Available online at www.sciencedirect.com
ScienceDirect
Journal of Bionic Engineering 4 (2007) 123–131

Static and Dynamic Mechanics Analysis on Artificial Hip Joints with Different Interface Designs by the Finite Element Method

Hai-bo Jiang

College of Mechanic and Electrical Engineering, China University of Mining and Technology, Xuzhou 221008, *P. R. China*

Abstract

Four different structural models of artificial joints were developed and the finite element method (FEM) was employed to investigate their mechanical characteristics under static and dynamic conditions. The materials used in the FEM calculation were ultra-high molecular weight polyethylene (UHMWPE), 316L stainless steel, CoCrMo alloy and Ti6Al4V alloy. The stress distribution, strain, and elastic deformation under static and dynamic conditions were obtained. Analysis and comparison of the calculation results of different models were conducted. It is shown that with the same parameters the model of a metallic femur head covered with an artificial cartilage layer is more similar to the structure of the natural human joint and its mechanical characteristics are the best of the four models.

Keywords: finite element analysis, stress, articular joint

---

1 Introduction

The hip joint is one of the most important weight-bearing and shock-absorbing structures in the human body during jumping, running and the gait cycle. It is well known that fully understanding the joint stress distribution is very useful for both pre-operative planning and post-operative rehabilitation. The short- and long-term behavior of a total hip joint replacement is dependent on obtaining the optimal stress distribution within the bone-implant construct[1-4]. The structure, shape and material are the three main factors in the design of the prostheses. This research is focused on the structural analysis. The currently used artificial hip joint in clinic and research is shown in Fig. 1. There are three parts to the artificial hip joint, the metallic femur head, the UHMWPE layer and, sometimes, the metallic cup covering the UHMWPE layer for better fixation on the pelvis[5,6]. The natural human hip joint is composed of two cartilage layers and synovia (shown in Fig. 2). There are significant structural differences between natural and artificial joints, which

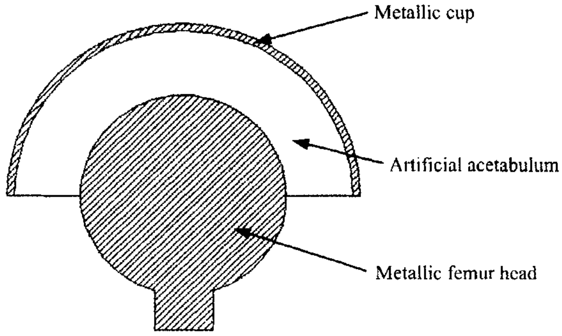


Fig. 1 Structure of normal artificial joint.

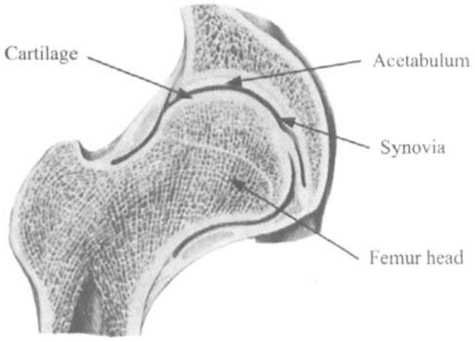


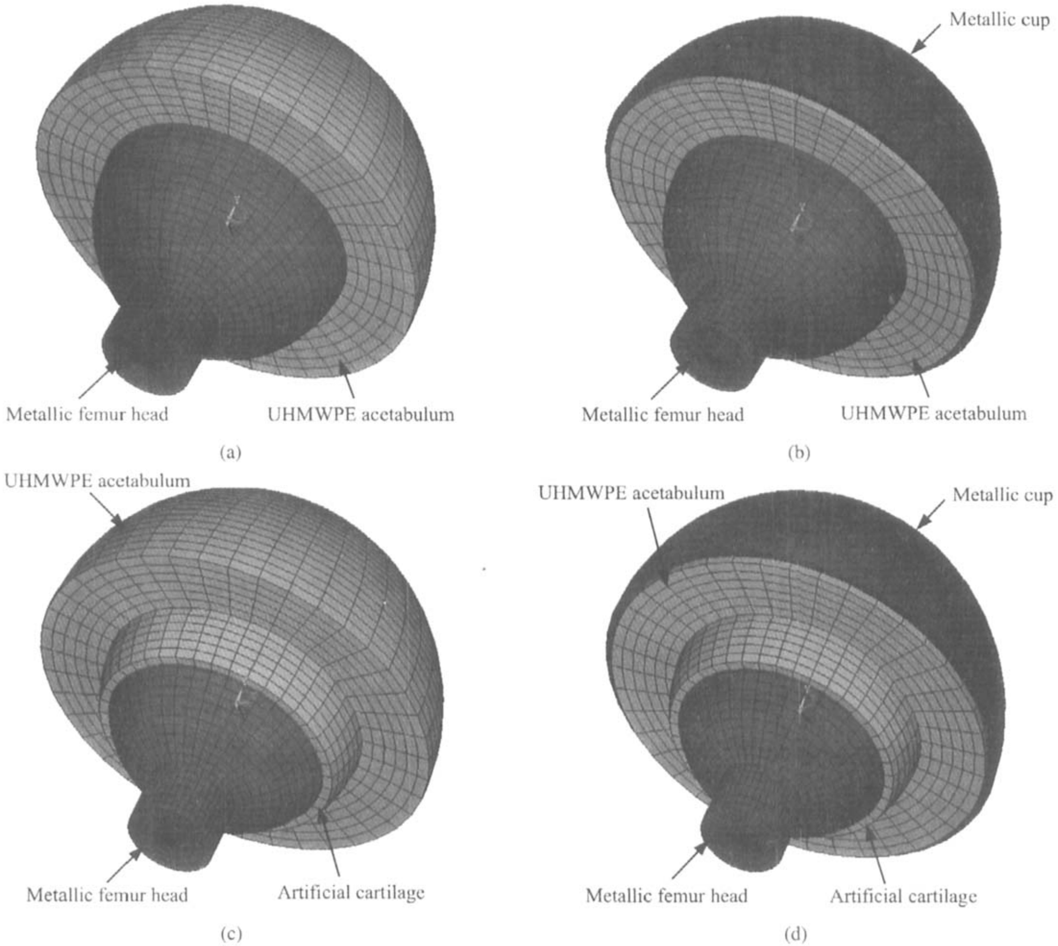
Fig. 2 Section of human hip joint.

