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NUMERICAL STUDY OF STRESS REDUCTION IN THE CEMENT OF TOTAL HIP PROSTHESIS USING ELASTOMERIC STRESS ABSORBER

NUMERIČKA STUDIJA SMANJENJA NAPONA U CEMENTNOJ TOTALNOJ PROTEZI KUKA PRIMENOM ELASTOMERA

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- stress absorber
- finite element method

Ključne reči
- proteza kuka
- cement
- koncentracija napona
- smanjenje napona
- metoda konačnih elemenata

Abstract

Some daily movements of patients with hip prostheses generate stress concentration in polymethylmethacrylat (PMMA) cement, especially in the stem/cement/bone interfaces. High stress values can damage the cement and lead to loosening of the prosthesis. This work is devoted to the development of a redesigned prosthesis type in order to minimize stress concentration in the cement leading to a proposed prosthesis with an integrated elastomer between the stem and the femoral head to relieve this problem. 3D-finite element model is carried out to investigate the effect of the incorporated elastomer which permits to partially absorb load transfer in the cement. The results of the proposed model compared to those of a conventional prosthesis provide an acceptable solution for reducing stress level in the cement and consequently increasing the lifetime of the total hip replacement avoiding thus loosening.

Izvod

Neki dnevni pokreti pacijenata sa protezama kuka izazivaju koncentraciju napona u polimetilmetakrilatnom (PMMA) cementu, posebno u spoju stablo/cement/kost. Visoke vrednosti napona mogu oštetiti cement i dovesti do labavljenja proteze. Ovaj rad je posvećen razvoju redizajniranog tipa proteze kako bi se minimizirala koncentracija napona u cementu što nas dovodi do predložene proteze s integrisanim elastomerom između stabla i glave butne kosti kako bi se rešio ovaj problem. 3D-model konačnih elemenata je izveden kako bi se ispitao učinak ugrađenog elastomera koji omogućava delimičnu apsorpciju prenosa opterećenja u cementu. Rezultati predloženog modela u poređenju sa rezultatima konvencionalne proteze daju prihvatljivo rešenje za smanjenje nivoa napona u cementu i kao posledica produžavanje vek totalne totalne proteze kuka, čime se izbegava labavljenje.

INTRODUCTION

Several hip prosthesis fixation techniques have been introduced in orthopaedics and recently, Charnley's low friction cemented total hip arthroplasty has proven to be highly effective. The life of prostheses designed for a long term can be shortened by unforeseen fracture of the stem, inadequate cementation, or improper positioning. For this purpose, the introduction of high-grade metal alloys and improved cementation techniques may prove to be solutions to these problems. The stress fields in the bone-prosthesis structure depend on the amplitudes and orientations of the loads, the geometries of the structure, the mechanical properties of the materials and physical conditions at the level of the contacts of materials. The finite element method (FEM) is a very suitable technique to interrelate these aspects quantitatively as shown by Huiskes et al. /1/, while in /2/ they introduce a method of numerical shape optimisation for prosthetic design to minimize interface stresses. However, stress shielding of the femur is known to be a principal factor in aseptic loosening of hip replacements, thus, Joshi et al. /3/ present a study which explores the hypothesis that through redesign, a total hip prosthesis can be developed to substantially reduce stress shielding, and Gross and Abel /4/ consider the use of a hollow stemmed hip implant for reducing the effects of stress shielding, while maintaining acceptably low levels of stress in the cement using finite element modelling. However, the relationship between residual stress and cracked cement has not yet been established. To investigate if any relationship exists, a physical model has been developed by Lennon and Prendergast /5/ which allows direct observation of damage accumulation around cemented femoral components of total hip replacements. Concerning the experimental part, a project is based on the clinical observation that higher subsidence (distal migration) correlates with early revision of hip prostheses to develop a pre-clinical testing platform for cemented femoral hip implants as measured by Maher and Prendergast /6/. The relationship between cement fatigue damage and implant surface finish in proximal femoral prostheses has been treated by Lennon et al. /7/ and has shown that, despite generally higher stresses in cement mantles of polished stems, the micro-damage does not apparently accumulate at a faster rate for those stems. A numerical study with four different stem shapes of varying curvatures for hip prosthesis is conducted by Senalp et al. /8/ to determine the fatigue endurance of cemented implant and to reduce sliding of the implant in the bone-cement. The effect of the position and orientation of a crack in the cement mantle under various loads using the finite element method has been studied by Bachir Bouiadjra et al. /9/, Ouinas et al. /10/, Bounoua et al. /11/, and Benouis et al. /12/. Furthermore, the hip prosthesis fracture due to the effect of a bony inclusion in the cement is studied by Cherfi et al. /13, 14/. In this work, a three-dimensional finite element method is employed to analyse both conventional and proposed prosthesis. In the second one, an elastomeric stress absorber is integrated between the stem and femoral head in order to reduce the load transfer to the cement as developed in the study by Mehdi et al. /15/. The two models are modelled using Solidworks® CAD software.

