PREVISION OF CEMENT BONE FAILURE IN A HIP ARTHROPLASTY: NUMERICAL MODEL AND IN VITRO CORRELATION RESULTS

1Ramos, A., 2Andrade-Campos, A, 1Completo, A., 1Relvas, C. and 1Simões, J. A.

1Biomechanics Research Group, Departamento de Engenharia Mecânica, Universidade de Aveiro; email: a.ramos@ua.pt,
2GRIDS Research Group, Departamento de Engenharia Mecânica, Universidade de Aveiro; email: gilac@ua.pt.

SUMMARY
The cemented hip arthroplasty presents high success levels. However, the revisions occur through different processes in which some of them are due to the failure of bone cement. This paper presents a numerical model for predicting failure of cemented bone in hip arthroplasty. The finite element geometric model was built considering an in vitro Müller straight arthroplasty. The stiffness of each element is associated with a damage function whose maximum value is reflected in the failure of the cement element. The failure criterion is a function of the principal stresses adapted from the Hoffman failure criteria in the analysis by finite element method. In this case, each element can be considered as a particle or cement block. The numerical predictions were compared with in vitro results. Four arthroplasties were performed experimentally in vitro and their results compared with the fatigue process model after 1 million cycles. An overall correlation between the numerical model for predicting failure and the observed experimental damage (crack length/area) was noticed, especially in the detection of critical zones of the cement after fatigue test.

INTRODUCTION
Total hip replacement is the most successful surgical technique in orthopedics, with success rates between 89% and 96% at 6 and 18 years of survival [1] depending on the type of stem and type of fixation among other factors associated with the process of failure.

The replacement of this type of implant may occur in the short term and it is usually related to several factors including the geometry of the rod and the skill of the surgeon [2]. Other factors are also mentioned as important to the success of hip replacement in the long term, such as type of cement and cement thickness [3]. The phenomena the most critical in the failure of hip arthroplasty is aseptic loss, dislocation and deep infection among other factors [2]. The stem-cement interface has been considered critical in the initiation of cracks in cement, due to the complex phenomenon that occurs in the polymerization [4]. It is worth notice that it is not well known the mechanism of the complex process of failure of the arthroplasty. Some authors have attempted to numerically develop a protocol to distinguish between the called good and bad prostheses in order to minimize the occurrence of premature failure [5].

The present study aims to develop and validate a numerical model to predict failure of the cement.

METHODS
The Cemented arthroplasty addressed in this study uses the Müller Straight stem femoral shown in Figure 1. The stem is made of cobalt chromium alloy and was one of the most applied in our country a decade earlier. This stem appeared on the market in 1977 and was designed by Sir John Charnley in partnership with Professor Müller. This prosthesis presents in the Swedish records success rates of 97.8% at 10 years. The prosthesis used in the test has a modular head with 28mm diameter and 10mm size. The prosthesis was inserted in a composite femur of Sawbones ® (model 3403, Pacific Research Labs, Vashon Island, WA, USA) following the protocol established by an experienced surgeon. As Fixation, it was used as bone cement Simplex P (Stryker ®) with manual mixing and injection gun in the femoral canal. Four hips were implanted in which 3 for fatigue test and one to control for the process of polymerization. The geometry of the cemented arthroplasty was obtained by axial CT scan together with the constant spacing of 5 mm. After rebuilding the CAD model, the finite element model was created. It contains 446,692 tetraedric elements. The high number of element is justified by reason of breaking up the cement mantle in many parts as possible.

Figure 1: A CAD model and in vitro Müller arthroplasty after section procedure.

This geometric model was subjected to a cycle of elastic finite element analysis in which each corresponds to a certain period of time. Additionally, a model for predicting failure and damage was developed by the authors. This model predicts the failure of the cement, or more specifically the cement particle, and subsequently creates damage in the finite element that represents the particles of cement (see flowchart in Figure 2).
In order to detect the bone cement failure, a Hoffman criterion for composites was adapted and applied [6]:

\[ Y = \Phi_1 \sigma_1^2 + \Phi_2 \sigma_1 + \Phi_3 \sigma_2^2. \]  

Where \( \tau \) is the shear tension and \( \sigma \) is the principal maximum tension in each cement element. Damage is considered if \( Y > 1 \). Constants were defined as critical values for maximum tension and compression, \( \Phi_1 = 1.786E10^{-3}; \Phi_2 = 0.1107; \Phi_3 = 2.778E10^{-2} \). The model was implemented in a user-subroutine in the finite element program Msc.MARC ®. The properties of the remaining materials of arthroplasty, cortical bone, sponges bone, cement-bone and stem were linear elastic.

**RESULTS AND DISCUSSION**

The numerical results show the critical intermediate zone in the medial aspect (section 5 to 6) region (figure 3). The distal posterior aspect is presented as the most critical aspect; however it also occurs in the anterior and posterior. This region is defined by other studies as critical to the cement. The medial intermediate area becomes critical due to the geometry of the stem that reduces the thickness of cement in this region and the disappearance of cancellous bone. In the experimental results (figure 3), it was observed an incorrect position of the stem in femoral canal, with a valgus position in the 4 models. This phenomenon is due to the geometry of the implant on the medial aspect, with very different radius of curvature. In the experimental results, no statistically significant difference of damage was found between stems (\( p > 0.05 \)). The sections analyzed showed that the accumulated damage is critical in medial aspect with more damage (\( p < 0.005 \)) in both interfaces. The lateral aspect presents high damage but no significant difference was found (\( p = 0.059 \)) in stem-cement interface. In the bone cement interface the damage on lateral aspect present significant difference (\( p = 0.004 \)). The experimental results revealed a critical region also observed in the lateral aspect to the bone cement interface in sections 5 and 6, and not appear in the numerical results. The experimental and numerical results present some correlation as see in figure 3 proximal and distal regions.

**CONCLUSIONS**

The numerical model results present some correlation with experimental results of damage after one million cycles of fatigue. However, there are still some factors to explain, including the occurrence of damage in numerical models on the lateral aspect in the tip. The experimental results revealed that the critical region is the distal zone as shown in other studies. The study also allowed us to observe the importance of the geometry of the stem in the formation of the cement mantle, and the correct position in the femoral canal.

**ACKNOWLEDGEMENTS**

Acknowledgments to the FCT Portuguese Foundation by the project support PTDC/EME-PME/112977/2009.

**REFERENCES**