Corresponding author: Hai-bo Jiang
E-mail: jhb654cumt@163.com

influence the mechanical characteristics of the joint. We have proposed bionic hip joint models with a layer of cartilage between the femoral head and the acetabulum. The proposed models are more similar to the natural hip joint than the current artificial joint. The aim of this study is to analyze and compare the differences between the proposed models and normal prosthetic hip joint in terms of stress distribution and deformation distribution under different loading states, both static and dynamic.

2 Finite element model

Four different hip joint finite element (FE) models were developed in ANSYS (Ansys Co. version 8.0). Fig. 3a to Fig. 3d show schematically the hip joint models, consisting of the metallic cup, metallic femur head, UHMWPE artificial acetabulum and artificial femoral head cartilages. In the first model a UHMWPE artificial acetabulum matches the metallic femur head prosthesis, as shown in Fig. 3a. In the second model a metallic cup covers the UHMWPE artificial acetabulum as shown in Fig. 3b. In the third model there is a layer of artificial cartilage covering the femoral head, as shown in Fig. 3c. The last model is similar to the third model except that a metallic cup covers the UHMWPE acetabulum, as shown Fig. 3d. The diameter of the femoral head is 28 mm and the thickness of UHMWPE artificial acetabulum is 8 mm, similar to the standard sizes normally used in the clinic. 20-noded hexahedral elements were selected to mesh the FE models. The surface-surface contact pair was created between femur head and acetabulum with contact elements (target 170 and contact 174). The metallic cup matching the UHMWPE layer and the artificial cartilage matching the femoral head are two assembled parts developed with finite element analysis (FEA) software.



(a) (b) (c) (d)

Fig. 3 FEA model of a hip prosthesis meshed with Solid 95 element.

3 Material properties

Five different implant materials were used in this finite element simulation. Ti6Al4V, 316L stainless steel and CoCrMo alloy were used for the metallic femur head and the metallic cup due to their wonderful biocompatibility behavior in clinical conditions. The acetabulum layer is made of UHMWPE polymer and the femoral head cartilage is made of artificial cartilage. In this work, some assumptions are still inevitable. The elastic modulus of the material of the metallic femoral head is at least two orders of magnitude greater than that of UHMWPE and cartilage, therefore the femoral head was assumed to be rigid. All materials were assumed to be homogeneous, isotropic and linear elastic solid. The important material parameters required for the FEM analysis are the elastic modulus and the Poisson ratio, which are listed in Table 1.

Table 1 The parameters of joint materials

Materials	Elastic modulus (GPa)	Poisson ratio	Source
UHMWPE	1.4	0.3	Ref. [5]
Cartilage	2	0.3	Ref. [7]
CoCrMo	230	0.3	Ref. [8]
Ti6Al4V	110	0.3	Ref. [1]
316L	196	0.3	Ref. [9]