MATERIALS AND METHODS

The principal components of the total hip prosthesis are shown in Fig. 1. The two geometrical prosthesis models are presented in Fig. 2: conventional and the redesigned model with an incorporated elastomer between the stem and the femoral head.

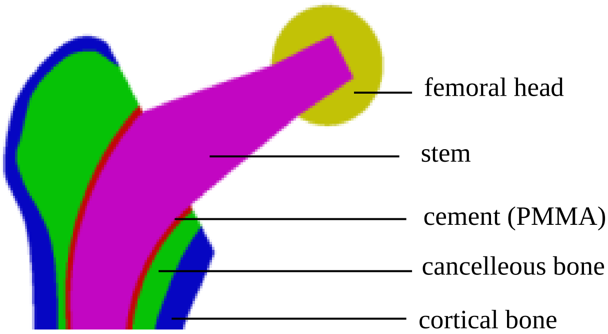


Figure 1. Geometrical model of the total hip prosthesis.

For simplified reasons, the mechanical behaviour of all components is considered isotropic and linear elastic, although in reality the femoral bone is an anisotropic material while the elastomer exhibits hyper-elastic behaviour. Table 1 gives their mechanical elastic properties. In the proposed model, a 0.5 mm thickness of an elastomeric material is added between the femoral head and the stem. Both models are meshed with quadratic tetrahedral elements C3D10 chosen for the model shape complexity, Fig. 3a. The element size and type remain the same for both models to avoid any influence of the mesh on the results.

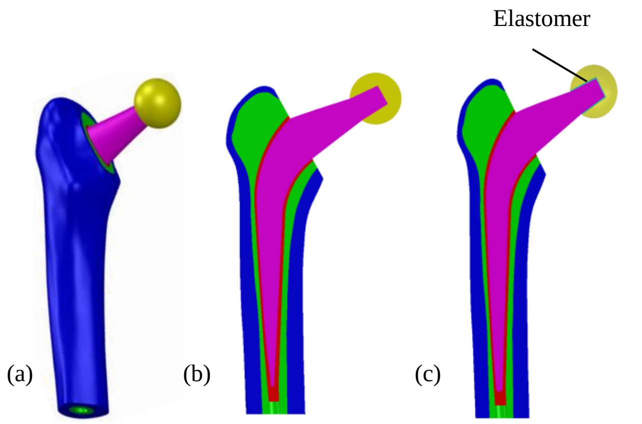


Figure 2. Detailed both geometrical models: a) full model; b) detailed conventional model; c) detailed proposed model.

Table 1. Mechanical properties of the hip prosthesis components.

Prosthesis components	Young's modulus (MPa)	Poisson ratio
Cortical bone	17000	0.3
Cancellous bone	130	0.2
Cement (PMMA)	2300	0.3
Stem	110000	0.3
Femoral head	110000	0.3
Elastomer	6	0.49

