THE PRIMARY STABILITY OF A CEMENTLESS HIP PROSTHESIS UNDER THE COMPRESSIVE LOADING

XiaoSu Hu, Florence Labesse-Jied, Guillaume Demey*, and Tarik Ait Si Selmi*

LaMI, University Blaise Pascal, Clermont-Ferrand, France
*** Center Livet - Croix Rousse Hospital, Lyon, France**

The objective of this research is to better understand the problems of primary stability of cementless hip prosthesis. The present study is aimed to develop a finite element model of the coupled system "femur-cementless prosthesis" which represents the implant in its environment particularly under the compressive loading. Its primary stability is investigated by quantifying the migration of the femoral stem in the femur and by analyzing the stress and strains engendered. We have made experimentations on ten fresh human femurs. A good agreement is observed between the experiments and the prediction by our finite element model for the prosthetic head displacement.

KEY WORDS: primary stability; cementless hip prosthesis; finite element model

INTRODUCTION:

With the aging of population, osteoporosis and fractures of the upper end of femur have become a major public health problem. Its pathologies are multiplied by the variety of new lifestyles and work styles, especially the disastrous sports. Football, skiing or tennis solicits largely to the hip joint. In many sports, sudden movements, changes of direction, and receipt of a leap, etc., which can bring up to ten times the body's weight at the hip joint. Fractures of the upper end of the femur occur quite frequently. In France, the number of the Total Hip Arthroplasty (THA) is estimated at between 50000 and 100000 per year. The most common cause is the lack of primary stability for the aseptic loosening of cementless hip prosthesis (Malchau et al., 2000). The present study is aimed to develop a finite element model "femur-cementless prosthesis", its primary stability is investigated by quantifying the migration of the femoral stem in the femur as well as by analyzing the stress and strains engendered. This FE model is validated by the experiments on ten fresh human femurs.

METHOD:

Ten fresh human femurs are collected by using a standardized surgical technique. The length of the femur is set at 250mm. The femoral stem DePuy Coral® standard is a cementless implant coated hydroxyapatite used mostly throughout the world in the last twenty years. The test machine used is Zwick Roell®, model: ProLine. It's coupled with software testXpert®. The fixation of the femur is realized in a cylindrical metal base. The femur is placed at the bottom of the base, fixed by a metal alloy, submerge depth is 110mm. The orientation of the femur reproduces the standing position (Figure 1). The test is static: the compressive force began at 200 N and is growing in a linear mode of 20 N/s. The testing procedure is stopped as soon as a fracture of the femur occurs. Otherwise, the maximum force applied is 15 KN. The force is noted by electronic sensors located on the machine and it connected to a computer. The data are processed by the software testXpert® as graphs.