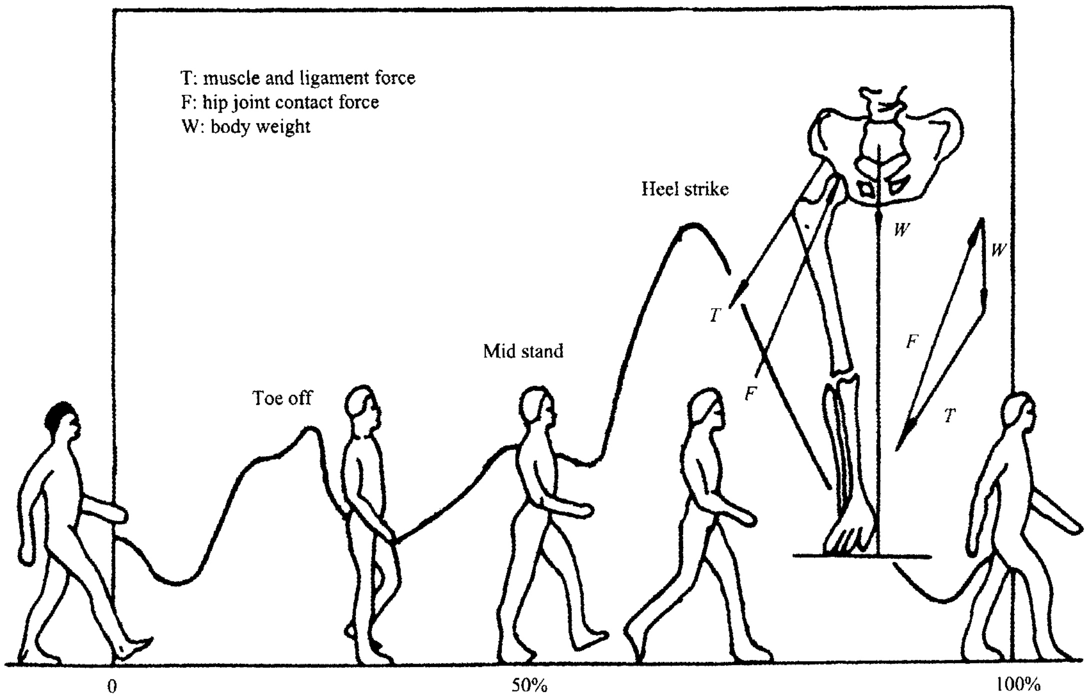


Fig. 4 Sketch map of gait cycle.

4 Loading conditions

4.1 Static analysis

In the static analysis, the models simulate a human standing. In standing the joint bears approximately one third of the weight. Assuming the weight of the person to be 60 kg, then the load on the hip joint is 200 N. The direction of the force points to the centre of the femoral head. In the analysis, the degree of freedom (DOF) of acetabulum backing should be fixed in order to simulate standing. The loading time is one second.

4.2 Dynamic analysis

The magnitude and distribution of stress and displacement during walking are important to understand the working of the artificial joint. The dynamic process analysis is the key point of this work which can benefit the evaluation and redesign of artificial joint.

In dynamic analysis, the DOF of the acetabulum backing is also fixed. The measured angle of hip joint during normal walking is approximately 25° (in slow walking). The change of angle must be influenced by displacement in the Ansys software. If the length of joint handle, R, is about 20 mm, then the length of the chord, l, is given by

$$l = 2R\sin\frac{\theta}{2} ,$$

where $\theta = 25°$, the measured angle. Then we have the length of the chord, $l = 8.65$ mm, which is also the displacement in spherical coordinates to simulate joint movement during slow walking and sliding in the XY plane. The force on the joint varies during the gait cycle as shown in Fig. 4. The peak loading occurs at heel strike, mid-stand and toe-off. Numerical values are given in Table 2[10]. Different gait parameters were calculated with different peak joint forces. Loadings at the three points are important for evaluating joint characteristics.

Table 2 Joint force during a gait cycle

Gait	Peak force	Value (N)
Heel strike	4.64 BW	3637.76
Mid stand	3.51 BW	2751.84
Toe off	4.33 BW	3394.72
	BW (body weight) = 60 kg	

5 Results and discussion

5.1 Static results

Fig. 5, Fig. 6 and Fig. 7 are the histograms of the elastic deformation, stress and strain of joint under static loading. With the artificial cartilage covering the femoral head (models (c) and (d)), both the deformation and the peak stress of the UHMWPE acetabulum are approximately 10% lower than without artificial cartilage ((models (a) and (b)). The reason is that the artificial cartilage covering femur head increases the contact area between the femoral head and the acetabulum and the load is dispersed onto the added area which decreases the elastic deformation and the peak stress. The metallic cup has little influence on the deformation and stress of the acetabular layer. Comparing three different implant materials, the deformation, stress and strain of Ti6Al4V are smaller than that of other materials, which is because the elastic modulus of Ti6Al4V is lower.

As shown in Fig. 6 and Fig. 7, comparing model (a) with model (b), the metallic cup leads to decrease in

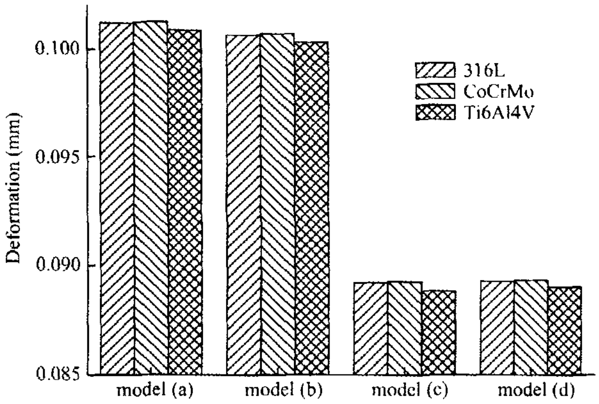


Fig. 5 Deformation histogram during static analysis.