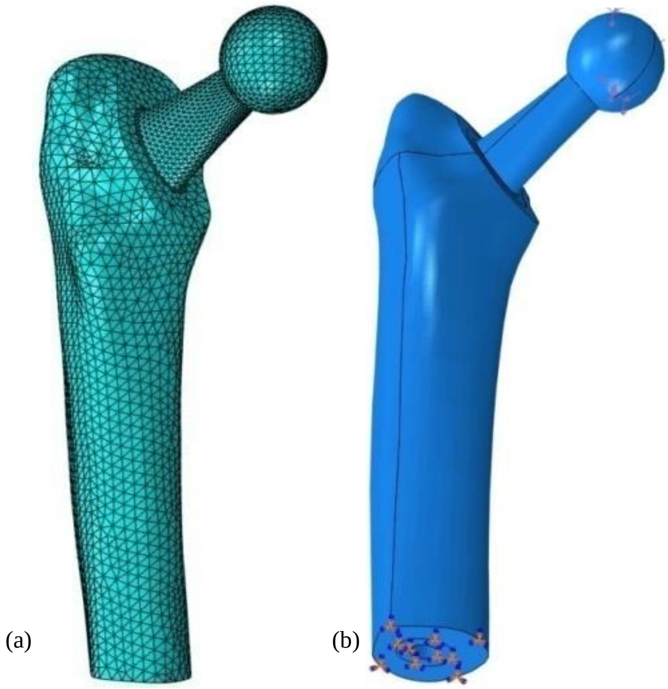


Figure 3. The mesh, loading and fixation of the model: a) typical mesh; b) loading and boundary conditions.

Three daily motion situations are chosen: walk normally, to go upstairs, and get up from a chair. Then, three loading types are addressed respectively, Load 1, Load 2 , Load 3 and are shown in Table 2, according to Foucat /16/. The forces in the 3 directions as well as their resultant are given in percentage according to the weight of the body of the patient which is equal to 750 N.

BOUNDARY AND LOADING CONDITIONS

The bottom of the cement is blocked along the axis (*zz*): $U_z = 0$ while the bottom of bone is considered embedded: $U_x = U_y = U_z = UR_x = UR_y = UR_z = 0$. All interfaces are assumed fully bonded to ensure prosthesis stability.

The loading is introduced for each situation according to the 3 directions with the values listed in Table 2. Acting forces are defined as 3 components applied on the femoral head: F_x, F_y and F_z.

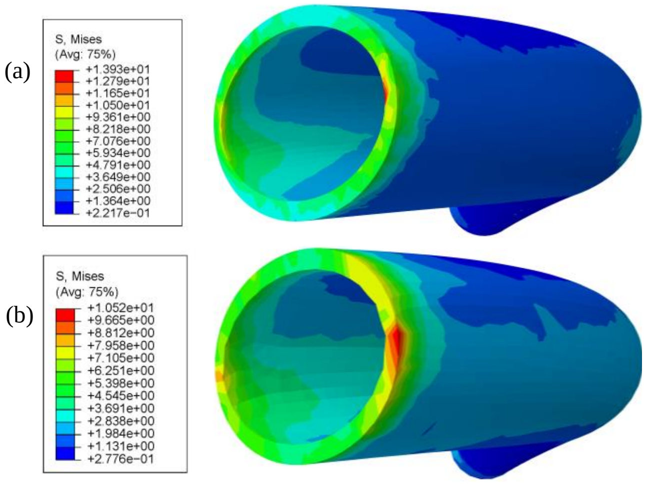
Table 2. Three loading situations with corresponding acting forces.

Load	Movement	% Force weight			
		Force components			Resulting force
		F_x	F_y	F_z	F
Load 1	Walk normally (3.9 km/h or 1.09 m/s)	-54	32	225	233
Load 2	To go upstairs (walking height: 17 cm)	-60	61	237	252
Load 3	Get up from a chair	-53	23	182	190

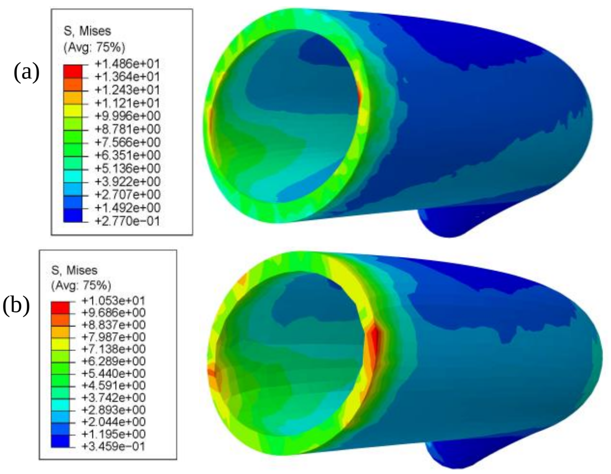
ANALYSIS AND RESULTS

Numerical analysis of both models is done using Abaqus code® based on finite element method (FEM), /17/, in the same loading and boundary conditions. In order to compare stress levels, choice was on the cement body (PMMA), principal connection between stem and bone, ensuring the stability of the prosthesis.

