FINITE ELEMENT MODEL OF THE FAILURE OF STEM-CEMENT INTERFACE IN TOTAL HIP ARTHROPLASTY

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The bone cement is characterized by weak mechanical strength. During normal activities of the patient, the cement mantle in hip prosthesis is subject to heavy load which can provoke the failure of the cement-bone and cement-stem interfaces. In this study, the damage of the cement-implant interface in total hip arthoplasty was evaluated using the three-dimensional finite element methods. The analysis was done for three activities of the patient: normal walking, climbing upstairs and downstairs. The obtained results show that the downstairs activities are the most dangerous since they give higher risk of failure of the cement-stem interface. It was also shown that the failure risk is higher at the proximal zone of the prosthesis which is in agreement with the radiographic observations.

Key words: Hip prosthesis, Cement, Stem, Interface, Damage, Finite element method.

1. Introduction

A cemented hip implant design introduces a layer of polymethylmethacrylate (PMMA) bone cement between the femur and the prosthetic component. The role of the cement is to ensure the fixation of the implant to the bone. Among the cement advantages is its capacity to stick to the bone porosities to ensure good fixation of the implant. In addition, the relatively rapid drying of the cement (on average 10 minutes) gives the surgeon assurance that the implant is perfectly fixed. However, as a polymeric material, the PMMA bone cement may degrade over time and consequently it can be damaged locally.

The damage accumulation leads to the cement failure and eventually to the implant loosening. The consequences of the cement failure can be quite severe on the patient. Indeed, the implant loosening necessarily leads to a second surgical procedure to reintroduce a new implant.

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The cement failure occurs with the fragmentation of the cement into small debris which can cause inflammation of the tissue surrounding the bone. Several researchers confirmed that the accumulation of damage in the cement mantle of hip prosthesis is the principal cause of the implant loosening [1-5].

By analyzing several published papers that have dealt with the failure of cemented hip prostheses, we have found a divergence concerning the region where this failure occurs. Indeed, researchers have confirmed that this failure occurs mainly at the cement-bone interface [6-8] while others claim that the cement-stem interface is the main site of the implant loosening [9-12]. For us the damage initiation in the cement can occur at any place in the mantle and this damage propagates under the effects of mechanical loading to meet one or both interfaces and thus the total failure will be triggered.

It was shown by Cristofolini et al [13] that the microparticles of cement present on the interface may hinder the success of the implementation particularly under sever position of the patient. Some research has established a close relationship between the cement thickness and the risk of implant loosening. The reduction of the cement thickness increases the number of micro-cracks in the mantle. It was confirmed that value of 2 mm can be considered as an optimal value of the cement thickness. In reality there are many factors influencing the damage of the orthopedic cement, including: the conditions of the operation, the polymerization of the cement, the age of the patient, the surface polishing between the cement and the stem etc.

But from our point of view, the most critical parameter is the level of the applied load on the prosthesis. This load repeated cyclically and can cause the damage by fatigue of the cement. This damage leads to the development of microcracks which, by coalescence, causes the total debonding between the implant and the bone. The analysis of the evolution of the damage in the cement mantle in relation with the applied load level is thus essential to predict the durability of the cemented hip prosthesis.

2. Finite element model

To give a credibility to this study we took a CT scan image of the femur bone then the Ceraver-Osteal model of the hip implant was introduced in the femur using the CAD software Solidworks (see figure 1). The cement mantle serving as a fixation between the bone and the implant was implemented in the CAD model. In constructing our prosthesis model, we tried to get as close as possible to the real model obtained after surgery. All components of the hip prosthesis were modeled: The cortical and the cancellous bones, the femoral implant and the cement mantle. We assumed that all materials are homogenous and have elastic behavior. The materials properties are given in table 1.

Table 1

The properties of the artificial hip components [10].