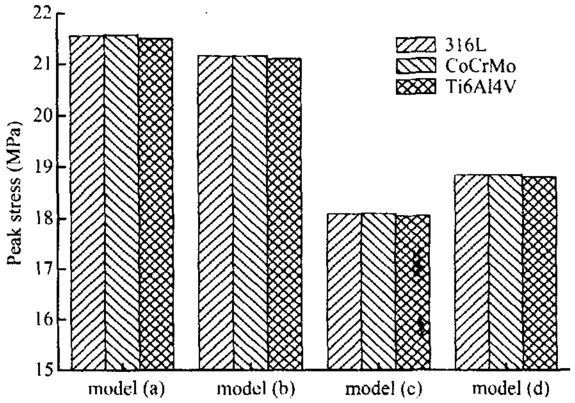


Fig. 6 Peak stress histogram during static analysis.

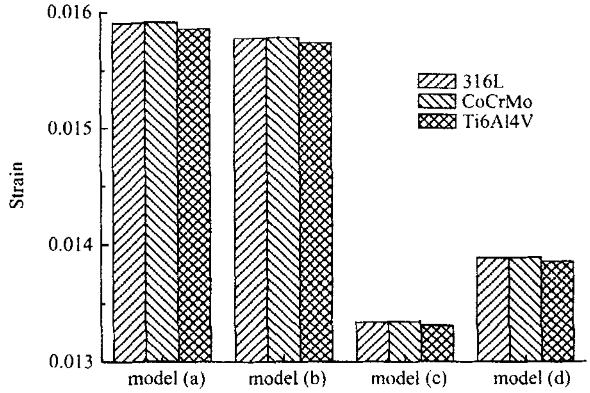
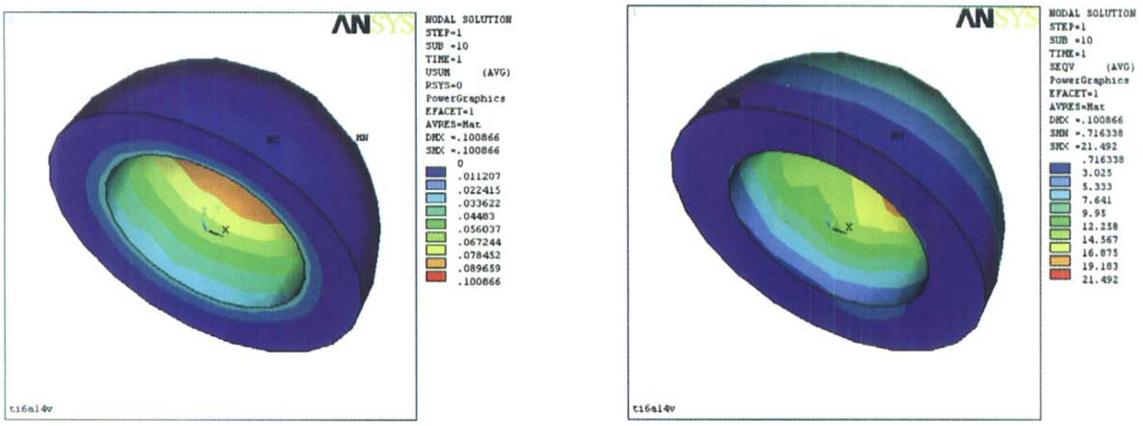


Fig. 7 Strain histogram during static analysis.

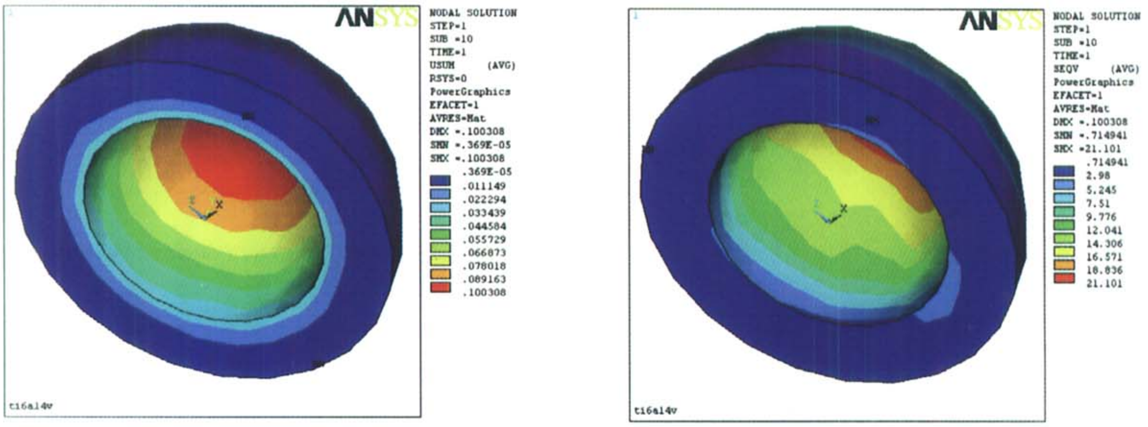
stress and strain. By contrast, comparing model (c) and model (d), the metallic cup leads to increase in stress and strain. The metallic cup can avoid the loosening of the artificial acetabulum that may be caused by creep of the UHMWPE layer, but it should decrease deformation of models (b) and (d) as shown in Fig. 5.