Load 1



Load 2



Load 3

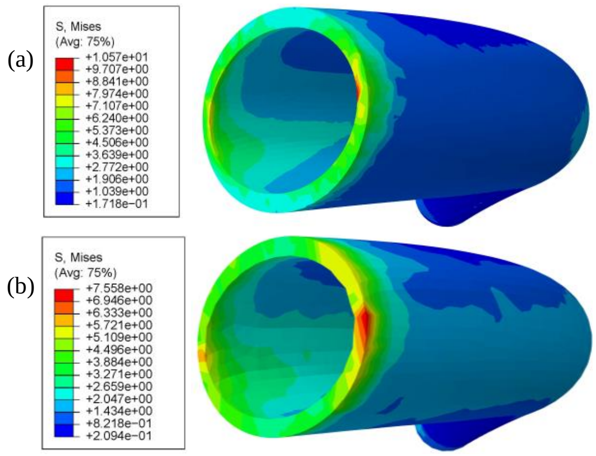


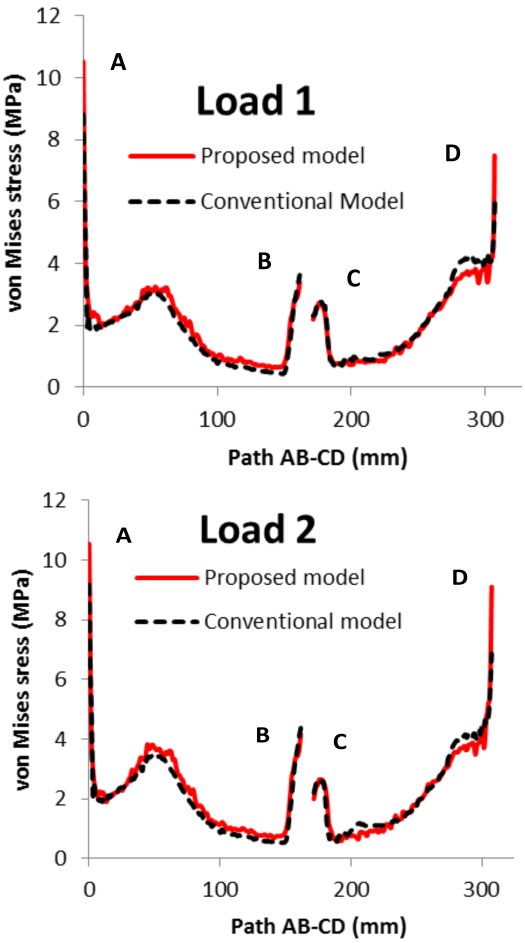
Figure 4. Comparison of von Mises stress in the cement of both: a) conventional and b) proposed models, for Loads 1, 2, and 3.

In Fig. 4 the equivalent von Mises stress distribution is shown in cement (PMMA) in the conventional and proposed model. It is observed that the high levels of stress located in the stem/cement interfacial zone in the conventional model for the 3 situations are reduced in the proposed model. In fact, until 29 %, a reduction is observed relatively to the results obtained for the conventional implant. This is due to the presence of the elastomeric material which plays a stress barrier role while forces are transferring unto the interface.

The stress distribution in the cement body (PMMA) led to trajectories choice: external interface bone/cement AB-CD and internal interface stem/cement EFG as indicated in Fig. 5.

Figure 6 shows the stress plot on the AB-CD path for the three load cases. It is clear that on this trajectory, point A is subjected to the highest levels of stress for both models of the prostheses. Nevertheless, it is observed that in this point A, stress level increases in the proposed prosthesis case (red line) compared to the conventional one. The difference of this increase for the largest values on this path varies for the three load cases 19.3% (8.8 to 10.5 MPa), 14.6% (9.1 to 10.5 MPa), and 12.8% (6.7 to 7.5 MPa), respectively. In the same way, on the CD trajectory, the concentrated stress is located in point D with a lower level than in point A for the two models. In the proposed model, the stresses also increase 38.6% (6.24 to 8.65 MPa), 32.6% (6.86 to 9.10 MPa), and 22.8% (5.16 to 6.34 MPa).