Materials	Young's modulus E [Mpa]	Poisson ratio ν	Density [kg\m3]
Cortical bone	15500	0,28	1990
Concelleous bone	389	0,3	500
Stem [Ti-6Al4V]	110000	0,3	4430
Cement PMMA	2700	0,35	1200

Fig.1. 3d model resulted from Ct scan

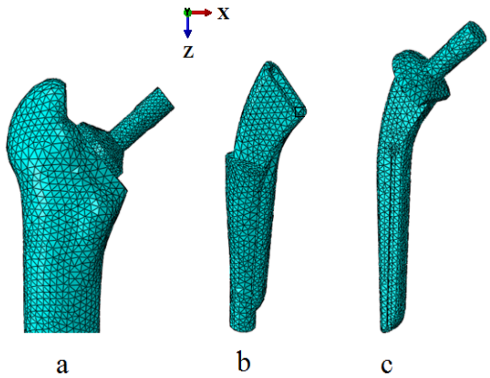


Fig. 2. Mesh models, a) Prosthesis, b) Cement mantle, c) Implant

The CAD model of the prosthesis was converted in three dimensional finite element models using the FE commercial code Abaqus. The stem-cement and bone-cement interfaces were modeled with frictional contacts.

We have meshed the prosthesis structure with tetrahedral elements of high nodes. The choice of this type of elements may be justified by the irregularity of the geometries of the different components of the prosthesis (cement, bone and stem). The tetrahedral elements are more suitable for modeling curved shapes. Figure 2 presents typical mesh model of the cemented prosthesis.

It is known that the modeling of the applied loads on femoral implants is very complicated because this load is not concentrated directly on the femoral head but is transmitted, through the acetabular cup depending on each position of the human body.

The loads on the implant head depend on the weight of the patient, his age and his position. In order to increase our chances of having a valid prediction of the bone cement failure, we searched the literature to have the most accurate values of the applied forces on the femoral implant head during different activities of the patient.

From our point of view, the best work carried out in this context is that of Bergman et al [14]. These authors have performed a titanic work by recording the efforts transmitted by the cup to the femoral head for different patients and different activities (normal walking, climbing upstairs and down stairs).

Figure 3 shows the results of Bergman et al [14] for a patient of 70 kg weight for one cycle of activity. We have applied these efforts on our FE model and figure 4 shows the different boundary conditions.