With different materials, the distribution trends of the deformation, stress and strain are similar. Fig. 8 shows the contour images of Ti6Al4V under static load. Comparison of the four models shows that the metallic cup can induce non-uniform distributions of deformation and stress.



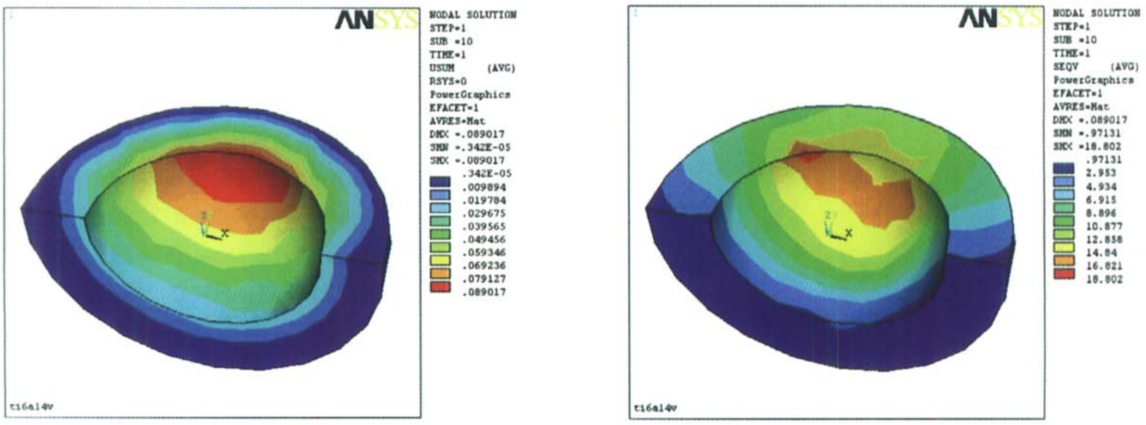
(a) Deformation of model (a)

(b) Stress of model (a)



(c) Deformation of model (b)

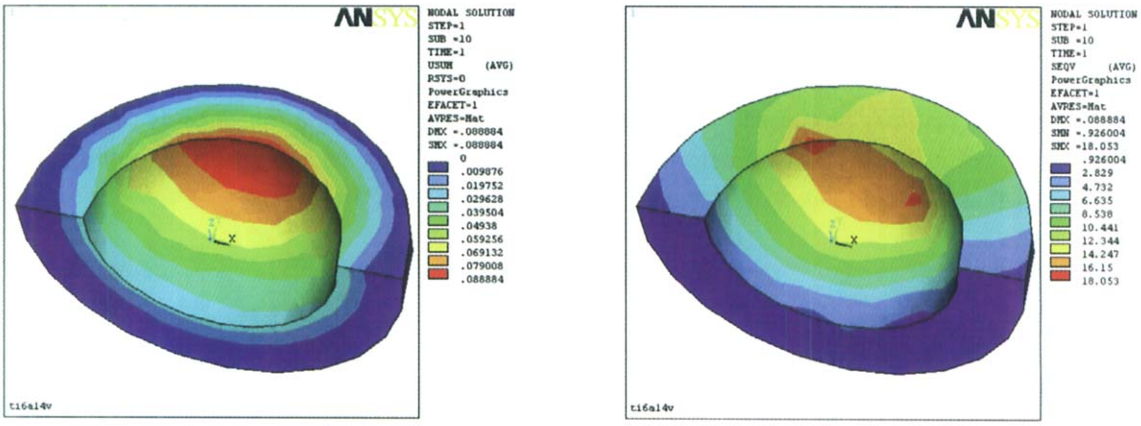
(d) Stress of model (b)



(e) Deformation of model (c)

(f) Stress of model (c)

Fig. 8 Contour image of acetabulum during static cycle.



(g) Deformation of model (d)

(h) Stress of model (d)

Fig. 8 Continued.

5.2 Dynamic results

Figs. 9, 10 and 11 are the deformation, peak stress and strain under dynamic loading, which is nonlinear and is much more complicated than static loading. Deformation, peak stress and strain under dynamic loading are much higher than under static loading. As shown in Fig. 10, in dynamic loading, the peaks of stress of models (c) and (d) are much lower than that of models (a) and (b). Fig. 11 shows that the peaks of strain of models (c) and (d) are also lower that of models (a) and (b). This indicates that the dynamic characteristics of the artificial joint are significantly influenced by the cartilage layer covering the femoral head and the metallic cup, that is, for all simulated materials, the deformation, the peak stress and strain of model (d) are of the minimum.

