of different damages, tensile and compressive failures and yielding, are shown in Fig.4. Different types of loading configuration conducted in this study suggested different type and location of element failure. Element of failure in tensile direction was indicated as white, while yellow and red color presenting compressive yielding and failure elements, respectively.

Bending effects from prosthesis stem during stance lead to elements failure at the distal end of femoral shaft as shown in Fig.4a.

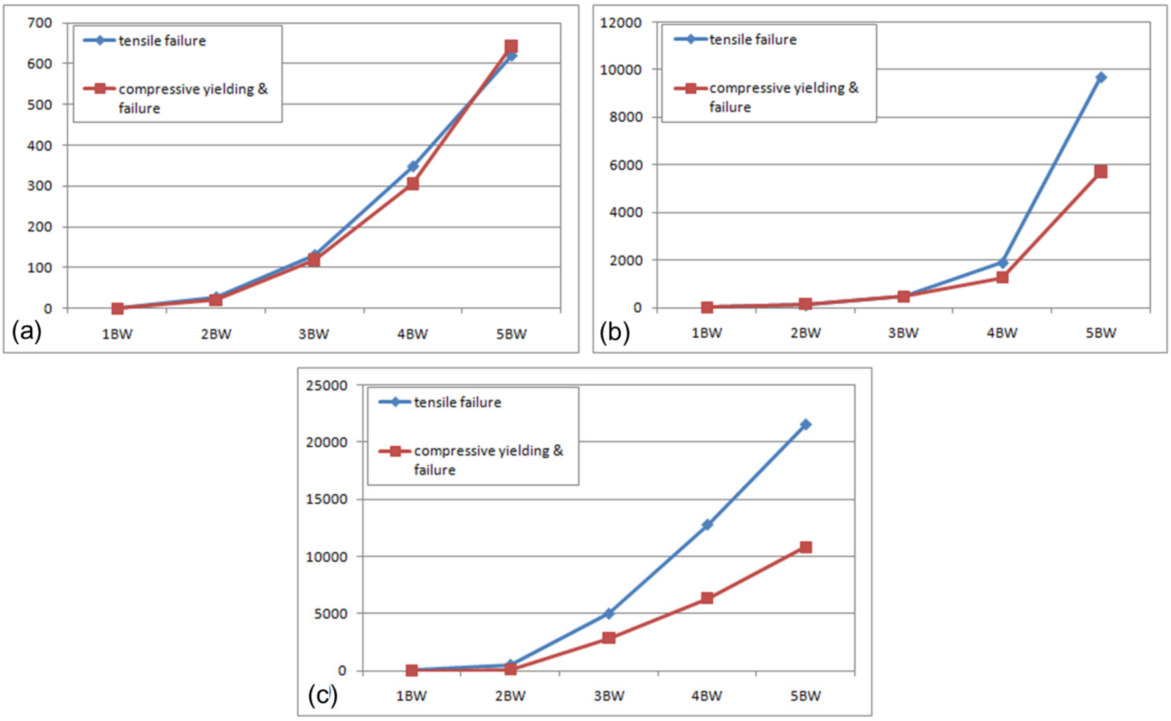

Fig.3 Increment of element failures by increasing body weight (BW) loading for different configurations: (a) SC, (b) TC and (c) BC.

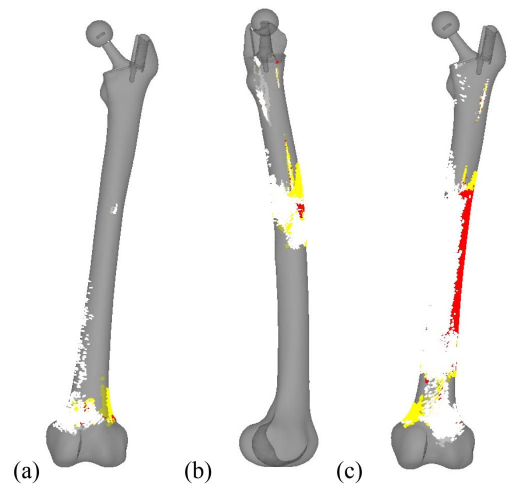

Fig.4 Damage distribution patterns: (a) SC, (b) TC and (c) BC.

Failure of elements was also projected at the distal stem which may initiate to stem loosening. Configuration of TC and BC presented extreme numbers of element failure in high impact loading. Results of predicted fracture location at 5BW loading were shown in Fig.4b and Fig.4c for TC and BC, respectively. Both cases estimated bone fractures at the middle of femoral shaft and around the distal prosthesis. Besides, indication of element failures interfaces between implant and bones suggested for unstable prosthesis and inadequate bone stock. Extreme and high impact loading (5BW) applied in the analysis might overestimate the real magnitude during respective activity. But, the current findings suggested that both torsion and lateral bending configurations produced greater consequences at lower impact loading.

4. Conclusions

Computational analysis using the CT-image based finite element method was performed to predict damage formulation of bone implanted with prosthesis. The conclusions were obtained as follows:

(1) Introduction of different types of loading condition was capable to consider different types of damage formation in femoral model with hip prosthesis.

(2) Introduction of different kinds of damage formation, namely, tensile failure, tensile yielding and compressive failure, was enable us to predict different types of fracture behavior associated with hip prosthesis.

(3) Bending effects from prosthesis stem during stance lead to element failure at the distal end of femoral shaft. Failure of elements was also projected at the distal stem which may initiate to stem loosening.

(4) For the TC and BC conditions, bone fractures were predicted at the middle of femoral shaft and around the distal prosthesis. Besides, indication of element failures interfaces between implant and bones suggested for unstable prosthesis.

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