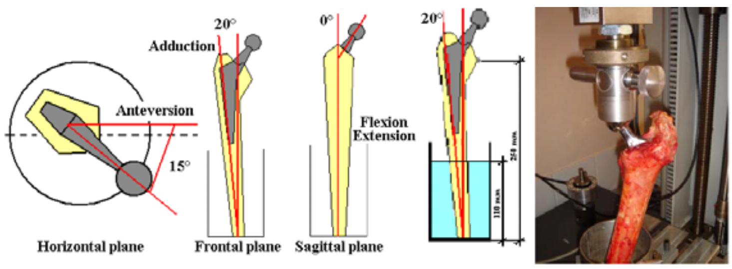

Figure 1: Position of the femur in cylindrical base

For the finite element model, firstly, the shape of an intact femur is obtained by 3D scanning through a combined solution of a portable measurement arm, (brand: Romer®, series: Sigma) with a digital laser camera, (type G-Scan™ RX2). Then under the surface reconstruction software: 3D Reshaper®, a surface model of the femur, based on the cloud of points collected, has been established. Subsequently a voluminal model has been constituted from the surface model by software CATIA V5 R16. Secondly, for the prosthesis, the IGES data (size 12) are supplied by the company DePuy Orthopaedics Inc., Johnson & Johnson Company. The assembly 3D has been accomplished with the software CATIA V5 R16. The positioning of the prosthesis relative to the femur is realized from stereo radiographs and validated by the orthopaedic surgeon. The boundary between cancellous bone and cortical bone is determined by analyzing the radiographs. The femoral head is made of alumina ceramics, E=350000MPa, υ=0.23. The femoral stem is made with titanium alloy TA6V4, E=115000MPa, υ=0.31. On the other hand, mechanical characteristics of the bones are very dispersed in the literatures depending on the individual, measure method, how to obtain and treatment of the sample etc. For the cancellous bone, the Young's modulus varies from 75 MPa to 2988 MPa (Wirtz et al., 2000; Chevalier et al., 2007). For the cortical bone, his elastic modulus is less dispersed (Duchemin et al., 2007; Kaneko et al., 2003), between 4.4 GPa and 26.4 GPa. In our FEM, the femur is modeled in two separate types of isotropic and homogeneous tissue: the cancellous bone and cortical bone. 1000MPa is chosen for the Young's modulus of the cancellous bone. And then different $E_{cancellous}$ (i.e. 400, 500, 600, 700, 800, 1200, 1400, 1600, 1800 and 2000MPa) are selected to evaluate its influences. 20GPa is defined for the $E_{cortical}$. For the Poisson's ratios υ, 0.3 has been defined for both (Pancanti et al., 2003). For a deterministic finite element model, the mesh is finally achieved by combining the mesh generator of CATIA and FEMAP V9.3.1. In total, our model (Figure 2) is consisted 18671 nodes and 79067 tetrahedral linear elements.

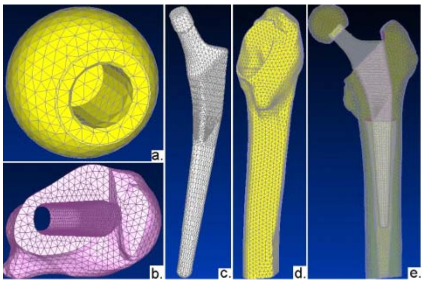

Figure 2: (a) Meshing of the femoral head [3mm] (b) Meshing of the cancellous bone [1.5~3mm] (c) Meshing of the femoral stem [0.3~3mm] (d) Meshing of the cortical bone [3mm] (e) Finite element model of the coupled system "femur-cementless prosthesis"

A surface-surface contact has been adopted for the friction between the femoral stem and cancellous bone. For the friction coefficient at the interface of cementless femoral stem and cancellous bone, to our knowledge, is not known. In modeling the friction behavior, 0.3 is the most cited (Viceconti et al., 2000) for $f_{stem\text{-}cancellous}$, and then the different values (i.e. 0.1~0.6) are chosen for investigating its influence. The distal part of the femur is immobile. The compressive loading is similar to the experiments, but F_{max}=3000N. According to the theory of Pauwels balance, walking can be treated as a succession of unilateral compression. This value corresponds to a person of 75kg in the unilateral compression position.

RESULTS:

We found that the third experimental result was evidently dispersed against the others (Figure 3 left). For the following analysis, this datum will be ignored. The average of implant's displacement is 596.4μm for the remained nine results when the loading attained to 3000N (Figure 3 right), the most displacements of the reference point on the femoral head situated approximately 540μm. If we neglect the individual difference, the average of the experimental results is 551 μm for the prosthesis size 12. With the configuration we specify that previously, the result, provided by our model, is 540.3 µm when the loading applied is equal to 3000 N.