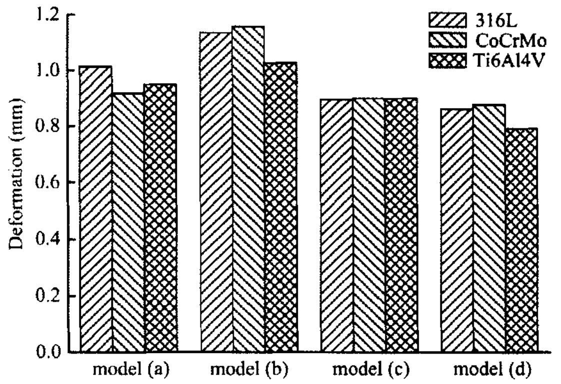


Fig. 9 Deformation histogram during dynamic analysis.

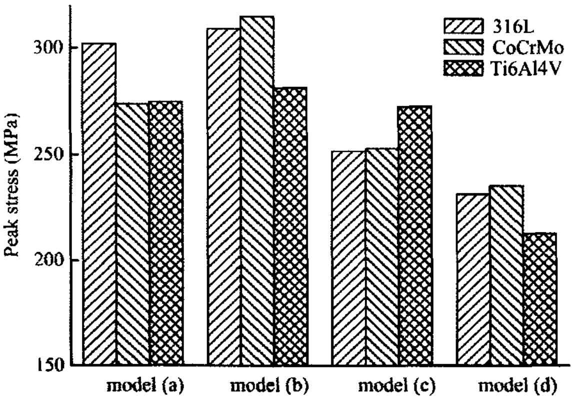


Fig. 10 Peak stress histogram during dynamic analysis.

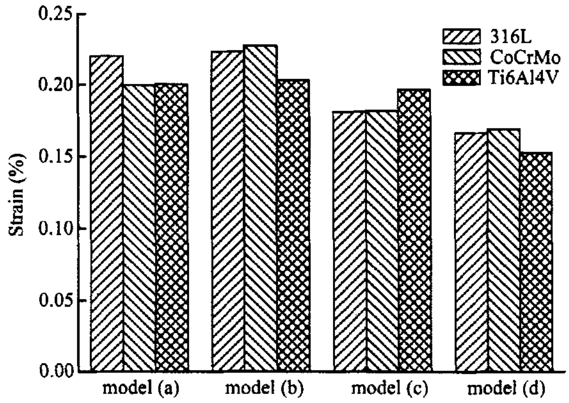
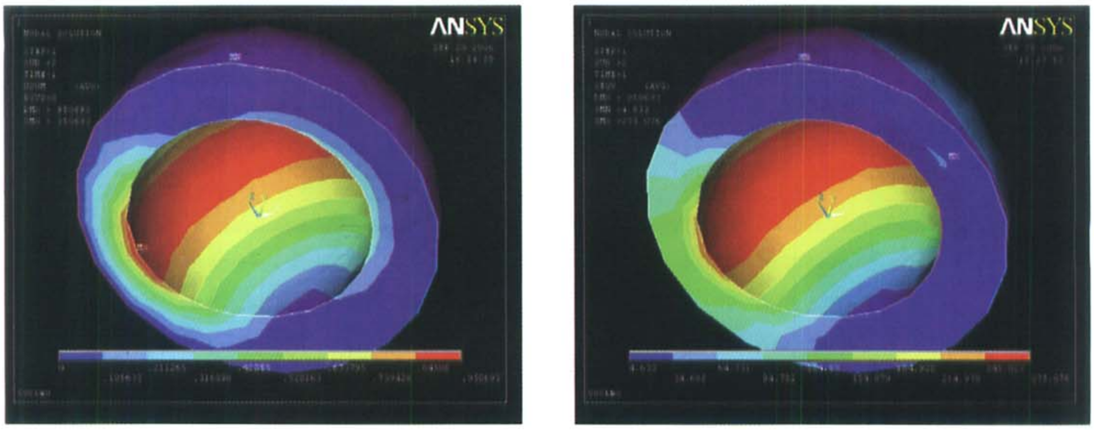


Fig. 11 Strain histogram during dynamic analysis.