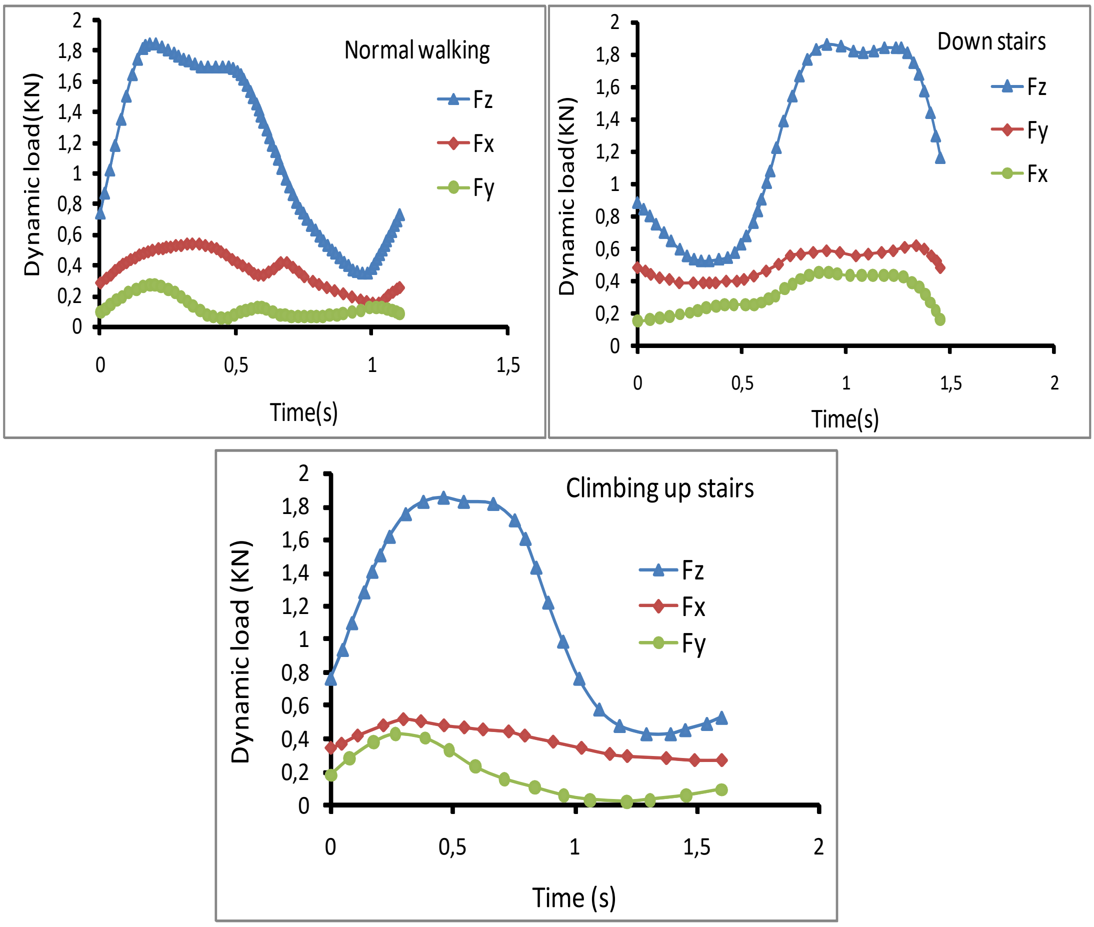


Fig.3. The variation of forces applied on the prosthesis during three activities for *BW* = 70 kg [14]

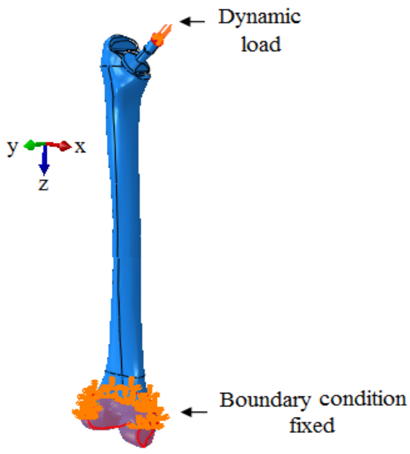


Fig. 4. Boundary conditions

3. Failure criterion of the cement mantle

To predict the cemented implant loosening, we have used the Hoffman criterion [15]. This criterion gives the index of failure by the following expression:

$$FI = \frac{1}{\sigma_t \sigma_c}\sigma^2 + \left(\frac{1}{\sigma_t} - \frac{1}{\sigma_c}\right)\sigma + \frac{1}{\sigma_s^2}\tau^2 \qquad (1)$$

Where:
FI : the failure index
σ_t : The ultimate tensile stress of the interface cement-stem: 8 MPa [16]
σ_c : The ultimate compressive stress of the interface cement-stem: 70 MPa [16]
σ_s : The ultimate shear stress if the interface stem-cement: 6 MPa [16]
σ and τ are the values of the normal and the shear stresses respectively. The failure index varies between 0 and 1. The 0 value corresponds to no damage and the unit value correspond to the total failure of the interface stem-cement.

4. Results and Discussion

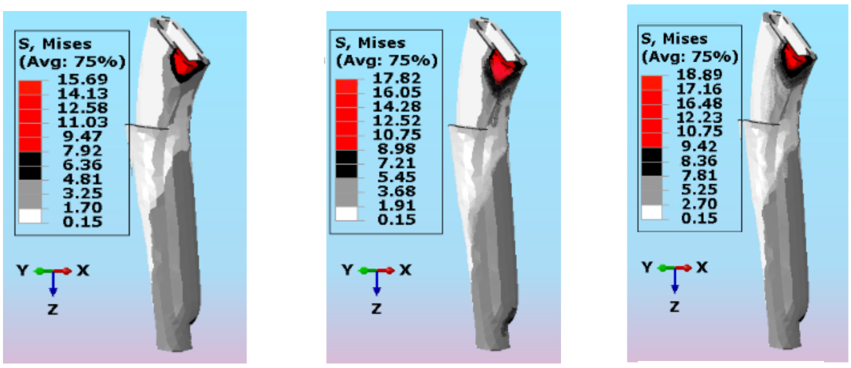
The main objective of this study is the evaluation of the damage in the cement mantle of hip prosthesis under three activities of the patient: normal walking, climbing upstairs and downstairs. The dynamic analysis was done in one cycle of the activity. The cement damage was modeled using the failure index expression described in equation 1. The variation of the failure index FI allows us to predict the risk of loosening at the interface cement-stem of the prosthesis.