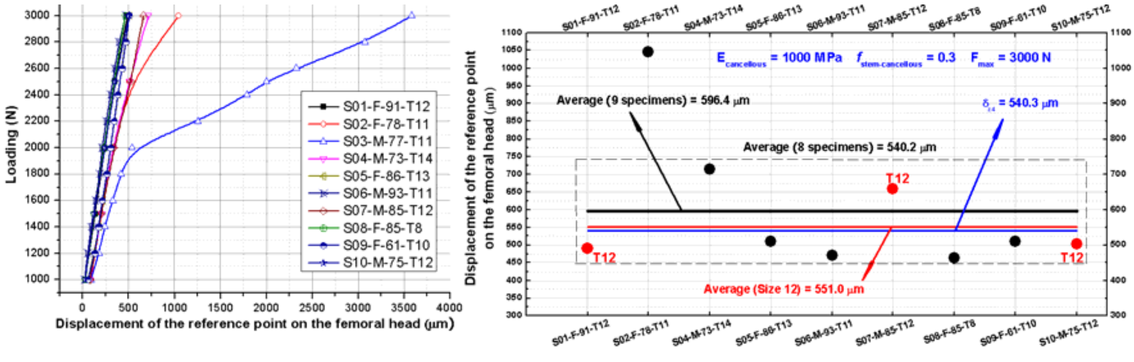

Figure 3: Experimental and simulative results

For the relative micromotion, it's computed by determining the relative displacement of each node on the stem surface with respect to the closest node on the interne surface of the cancellous bone. The results will be taken into two contact lines (medial line AD and lateral line BC), because the efforts on the anterior and posterior side of the cancellous bone are negligible when the solicitation applied in the direction of proximal distal. This has been demonstrated by the result of the contact pressure between the femoral stem and the cancellous bone. That's why we are primarily interested in the medial and lateral sides.

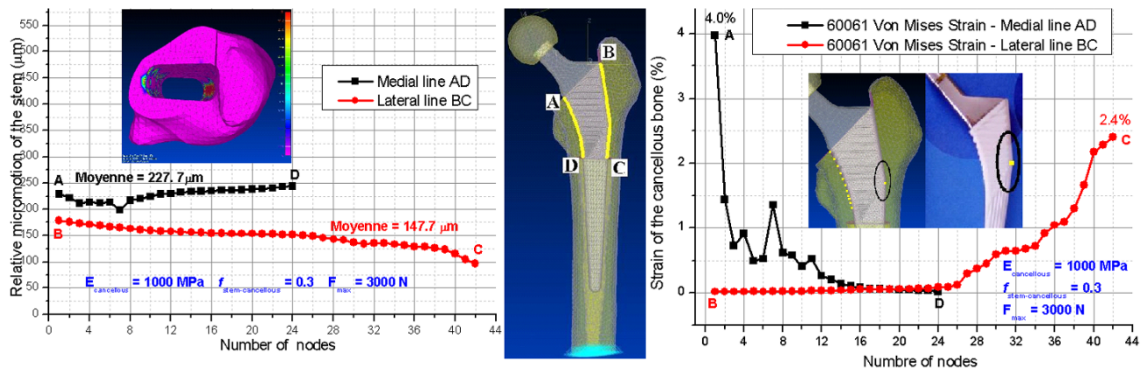

Figure 4: Micromotion of the implant relative to the femur and strains on the cancellous bone

We observe the migration of the stem in the femur evolved quasi-regular along both contact lines (Figure 4 left). This relative micromotion is approximately 228 µm on the medial and about 148 µm for the lateral side. For strains of the cancellous bone conducted by the implant, it's noted that the strains react depending on the pressing surface of the prosthesis onto the cancellous bone. In the medial region, there are several grooves (nodes N°1~12), the maximum strain 4.0% is located at the proximal part, in contrast to the lateral side, the distal part is the most deformed, 2.4%. It's also noted that there is a bulge in the lateral region (nodes N°26~34), the cause is the geometric elbow of the femoral stem at this location (Figure 4 right). The stress in the cancellous bone, we observe the same type of curve that for the strain, which is normal because they are correlative. The maximum respective values are 42.7 MPa and 26.5 MPa for the proximal part of the medial side and the distal part of the lateral side.