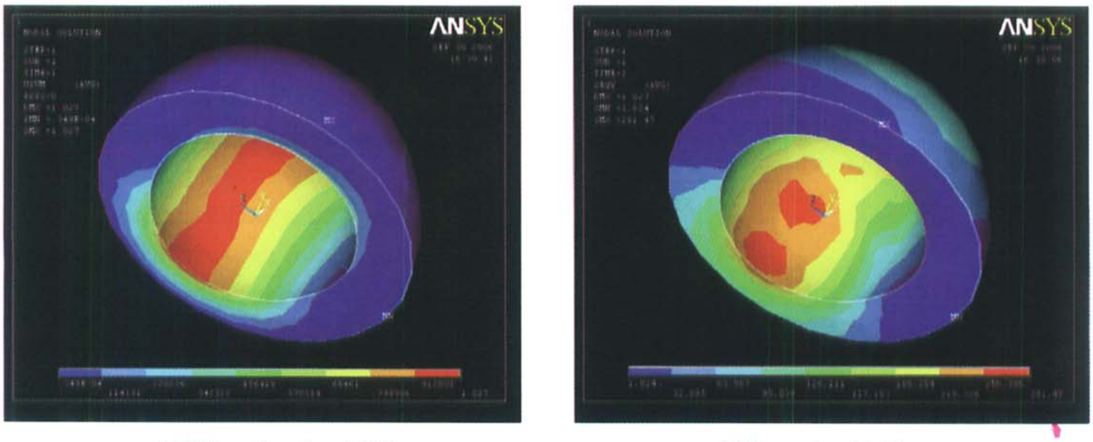
Fig. 12 shows the contour images of UHMWPE acetabulum, in which the material of the metallic cup of models (b) and (d) is Ti6Al4V. Without the cartilage layer, as shown in Fig. 12a to Fig. 12d, not only the stress and deformation of the hip joint are higher, but also the variations along the sliding direction are greater. So standing for a long time can induce large deformation in the artificial cartilage layer that could accelerate the material fatigue and shorten the service life of the joint.

Under the same condition, in contrast, with the cartilage layer, as shown in Fig. 12e to Fig. 12h, both the stress and deformation are lower. With the metallic cup, the peak stress in the acetabulum is discrete, as shown in Fig.12h. In model (c) the maximal stress occurs near the brim of the acetabulum in the sliding direction, as shown in Fig. 12f. Thus, the cartilage layer can extend the service life of the artificial joint.



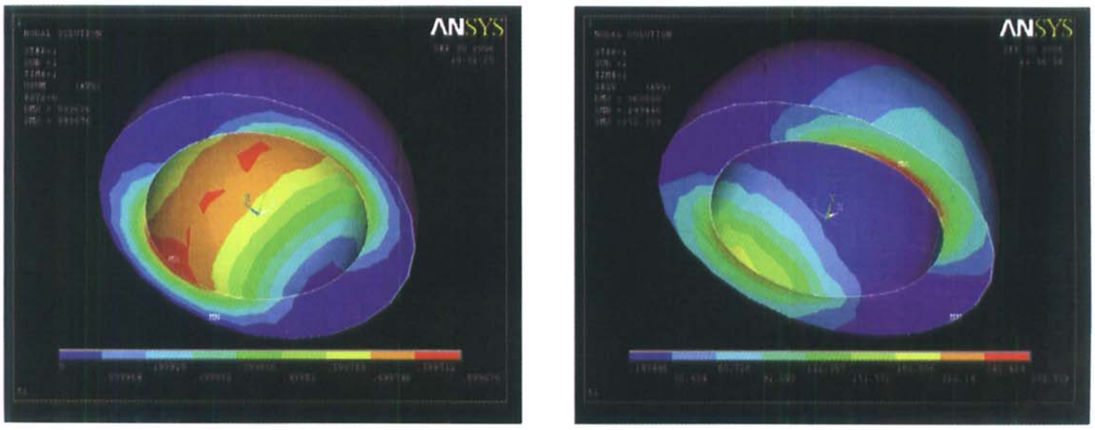
(a) Deformation of model (a)

(b) Stress of model (a)



(c) Deformation of model (b)

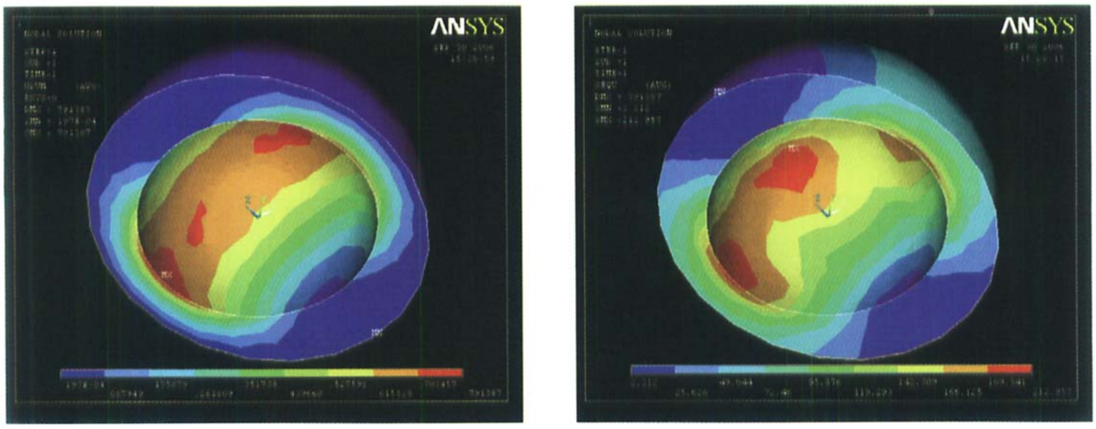
(d) Stress of model (b)



(e) Deformation of model (c)

(f) Stress of model (c)

Fig. 12 Contour image of acetabulum during dynamic cycle.



