ISSN 1392–1207. MECHANIKA. 2014 Volume 20(5): 452–459

Finite element simulation of stress distribution in the different components of Ceraver-Osteal hip prosthesis: static and dynamic analysis

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crossref http://dx.doi.org/10.5755/j01.mech.20.5.5372

1. Introduction

Lifetime of orthopedic implants is a health issue because of people ageing. 800,000 hip prostheses are implanted in Europe and the same order of magnitude in USA. Two ways of implanting femoral stems are available. First, femoral stem can be inserted in the femoral bone. Second, it can be inserted with bone cement between material constituting femoral stem and bone. Sir John Charnley was the first surgeon who fixed a femoral stem with a bone cement based on polymethylmethacrylate composition [1]. The long term success of hip total arthroplasty (HTA) depends on a number of factors such as the surgical technique [2], the material [3] and the design of the endoprosthesis [4]. One of the important applications of the computer modeling of human body is the area of joint replacement where a validated model can be used for surgery planning. It is known that the evolution of the total hip replacement has been influenced to a great extent by the knowledge obtained from gait analysis studies [5]. Finite element method (FEM) as one of the most advanced simulation technique has been used in orthopedic biomechanics for many decades. It is an important tool used in the design and analysis of total joint replacements and other orthopedic devices. Finite element modeling and analysis present a non-destructive design approach for bone–implant hip prosthesis. It allows many complex what-if scenarios to be studied in computer environment before the prosthesis is actually applied on the patient. This will save time for the design and prevent any permanent damage caused by mis-implementation of bone–implant hip prosthesis.

Contact forces in the hip joint must be known for tests on strength, fixation, wear and friction of implants, for optimizing their design and materials by computer simulation and for giving guidelines to patients and physiotherapists as to which activities should be avoided after a replacement. The movement in the hip joint has to be known when implant wear is tested or the load directions relative to the pelvis are calculated from the forces acting at the femur [6]. Forces applied to the prosthesis due to human activity generate dynamic stresses varying in time and resulting in the mechanical fatigue failure of implant material. Therefore it is important to ensure the hip prostheses against fatigue failure. The fatigue failure of hip prostheses was reduced significantly in the past two decades [7]. Since 1979, it has been using a Ceraver-Osteal model of cemented total hip arthroplasty (Fig. 1) with a titanium femoral stem [8]. The objective of this study is the analysis of the mechanical behavior of new generation of HTA by the computation of the stress distribution in the cement mantle. In this regard the stress field in the artificial hip components (prostheses, cement mantle, and bone) is analyzed statically and dynamically. Components were subjected to a dynamic load due to three activities (normal walking, up stairs and down stairs) and the peak static load of the same patient load walking. Two quantitative measures are calculated: stress distribution and peak stress. It has been shown that each measure may lead to differing conclusions.

Fig. 1 Osteal femur stem

2. Materials and methods

2.1. Model designs

In this study a new generation of HTA was studied numerically. This prosthesis is the Ceraver-Osteal model (BM3) developed in France. For three-dimensional solid model of hip total arthroplasty modelling, there are four major components have to be modelled; cortical bone, cancellous bone, femoral stem and bone cement. The complete CAD model was built using SolidWorks.

The three-dimensional solid model assembly of femur, bone-cement and implant was transferred to Abaqus Workbench by direct interface. Abaqus Workbench autoatically recognizes the contacts existing between each part and establishes the contact conditions for corresponding contact surfaces. In this work, Ceraver-Osteal model of the cemented total hip arthroplasty is designed (Fig. 2).