Before the presentation of the results relative to the failure index, we found useful to see the evolution of the stresses in the cement mantle during the three activities of the patient.

4.1 Stress distribution in the cement mantle

The distribution of the equivalent stress in the cement mantle was computed, we have conventionally named the three zones of the cement by:
-Proximal zone: close to the femoral head
-Median zone: in the middle of the cement mantle.
- Distal zone: the furthest region from the femoral head.

Figure 5 shows the stresses levels in the cement mantle for the three activities of the patient: we have presented the stresses level at the time t=0.18 s for normal walking, t= 0.48 s for climbing upstairs and t=0.8 s for downstairs activity. These times correspond to the higher load in the z direction for each activity. From figure 5, we can see that the higher stresses in the cement mantle are localized in the proximal and the distal zones. The stress intensity is more significant in the proximal zone because the applied load is transmitted directly to this zone. In addition the free edge caused by the section of the femur in the proximal region represents a locality of stresses concentrations. On the other hand, according to figure 5 we can also note that the downstairs activity presents higher stresses compared to others patient activities. We can thus confirm that when the patient climbs down the stairs, the risk of the implant loosening is higher particularly if this activity is repeated several times a day.



Normal walking, t=0.18s | Climbing upstairs t=0.48s | Downstairs t=0.8s

Fig. 5. Equivalent Stress levels in the cement mantle for different activities

To confirm the precedent results, we presented in figure 6 the variation of the maximal equivalent stress in the cement mantle against time for different activities of the patient during one cycle of the activity. It is clear that climbing down stairs gives higher stresses at the end of the cycle than normal walking and climbing up stairs. On the contrary, maximal stresses generated at the beginning of the cycle while climbing down are lower than walking and climbing up. The climbing down gives a maximal stresses of about 19 MPa which represents 70% of the ultimate stress of the cement (25 MPa). For climbing down activity, the time where the maximal equivalent stress has an ascending tendency is about 1s which is 65% of the global time of the cycle for this activity. This time is only 0.3s for the normal walking and 0.6 s for the climbing up stairs.

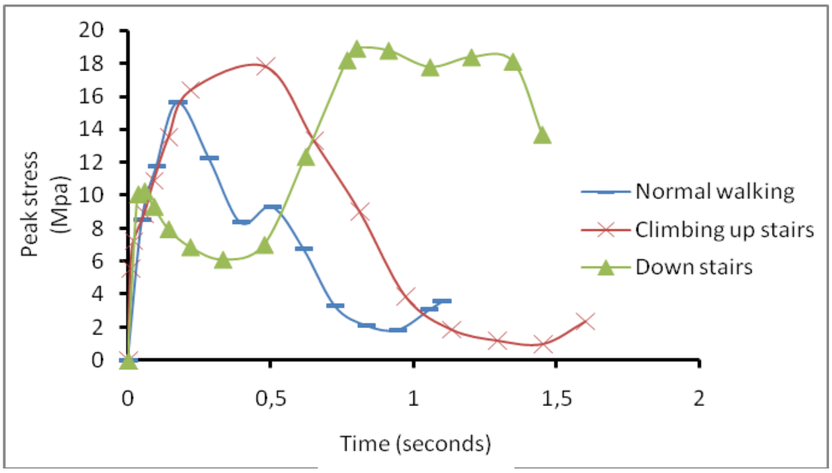


Fig. 6. Maximal stress in the cement mantle vs time for different activities

The time interval where the stress presents a peak is about 0.7 s for climbing down activity, it is less than 0.2 s for normal walking and about 0.5 s for climbing up activity. All these results confirm that climbing downstairs is the most dangerous activity for survival of the cemented hip arthoplasty.

