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FINITE ELEMENT ANALYSIS OF HIP PROSTHESIS STABILITY

Although the procedure of the hip surgery is successful for nearly 30 years it is still confronted to late complication for mechanical reasons, which are responsible of the replacement of prosthesis. The bone loosening causes micro-movements of prosthesis elements, which are no longer attached to the bone. The complications stem from the mismatch of materials properties between the bone and the prosthesis (for instance, the rigidity of the implant can be 5 to 20 times larger than the bone one). Actually after the surgical operation, the repartition of the loads is accentuated on the prosthesis, stiffer than the bone. This new repartition does not permit to maintain the structural integrity of the bone, leads to increasing the porosity of the bone. This natural adaptation is responsible for the instability of the system and in fact for bone loosening.

Since the first use of the FE for orthopaedic researches in 1972 it has been extensively used in three goals: to obtain fundamental data about structure of the skeleton and the muscles, to study the time adaptation of the implant in the tissue and finally to draw and study the stability of the prosthesis in the bone before the clinical experimentation. This last way interested us.

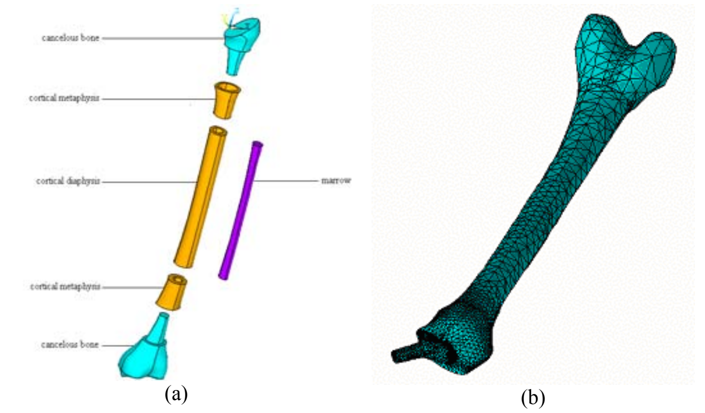

Fig. 1: Composition of the femur (a) and finite element model (b) of the biomechanical system “bone-implant”.

The femur was considered composing of several volumes with their own properties: the cortical parts of the bone (diaphysis and metaphysis) which are orthotropic materials in the cylindrical coordinate system, the spongious tissue and the marrow which are isotropic (Fig.1). The values of elastic modules were derived from the references and listed in the Table 1. The finite element model of the bone and prosthesis was developed by using software ANSYS5.5. The final mesh was composed of 52417 tetrahedral 4-nodes elements SOLID92 and 10907 nodes.

In this work we investigated 3 phases of the gait cycle (heel-strike, mid-stance and toe-off) which represent respectively 10, 30, and 45 percent of the gait cycle and stairs climbing as well.

Table 1. Elastic modules of the bone tissues

Tissue	Type of material	Young module (GPa)	Poisson module	Shear module (GPa)	Ultimate stress (MPa)	Density (g/cm^3)
Spongious	anisotropic	E=1	υ=0.316	-	-	0.8
Cortical metaphysis	orthotropic	E_r=9.3 E_τ=11.7 E_z=17.5	$\upsilon_{r\tau}$=0.302 $\upsilon_{\tau z}$=0.205 υ_{rz}=0.109	$G_{r\tau}$=4.23 $G_{\tau z}$=5.59 G_{rz}=6.03	~150 (traction) 49~68 (torsion)	1.8
Cortical diaphysis	orthotropic	E_r=11.6 E_τ=14.6 E_z=21.9	$\upsilon_{r\tau}$=0.302 $\upsilon_{\tau z}$=0.205 υ_{rz}=0.109	$G_{r\tau}$=5.26 $G_{\tau z}$=6.99 G_{rz}=6.29		

Marrow	anisotropic	$E=10^{-6}$	$\upsilon=0.499$	-	-	0.8
Prosthesis	anisotropic	$E=110$	$\upsilon=0.316$	-	950	4.5

Two models, i.e. an intact bone and the system “bone-implant” presented close displacements excepting during the stairs climbing. For the intact bone the most important displacement was in the head of the femur and vanished in the diaphysis. Indeed, during the climbing of the stairs the force on the hip joint is more important (7 or 8 times the weight of the body) and creates an important displacement of the head of the bone. But in the case of implanted bone the prosthesis stiffness limits the displacement of the head and generates new kind of displacement inside the bone.

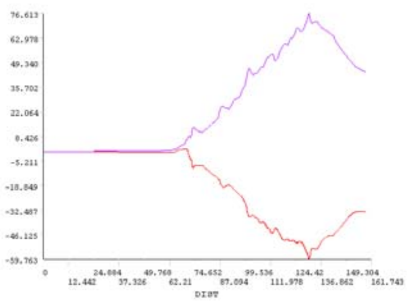

Fig.2: Equivalent von Mises and axial stresses (MPa) along lateral side of the prosthesis stem.

The largest stresses equal to 76.6 MPa were obtained for the third gait phase, especially around the lateral part of the prosthesis under the spigot (Fig.2). We especially noticed that stress redistribution is around the prosthesis. A higher stiffness of this implant is responsible for the lack of stresses in the other parts of the bone.

For the intact femur the cortical parts are submitted to stresses which value is around 28MPa during the third gait cycle. During the others cycles, the maximal stress is under the head of the bone that is different for the system bone-prosthesis.

It can be concluded that the “toe-off” gait-cycle is more traumatizing for the bone than the stair climbing one, in contrary to what we can imagine. However our data are not complete because these values just concern one step of the activity. May be during stairs climbing, there are some more traumatizing phases. The stress diminishes around the cortical part after the surgical operation because of the new load due to the stiffness of the prosthesis. This configuration can lead to the loosening of the prosthesis.

Because the maximal stresses was obtained for the gait cycle «toe-off» we decided to test the different implantations with the conditions that are linked to this cycle. First of all we considered the intact femur which was the reference model. It is important not to forget that the main problem we studied was to avoid the bone loosening which is caused by the stress-shielding linked to a new distribution of the stresses in the bone. It is considered that the bone density is diminishing in the proximal part of the femur and especially in the proximal-medial part after the surgical operation. The stress distribution in the femur shows that the load is important in the cortical diaphysis part of the bone. We also noticed that the redistribution was homogeneous and that the maximal stresses were located in the proximal-medial part where problem of bone adaptation is known. The value is 28MPa. However, stresses are globally increasing along the distal direction. Moreover the marrow and the cancellous bone have a weak loading.

It is highly interesting to compare the initial model (bone-implant) with the bone because with the prosthesis stresses are localised in a restricted volume. We notice that the loading is essentially located in the prosthesis, with a growing gradient of stress along the medial direction (the maximum is located in a small volume), and above all the proximal-medial part loading decrease. We can suppose that we still have problem of bone adaptation.

Then we investigated a different type of implantation where a prosthesis stem penetrated the cortical diaphysis part of the femur. In this configuration stresses are optimum in the prosthesis but it is interesting to notice that they are applied in two volumes close to the interface and that their values are weaker as previously.

<u>Conclusion</u>: This type of prosthesis is too stiff to give optimum results. Indeed, displacements are limited and especially the phenomena of bone adaptation can not be prevented and problems of bone loosening are likely to happen. The use of materials whose stiffness is closer to those of the bone is necessary.

REFERENCES:

1. *ANSYS Basic Analysis Procedures Guide*. 1998.