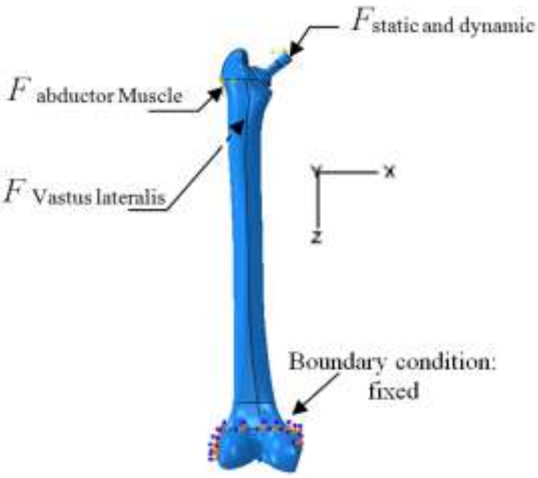


Fig. 2 Applied forces on the bone-cement–prosthesis assembly

2.2. Material properties

The material properties adopted were specified in terms of Young's modulus and Poisson's ratio for the implants and all associated components (Table 1). All materials were assumed to exhibit linear, homogeneous elastic behaviour [9].

Table 1

The properties of the artificial hip components [9]

Materials	Young's modulus *E*, MPa	Poisson ratio ν	Density, kg\m^3
Cortical bone	15500	0.28	1990
Cancellous bone	389	0.3	500
Stem (Ti-6Al4V)	110 000	0.3	4430
Cement PMMA	2700	0.35	1200

2.3. Loading and Boundary conditions

The contact forces *F* of the typical patient and their components are charted in Fig. 3 for the three investigated activities [10]. In this study, for static and dynamic analysis, a load is applied on the surface of the implant bearing as shown in Fig. 2. Static load represents a person of 70 kg (Table 2), this load analysis is based, by selecting the peak load during the normal walking activity. An abductor muscle load $F_{abductor\ muscle}$ is applied to the proximal area of the greater trochanter. An ilio tibial-tract load $F_{ilio\ tibial\text{-}tract}$ is applied to the bottom of the femur in the longitudinal femur direction (Bergman et al [11]). These authors measured in vivo loads acting at the hip joint.

Contact forces with instrumented implants and synchronous analyses of gait patterns and ground reaction forces were performed in four patients during the most frequent activities of daily living. Such information is required to test and improve wear, strength and fixation stability of hip implants.

For dynamic loads from three activities (normal walking, up stairs and down stairs) were chosen from the hip contact forces, these loads for a person of 70 kg are illustrated in Fig. 3.

The boundary condition was applied by fixing the distal epiphysis, which is the distal end of the femur that is connected to the knee [12]. The coordinate system used to represent the direction of the forces components is shown in Fig. 2. The femur is primarily loaded in bending [13]. The cement–bone and cement-stem interfaces were assumed rigidly fixed.

Table 2

Maximum loading configurations of the major muscles from normal walking activity [11]

Force, N	F_X	F_Y	F_Z
Joint contact force	-433.8	263.8	1841.3
Abductor muscle	465.9	34.5	695.0
Vastus Lateralis	-7.2	148.6	746.3