4.2. Determination of the failure index at the stem-cement interface

Implant loosening can occur at the cement-metal interface (straight arrow in Fig. 7) or at the cement-bone interface (curved arrow in Fig. 7). However, in relation to the mechanical loading the risk of the loosening is higher at the cement-metal interface because of the great difference between the mechanical properties of the metal (Titanium) and the cement. This difference favors the creation of high stresses at the metal cement interface. For this reason, we chose to analyze the damage to the implant-cement interface.

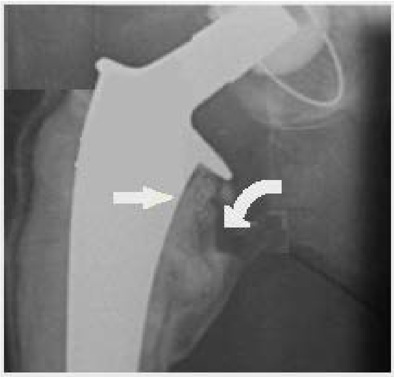


Fig. 7. Radiographic image showing the loosening [17]

Fig. 8 shows the variation of maximal values of failure index (FI) at the cement stem interface for different patient activities (Normal walking, climbing upstairs and downstairs).

The failure index is maximal for both climbing upstairs and downstairs activities. The maximal value of the failure index is 0.2. This maximal value occurs at a time of 0.5 s for the climbing up activity but for the climbing down the maximal value of FI is maintained over a time interval between 0.7 and 1.3 s. This means that the damage accumulation due to the loading cycle repetition is greater for the climbing down activity and consequently the risk of loosening is higher for this patient activity.

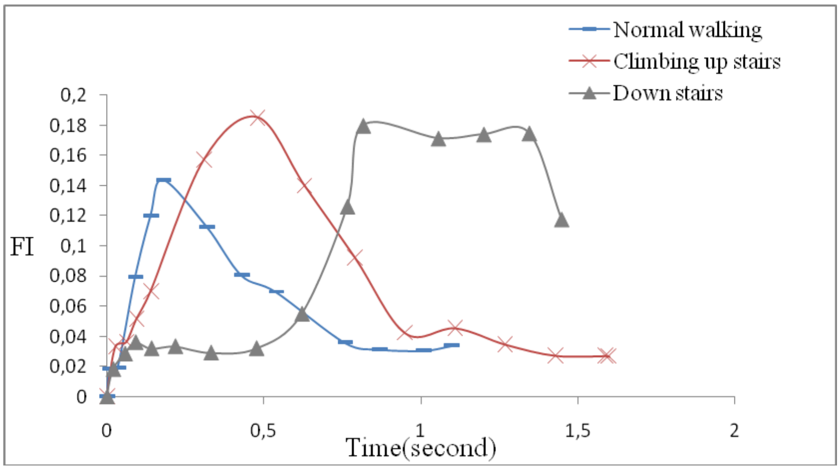


Fig. 8. Maximal values of FI vs Time for different activities

These results consolidate other researches which show that the debonding in cemented prosthesis occurs essentially at the metal-cement interface. Mechanically, this debonding is due to the combination of tensile and shear stresses at the implant-cement interface. It was numerically proved that the effect of the shear stress at interface is twice more consistent than the tensile stress [11].

To conclude this study, we tried to present the distribution of the failure index along the cement bone interface at the end of the cycles. Fig. 9 shows the four views representing the surface of the implant cement interface. We chose path in each face as shown in Fig. 9 and the distributions of the FI index along these paths are presented in Fig. 10.

We have used the climbing downstairs activity for the calculation of the failure index along the four paths since this activity is the most dangerous.