Figure 5. Stress path in the cement: AB-CD (external interface), and EFG (internal interface).



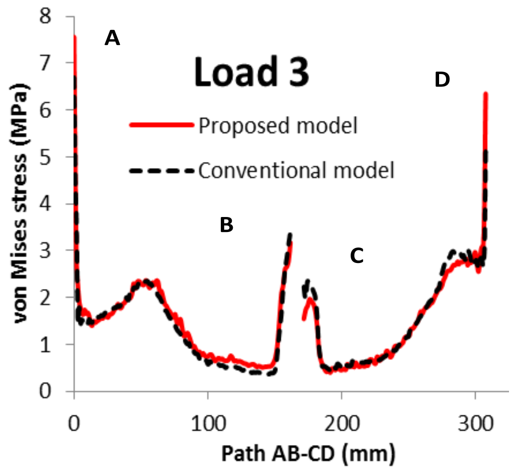
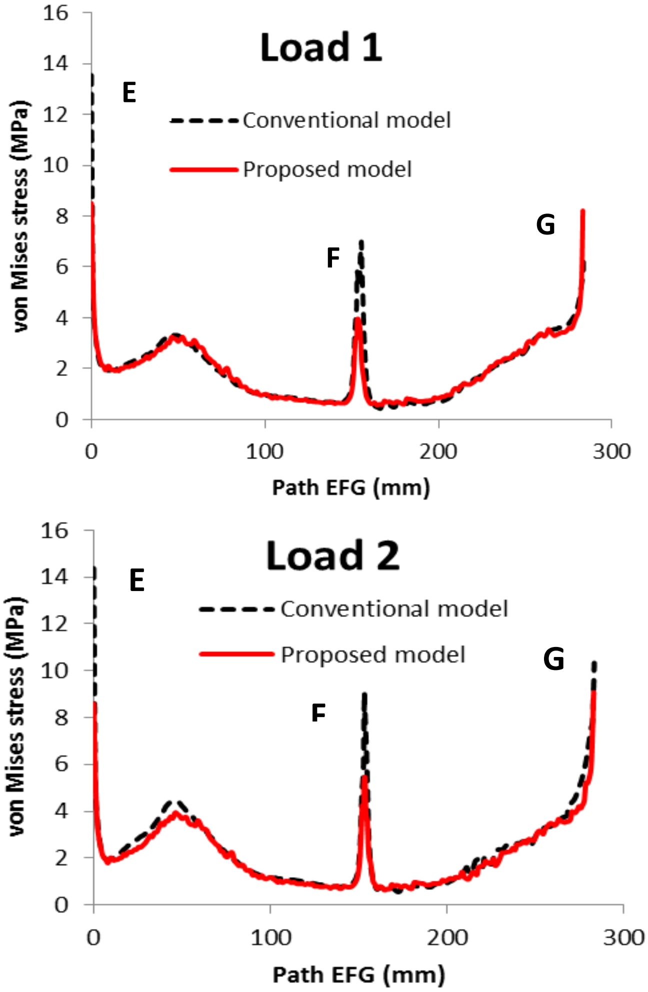


Figure 6. Distribution of von Mises stress along the cement path AB-CD for three loading cases in the two models.

The stress path in the EFG interface is shown in Fig. 7 for the three different loads. In the conventional model it is noted that in point E, stresses are the highest compared to those observed throughout the cement body. Contrary, in the proposed prosthesis the most concentrated zone observed a decrease in stress of 37.2% (15.5 to 8.5 MPa), 36.9% (14.4 to 9.1 MPa), and 40.5% (10.3 to 6.1 MPa), under Loads 1, 2, and 3, respectively. It is observed that the case of going upstairs seems to be the most constrained situation.