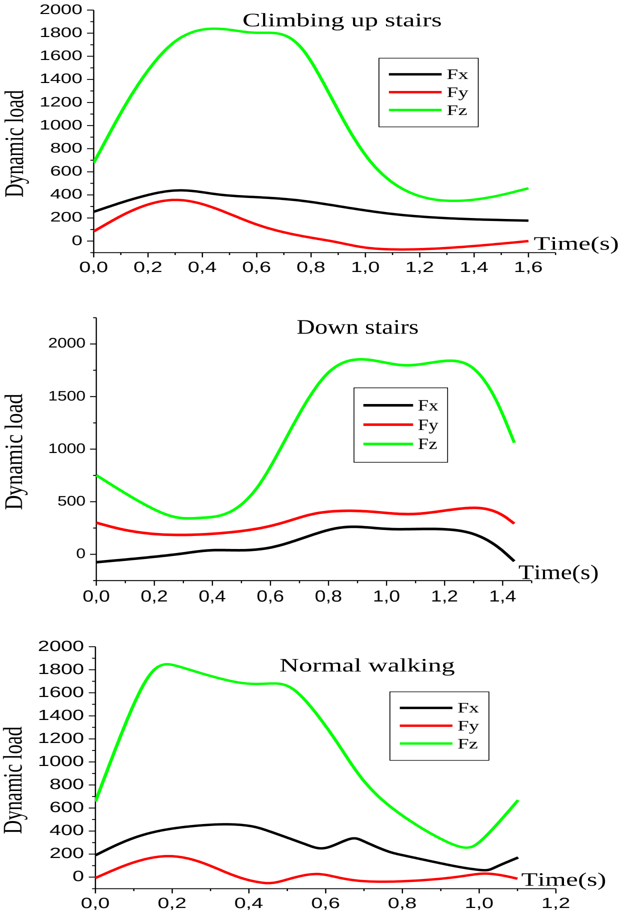


Fig. 3 The variation of forces applied on the prosthesis during three activities for *BW* = 70 kg [6]

2.4. Model Mesh

Finite element analysis (FEA) is a widely used research tool in biomechanics. A well-known problem in this type of analysis is the presence of singular points in the FEA model, causing the predicted peak stresses in particular to be dependent on the level of mesh refinement

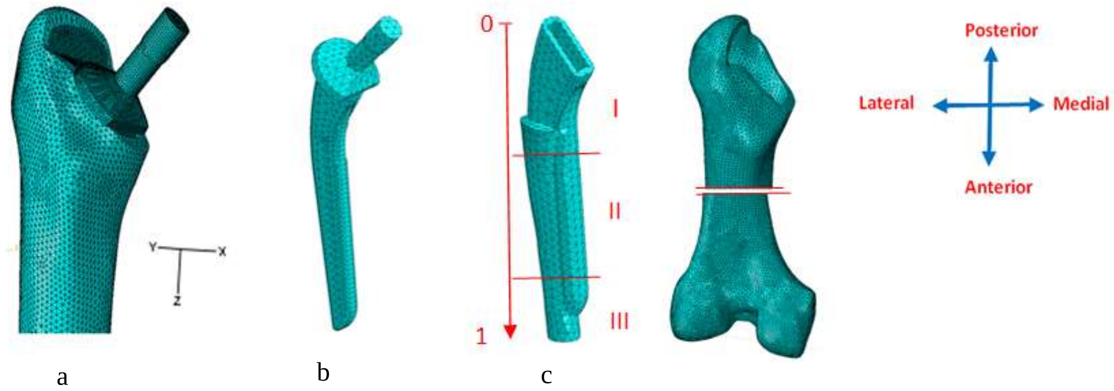


Fig. 4 Finite element meshes of hip prosthesis components: a- cemented hip stem, b-osteal stem, c-cement and (d) femur bone, I: Proximal part, II: Median part and III: Distal part

(Fig. 4). A method to reduce the mesh dependence would be of great value [14]. The model in this study is discretized by using tetrahedral elements. This is because the geometry of the femur is irregular. Tetrahedral elements are better to be suited and adjusted to curved boundaries compared to others elements. Discretizing by using tetrahedral elements with four nodes makes the meshing becomes easier. The complete Osteal model (stem, bone cement and femur) has in total 1223410 elements.

3. Result and discussion

Hip contact forces based on gait analysis data were previously calculated using simplified muscle models and various optimization methods [15-18]. Mechanical integrity can only be maintained if the overall stress is kept below some threshold over time [19]. Other practical problem is that the influence of cement porosity may dominate the effect of the stress [20]. These stresses may occur as tensile, compressive, shear, or a stress combination known as equivalent Von Mises stresses. This last depends on the entire stress field and are a widely used as an indicator of the possibility of damage occurrence [16]. During normal use of the joints experience cyclic stresses, which cause fatigue crack initiation and growth in the cement layer, leading to loss of structural integrity and eventual loosening of the implant [21].

In this study, we calculate the distribution of Von Mises stresses, in different components of the prosthesis (bone cement, stem and bone), using static loading and three cases of dynamics loading (walking, climbing up stairs, down stairs). In addition, it is necessary to analyze shear stresses distribution along the different regions of the cement mantle of the prostheses under static and dynamics analysis from up stairs activity.