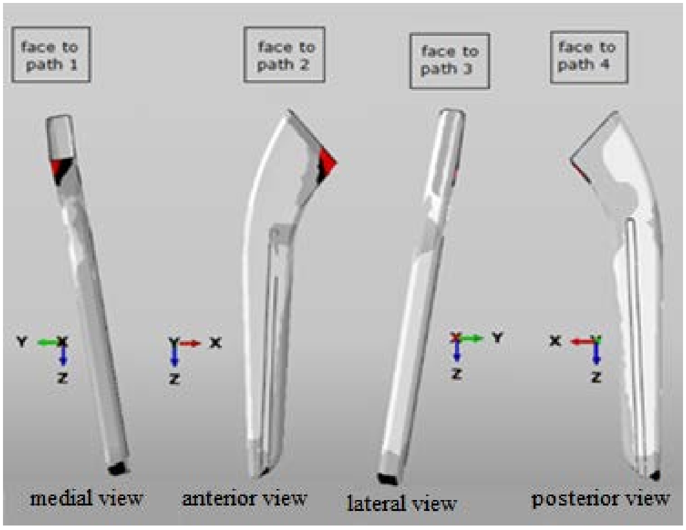


Fig.9. Different paths at surface of cement-implant interface for FI calculations

From Fig. 10, we can note that there are differences in the values of the failure index at the extreme zones (distal and proximal) where the index FI is relatively high and it strongly depends of the path of calculation. In the median zone the values of the failure index are weak whatever the path of calculation.

It is important to note that the failure index is maximal at the proximal zone of the prosthesis, its values exceeds 20% for path 1 at this zone. These results are in agreement with the radiographic image of figure 8 where it is clearly shown that the loosening of the implant is in the proximal zone either at the implant-cement interface or at the second bone-cement interface.

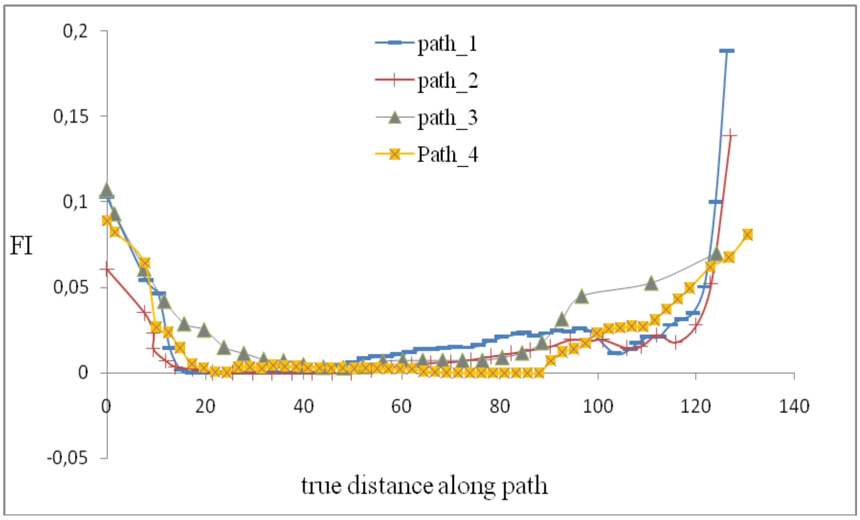


Fig. 10. Distribution of the failure index along different paths at the stem-cement interface

5. Conclusion

This work helps to understand the behavior of the stem-cement interface of a total hip prosthesis under the effects of dynamic loads from the three activities (Normal walking, climbing upstairs and downstairs). The two ends of the anterior cement face (path1) are overstressed zones and are therefore the most suitable places for the initiation of damage to the stem-cement interface. This is confirmed by the radiographic observations. The failure index (FI) shows that the anterior proximal end of the cement is the most exposed to the risks of debonding.

High overloads can come from an unsuitable effort, a shock or a accidental movement of the patient and are probable causes that can generate localized overstress. These induced charges generate high, sudden and fast stress concentrations and consequently promote risk of interface damage. Then, the proximal cement end of anterior side will be the first to debond.

The results show that the interface overstress generated at cement ends following high accidental loads can cause the creation of rupture zones of the cement-implant interface. As a consequence, the debonding initiates at the anterior proximal end of cement, then it spreads by fatigue in the cement until it causes the total loosening of the prosthesis.

This study can provide important lessons to surgeon who is called to implant prosthesis and to take into account specific characteristics of both ends of cement during the setting up of the cement and thus to guarantee in the long term the stability of the implant.

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