Considering the human bone is a living material, for our knowledge, the Young's modulus of cancellous bone and the coefficient of friction between the femoral stem and femur are two parameters which play the crucial roles for the primary stability of the cementless prosthesis. For this reason, a sensitivity study of the model is analyzed. This sensitivity research showed that for the prosthetic head displacement, there is a 32.54% increase and 13.21%

decrease when the cancellous elastic modulus ranged from 400MPa to 2000MPa compared with the reference value ($E_{cancellous}$=1000MPa). We also observed there was 32.44% augmentation and 10.35% diminution when the friction coefficient ranged from 0.1 to 0.6 compared with the reference value ($f_{stem\text{-}cancellous}$=0.3).

DISCUSSION:

A good agreement is observed by our finite element model on the displacement of the prosthesis between the experiments and the prediction. The error is less than 2% when the compressive loading 3000N applied on the femoral head for the prosthesis size 12. We concluded that this finite element model of the coupled system "femur-cementless prosthesis" can be used to research its primary stability and to quantify the migration of the femoral stem in the femur as well as analyze the stresses and strains engendered.
Micromotion between prosthesis and bone tissue is sometimes used as a parameter for the evaluation of fixation. There are several studies on the measurement and analysis of micromotion the cementless prosthesis with respect to the femur (Viceconti et al., 2000; Götze et al., 2002), the results for these micromotions vary between 9 μm and 529 μm. But, comparisons with other studies are complicated due to the difference in the methods and testing conditions used. In our model, we considered separately cancellous bone and cortical bone with two Young's modules. Actually the CT data can provide the accurate geometrical topology of bone, it can also supply the appropriate bone material properties, in this way, the assignment of bone tissue material properties for every element is more reasonable and accurate (Schileo et al., 2007). We are currently working on rotation primary stability. All the presented results are based on a deterministic model, how to take into account the incertitude of input parameters? How to evolve these uncertainties in the model? What are the implications for the results? A reliability methodology will be developed to study the mechanical performance of our system in stochastic context.

REFERENCES:

Chevalier, Y., et al. (2007). Validation of a voxel-based FE method for prediction of the uniaxial apparent modulus of human trabecular bone using macroscopic mechanical tests and nanoindentation, *Journal of Biomechanics doi:10.1016/j.jbiomech.2007.05.004*
Duchemin L. et al. (2007). Prediction of mechanical properties of cortical bone by quantitative computed tomography, *Med Eng Phys (2007), doi:10.1016/j.medengphy.2007.04.008*
Götze C., Steens W., Vieth V., Poremba C., Claes L. (2002). Primary stability in cementless femoral stems: custom-made versus conventional femoral prosthesis. *Clinical Biomechanics* 12, 267–273
Kaneko T.S., Pejcic M.R., et al. (2003). Relationships between material properties and CT scan data of cortical bone with and without metastatic lesions. *Medical Engineering & Physics* 25 (6), 445–454.
Malchau H., Herberts P., Söderman P., Odén A. (2000). Prognosis of total hip replacement. Update and validation of results from the Swedish National Hip Arthroplasty Register 1979–1998, *67th Annual Meeting of the American Academy of Orthopaedic Surgeons*, Orlando, FL, USA.
Pancanti A., Bernakiewicz M., Viceconti M. (2003). The primary stability of a cementless stem varies between subjects as much as between activities *Journal of Biomechanics* 36, 777–785
Schileo E., Taddei F., Malandrino A., Cristofolini L., Viceconti M. (2007). Subject-specific finite element models can accurately predict strain levels in long bones. *Journal of Biomechanics* 40, 2982–2989.
Viceconti M., Muccini R., Bernakiewicz M., Baleani M. (2000). Large-sliding contact elements accurately predict levels of bone-implant micromotion relevant to osseointegration. *Journal of Biomechanics* 33, 1611-1618
Wirtz D.C., Schiffers N., et al. (2000). Critical evaluation of known bone material properties to realize anisotropic FE-simulation of the proximal femur. *Journal of Biomechanics* 33(10):1325–30.

Acknowledgement
This work is supported by DePuy France, with Christophe Saint-Pierre. The authors would like to thank Guy Barbarat for his help.