3.1. Cement

Prosthesis durability is closely related to the stresses distribution along the structure elements of the HTA, particularly in cement which represents the weakest comparing the other elements. Moreover, the strong stresses are intolerable by the patient and can lead to the loosening of the HTA. Previous studies have demonstrated that during single limb support, the greatest stress in the cement mantle occurs at the distal tip of the prosthesis [22].

The peak tensile and shear stresses in this area are reported to exceed the fatigue endurance limit of cement, indicating that the longevity of the implant may be compromised [23].

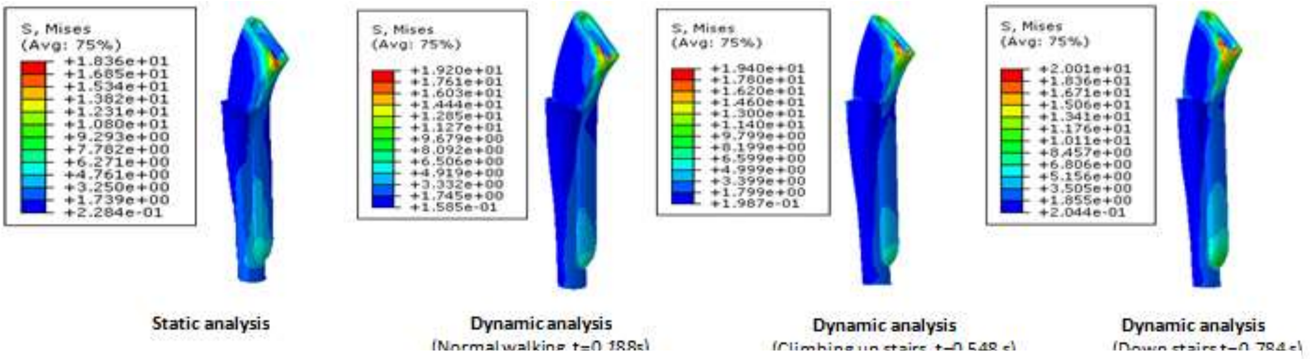
The Fig. 5 shows the distribution of equivalent Von Mises stresses in orthopedic cement of HTA, solicited by a static and dynamics loading for three activities: normal walk, climbing up stairs and down stairs. By comparing results, the dynamic loading generates higher stresses than static one.

It is observed that for all the cases, the distribution of the stresses in cement is not uniform. Therefore, the proximal and distal zones of cement generate the highest Von Mises stresses. For the static analysis, the maximum stress reach 18 MPa in the proximal part, this behaviour is due to the presence of the femoral neck effect and the load mechanism.

In the distal part, the stresses are about 10 MPa, the end of the implant increases the stresses values. In the medial part, the stresses are the lowest. For the dynamic analysis (Fig. 6), the stresses levels in the cement are high, especially in the proximal part. Compared to the stresses, generally the stresses in the cement of the dynamic loading from the down stairs activity are higher (the maximum stress is 20 MPa for the time = 0.784 s), while the stresses in the cement under dynamic load from the normal walking activity are lower (the maximum stress is 19 MPa for time = 0.188 s).

As for the results of HTA with Osteal hip prosthesis, it is found that the bone cement does affect the stress distribution on the femur. Bone cement is made of polymer that has relatively low Young’s Modulus, which is 2 GPa and it has a bad resistance to tensile loading (tensile strength = 25 MPa, compressive strength = 80 MPa and the shearing strength = 40 MPa) [24].

Irrespective of the method of analysis being used, maintaining the mechanical integrity is not a matter of reducing the *peak* stress in, e.g. the cement mantle or on the cement/bone and cement/prosthesis interfaces, although this criterion can be used to optimize a stem profile. The dynamic load simulation is the only way to represent the effect of the patient activity on the prosthesis durability and design. This is important if finite element models are to achieve their potential as pre-clinical testing tools [7].



a b c d

Fig. 5 Von Mises stress distribution on the cement under static loading (a) and dynamic loading from three activities: b - normal walking, c - climbing up stairs, d - down stairs