(g) Deformation of model (d)

(h) Stress of model (d)

Fig. 12 Continued.

Fig.13 illustrates four models of Ti6Al4V stress curve during gait cycle. With metallic cup fixation, models (b) and (d) have less stress than models (a) and (c). Even so, model (c) has a tiny change in stress during the gait cycle. The advantage of model (d) is clear in stress decreasing for having artificial cartilage and metallic cup.

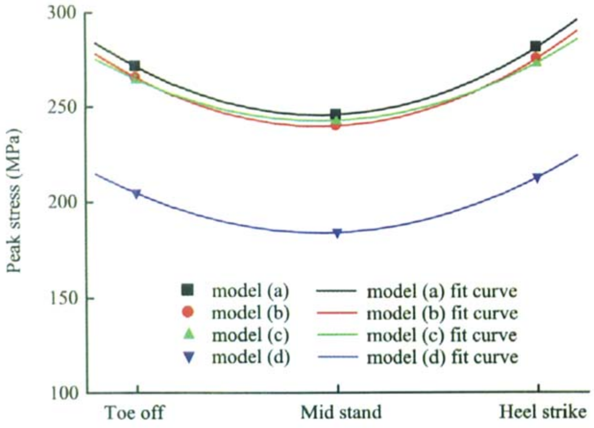


Fig. 13 Ti6Al4V material gait cycle stress curve.

6 Conclusion

The structure of an artificial hip joint is different from that of natural hip joint in which a cartilage layer covers the femoral head. This may significantly affect the mechanical characteristics of the joint. In this paper, four artificial joint models were proposed, two with an artificial cartilage layer covering the femur head, which is more similar to nature human joint, and two without the artificial cartilage layer. The static and dynamic mechanical properties of the models with different prosthetic materials were investigated by FEA. These properties include peak deformation, stress and strain, and the stress distribution. The effect of the metallic cup fixing the UHMWPE acetabulum was also investigated. The cartilage layer can spread the load and reduce the peak stress and deformation. The mechanical properties of the model with artificial cartilage layer and a Ti6Al4V cup are the best of the four models. This may provide useful information for the evaluation and redesign of an artificial hip joint.

Acknowledgement

The author wishes to thank the support from National Nature Science Foundation of China (50535050).

References

[1] Pyburn E, Goswami T. Finite element analysis of femoral components paper III: Hip joints. *Material and Design*, 2004, **25**, 705–713.

[2] El'Sheikh H F, MacDonald B J, Hashmi M S J. Finite element simulation of the hip joint during stumbling: A comparison between static and dynamic loading. *Journal of Materials Processing Technology*, 2003, **143–144**, 249–255.

[3] Scifert C F, Brown T D, Lipman J D. Finite element analysis of a novel design approach to resisting total hip dislocation. *Clinical Biomechanics*, 1999, **14**, 697–703.

[4] Godest A C, Beaugonin M, Haug E, Taylor M, Gregson P J.

Simulation of a knee joint replacement during a gait cycle using explicit finite element analysis. *Journal of Biomechanics*, 2002, **35**, 267–275.

[5] Bevill S L, Bevill G R, Penmetsa J R, Petrella A J, Rullkoetter P J. Finite element simulation of early creep and wear in total hip arthroplasty. *Journal of Biomechanics*, 2005, **38**, 2365–2374.

[6] Spears L R, Pfleiderer M, Schneider E, Hille E, Morlock M M. The effect of interfacial parameters on cup-bone relative micromotions: A finite element investigation. *Journal of Biomechanics*,2001, **34**, 113–120.

[7] Yoshida H, Faust A, Wilckens J, Kitagawa M, Fetto J, Chao E Y. Three-dimensional dynamic hip contact area and pressure distribution during activities of daily living. *Journal of Biomechanics*, 2006, **39**, 1996–2004.

[8] Li W, Lu H, Sun K, Qiao X Y. Three-dimensional finite element analysis of composite and metal femoral prosthesis. *Orthopaedic Biomechanics Materials and Clinical Study*, 2005, **2**, 1–4, in Chinese.

[9] Song J, Gelin J C, Barrière T, Liu B. Experiments and numerical modelling of solid state sintering for 316L stainless steel components. *Journal of Materials Processing Technology*, 2006, **177**, 352–355.

[10] Cheal E, Spector M, Hayes W. Role of loads and prosthesis material properties on the mechanics of the proximal femur after total hip arthroplasty. *Journal of Orthopaedic Research*, 1992, **10**, 405–422.