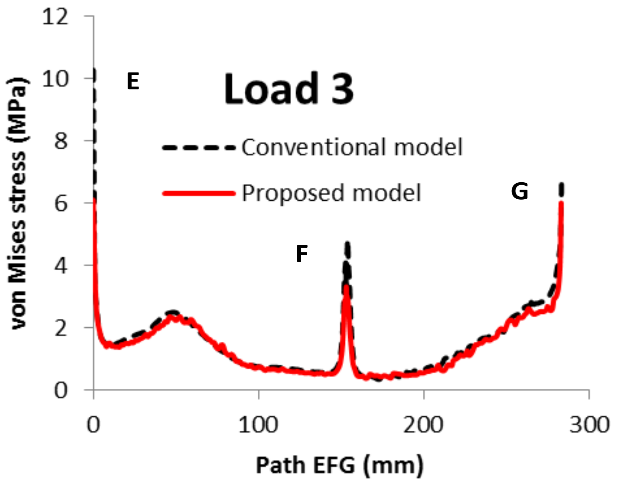


Figure 7. Distribution of von Mises stress along the cement path EFG for the three loading cases in the two models.

In the proposed prosthesis, it is noted that the stress levels decreased in this interface and in particular at point E which is the most stressed area in the whole body of the cement in the conventional prosthesis. The reduction in these highest stresses in the stem/cement interface, being the most sensitive, is estimated approximately 40% depending on the load.

DISCUSSION

The numerical results in the conventional hip prosthesis showed that the most stressed area of the cement is located in the internal cement/stem interface, especially in the vicinity of point E, 13.5 MPa, 14.4 MPa and 10.3 MPa with the three types of loading, respectively. This is due certainly by the eccentric compression loads inducing a bending moment that tends to debond the stem from the cement. This interfacial stress level proves to be dangerous that can initiate an interfacial crack propagating through this interface, causing the loosening. Also, highest risk situations are those of walking upstairs against the other two loads. However, the latter two are in common use and cyclical, but climbing stairs can be frequent if the patient lives in a building without an elevator.

To remedy this problem, a solution of stress reduction is proposed. This involves introducing an elastomeric material between the femoral head and the stem making it possible to reduce the stress level in point E by redistributing the stress field in the cement. This elastomer, through its deformation, slows down a force transfer rate to the prosthesis components allowing an equilibrium distribution of stress levels on the entire cement body.

Thus, for all the applied loads, the presence of the elastomer in this proposed prosthesis allowed to attenuate the stress concentration at point E observed in the conventional prosthesis by a balanced redistribution of stress field in the stem/cement interface. These redistributed stresses in the cement have increased at point A, 10.5, 10.5, and 7.5 MPa, and are the highest compared to those at other points. Consequently, the high stress levels in this concentrated interfacial zone stem/cement are attenuated and reduced substantially while some other zones will increase their stress levels without reaching the peaks previously noted. Especially, the stress levels noted at point E, appearing as an important difference in the conventional prosthesis as 13.5 MPa, 14.4 MPa, and 10.3 MPa were not significantly different in this redesigned prosthesis 8.5 MPa, 9.1 MPa, and 6.1 MPa. However, the numerical models used in the study are based on some limitations, notably those related to the constitutive laws of bone materials and to the characterization of the elastomer. After all, for a comparative study, the two models are subjected to the same boundary and loading conditions and are discretized with the same mesh.

CONCLUSIONS

In this finite element analysis of both conventional and elastomeric prosthesis, it is concluded that:
- The cement/stem interface stress level values in the new proposed prosthesis with elastomeric material are generally lower than those found with the conventional model.
- The maximum stress values are observed in the cement/stem interface of the conventional model with the three load types.
- The use of soft and flexible elastomer encapsulated between the stem and the femoral head with low rigidity is able to reduce or delay the load transfer to the cement.
- The peak stress concentration has moved from the cement/stem interface (in the conventional model) and moved with reduced level to the bone/cement interface (proposed model) because of the static equilibrium of forces in the new system.
- The stress level reduction in the cement of the proposed prosthesis has averaged 40%.

In conclusion, the integration of an elastomeric material as a stress barrier in the hip prosthesis made it possible to reduce the force transfer to the cement. This stress absorber reduces the stress on the cement and thus increases its lifetime avoiding the loosening.

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