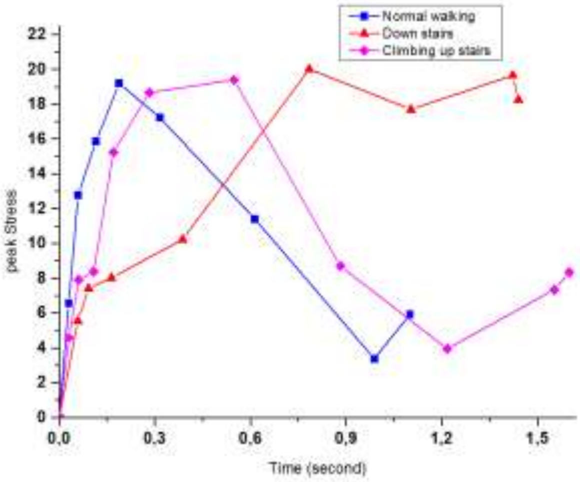


Fig. 6 Maximum Von Mises stress in the cement mantle during three activities

3.2. Implant

Forces applied to the prosthesis due to human activity generate dynamic stresses varying in time and resulting in the mechanical fatigue failure of implant material. Therefore it is important to ensure the hip prostheses against fatigue failure. The fatigue failure of hip prostheses was reduced significantly in the past two decades [15].

Comparing the stresses distribution on the hip prostheses, it can be observed that the stress concentration located also at the neck area. The higher stress is found in he prosthesis under dynamic loading from down stairs activity. The maximum stress is below 438 MPa for time = 0.784 s (Fig. 7). If the result is compared to the yield strength of Ti–6Al–4V (880 MPa), there is still a safety factor superior than 2. Therefore, this result is still in the acceptable range of safety. Whereas, the lower stress is found in the prosthesis under dynamic loading for normal walking activity, the maximum stress is predicted 330 MPa for the time = 0.188 s.

Fig. 8 shows the Von Mises stresses distribution within the implant for static and dynamic analysis (walk-

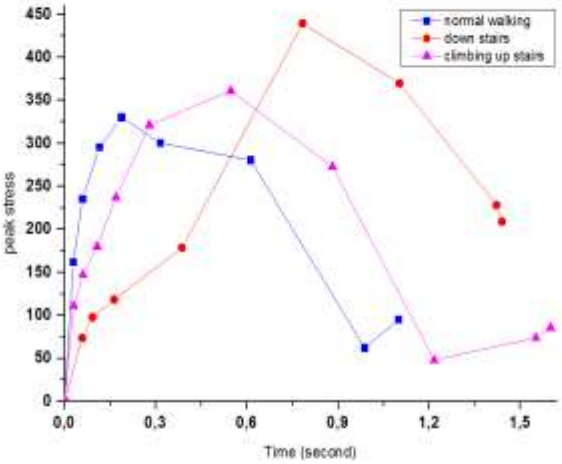
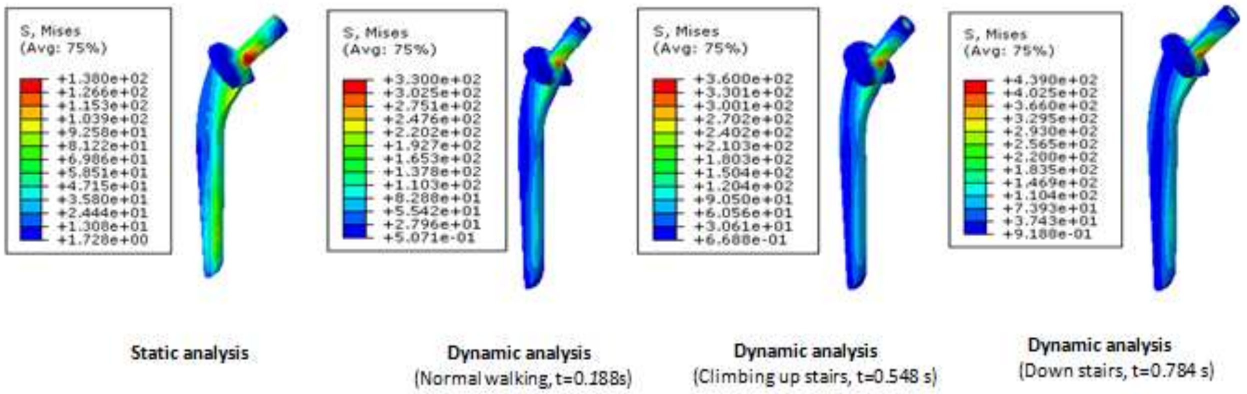


Fig. 7 Maximum Von Mises stress in the implant during three activities



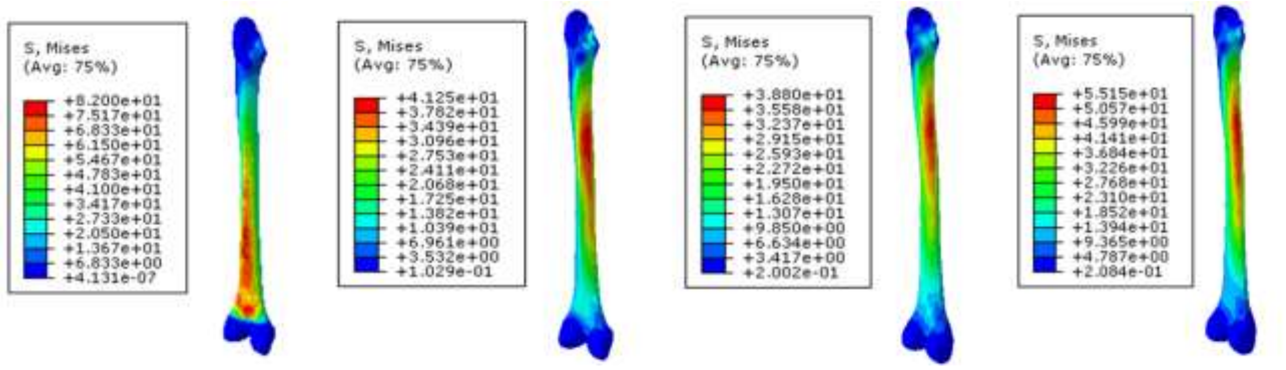
a b c d

Fig. 8 Von Mises stress distribution on the implant under static loading (a) and dynamic loading from three activities: b - Normal walking, c - climbing up stairs, d - down stairs ing, climbing up stairs and down stairs)For static analysis, the distribution of Von Mises stresses in the stem is not uniform, since it is localised on the proximal part, it can be observed that the stress concentration will occur at the neck area. Another time, this is reasonable since there is cross section transition at the neck area that should exhibit always a high stress. The maximum stress is below than 138 MPa.

3.3. Bone

Conventional design and analysis of bone-implant hip prosthesis rely on expert's knowledge, experience and ability to avoid any irreversible damage on the bones of patients. Because of the difficulty of performing implant tests in vivo, the models have been developed to carry out the structural analysis of implants before application on a patient. Accordingly bone-implant hip prosthesis could be designed and studied with computer simulations. The FEM is an advanced simulation technique that has been used in orthopedic biomechanics since 1972 [25].

Fig. 9 shows the Von Mises stresses distribution within the bone femur for static and dynamic analysis (walking, climbing up stairs, down stairs). For static analysis, the maximum stress is high at lateral aspect and low at distal and medial aspects, the maximum tensile stress exists in the distal part of the femur bone recording a value of 82 MPa. For dynamic analysis, the stress is still predicted to be high at medial and proximal regions of the femur, whereas the minimum stress is always found to be at the distal end of the femur. Compared to the stresses (Fig. 10), generally the stresses in the cortical bone in the case of the dynamic loading from the down stairs activity are higher (the maximum stress is 55 MPa for the time = 0.784 s), while the stresses in the bone under dynamic loading from the climbing up stairs activity are lower (the maximum stress reach 38 MPa for time = 0.548 s).



a b c d

Fig. 9 Von Mises stress distribution on the bone femur under static loading (a) and dynamic loading from three activities: b - normal walking, c - climbing up stairs, d - down stairs

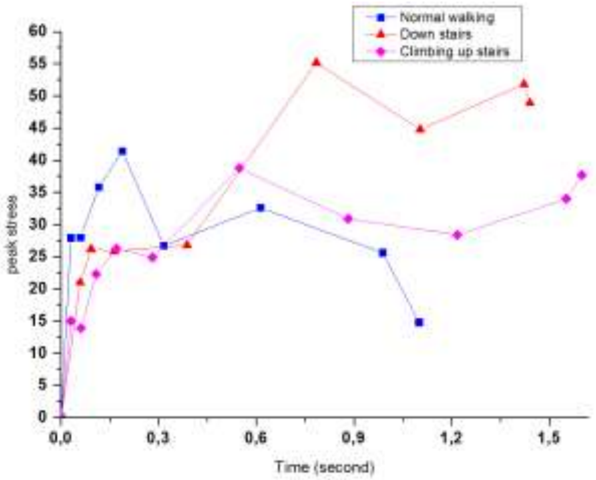


Fig. 10 Maximum Von Mises stress in the bone during three activities

In biomechanical term, one says that the portion of the femur is being stress shielded. In long term, it will cause bone sorption or bone loss. If this happens, the implant will have high possibility to loose and revision surgery is needed. Moreover, the revision surgery will be more complicated than the primary surgery.

3.4. Axial stresses

Performance and success of long-term survival of cemented HTA is an attachment of the prosthesis to the bone.

Cement–metal interface failures of separation of the stem–cement interface and fractures in the cement may initiate the initial loss of the fixation of the implant [17].

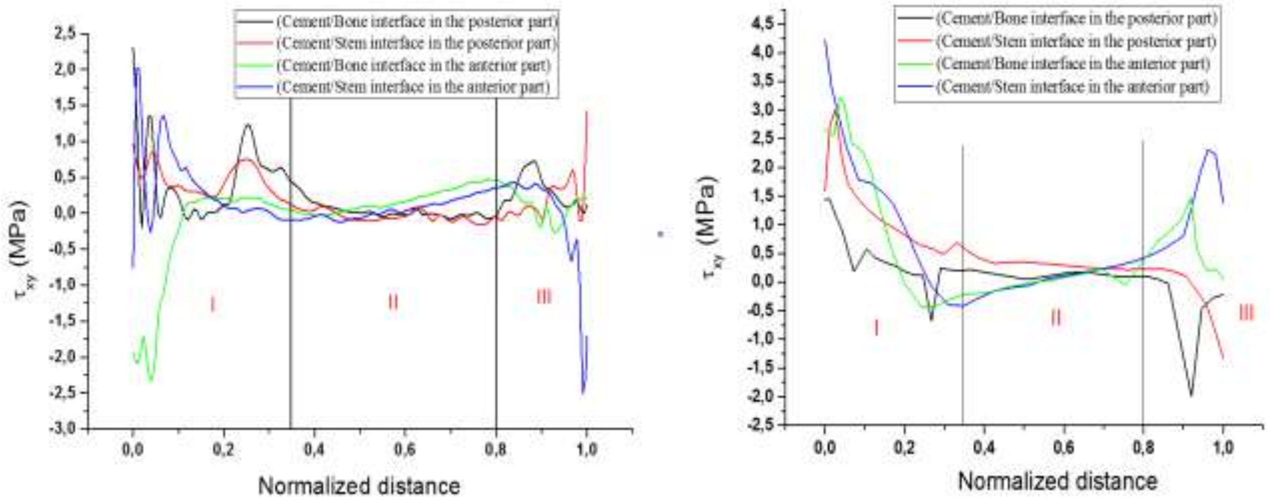
It is necessary to analyze the shear stresses distribution in the different regions of the cement mantle at the cement/bone and cement/prosthesis interfaces because it is considered as the weakest component in the assembly of total hip arthroplasty.

In this study we have chosen to analyze the stresses distribution in the cement subjected to static load and dynamic load from down stairs activity.

Fig. 11 shows the variation of the shear stress τ_{xy} along the cement/bone and cement/stem interfaces in the different regions. When the prosthesis is loaded, it will carry the entire applied load. Then, the load will be transferred down along the prosthesis.

When the load is transferred to the regions of the hip prosthesis, the load sharing will occur.

This is due to the shear stress generated between the contact surfaces. The highest stress is observed in the medial side at cement/bone with a value of 4.2 MPa (dynamic analysis).


Static analysis

Dynamic analysis
(Down stairs)

Fig. 11 The variation of the shear stress τ_{xy} along the cement/bone and cement/stem interfaces in the different sides (lateral and medial) of the cement mantle for the static and dynamic analysis (down stairs) I: Proximal part, II: Median part and III: Distal part

4. Conclusion

The objective of this study is the analysis of the mechanical behavior of new generation of HTA by the computation of the stress distribution in the cement mantle.

This distribution can give a precise idea on the loosening of the prosthesis and consequently the fatigue life of the HTA can be predicted.

This means that the HTA designers must take into account the dynamic stress variation in order to predict the fatigue life of total hip prosthesis.

The comparison between the present results and those of references [26] and [27] confirm that the Osteal model of the hip prosthesis gives weak shear stresses in the cement mantle compared to the well-known Charnley model. The Osteal prosthesis can have longest lifespan. The analysis of the stress distribution in the cement mantle shows that the risk of loosening of the prosthesis is maximal at the neck region of the hip prosthesis. This region of the cement must be reinforced. The author will study in future works the behavior of the prosthesis under choc or during accident.

Acknowledgment

The Authors extend their appreciation to the Deanship of Scientific Research at King Saud University for funding the work through the research group No. RGP-VPP-035.

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ĮVAIRIŲ DUBENS KLUBO KAULŲ „CERAVER-OSTEAL“ PROTEZŲ ĮTEMPIMŲ PASISKIRSTYMO MODELIAVIMAS BAIGTINIAIS ELEMENTAIS: STATINĖ IR DINAMINĖ ANALIZĖ

Reziumė

Šioje studijoje skaitiniais metodais analizuojamas naujos konstrukcijos klubo protezas. Baigtinių elementų metodas naudojamas įtempimų pasiskirstymui klubo protezo komponentuose (galvutėje, sutvirtinančioje mantijoje ir kaule) nustatyti. Statinės apkrovos analizė naudojama parenkant ribinę apkrovą normalaus ėjimo metu. Bergmano ir kitos apkrovos sąlygos buvo įdiegtos baigtinių elementų modelyje skaičiuojant normalaus ėjimo dinaminius įtempimus, lipant ir nulipant laiptais. Gauti rezultatai parodė, kad nauji klubo protezo modeliai silpnina šlyties įtempimus sutvirtinančioje mantijoje lyginant su tradiciniais modeliais. Be to apkrovos nulipant laiptais lydimos didesnių šlyties įtempimų sutvirtinančioje mantijoje.

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FINITE ELEMENT SIMULATION OF STRESS DISTRIBUTION IN THE DIFFERENT COMPONENTS OF CERAVER-OSTEAL HIP PROSTHESIS: STATIC AND DYNAMIC ANALYSIS

Summary

In this study a new generation of total hip prosthesis is analysed numerically. The finite element method is used to analyze the distribution stresses on the hip prosthesis components (stem, cement mantle and bone). The static load analysis is used by selecting the peak load during the normal walking activity. The loading conditions of Bergman et al were implemented in the finite element model to compute the dynamic stresses under normal walking, climbing up stairs and down stairs loading. The obtained results showed that the new models of hip prosthesis weaker shear stresses in the cement mantle compared to the conventional models. In addition, the case of down stairs loading leads to higher shear stresses in the cement mantle.

Keywords: Biomechanics; prosthesis; cement mantle; finite element; stress analysis.

Received October02, 2013
Accepted August 20, 2014