FINITE ELEMENT BONE MODEL INCORPORATING HETEROGENEITY AND ANISOTROPY FROM CT

C.M. Müller-Karger, C.A. Larrazabal
Departamento de Mecánica, Universidad Simón Bolívar, Caracas, Venezuela.
email: cmuller@usb.ve, http://www.did.usb.ve/biomecanica

INTRODUCTION

This investigation seeks to achieve a heterogeneous and anisotropic characterization of bone in a simple form and with low computational cost. The ultimate purpose is to create a model and a platform to design and simulate medical devices. CT is used to develop a geometric reconstruction of the bone, and to assign the heterogeneous and symmetric mechanical properties to the elements of the model. The directions of symmetry of the material are determined based on prior knowledge that they are aligned with the principal stresses (Wolf Law). Bone material is considered to be orthotropic.

Several models based on CT consider the bone to be heterogeneous and isotropic. Only a few models take into account anisotropy, using either bone remodeling theories [1,2] or complex trabecular models [3].

METHODS

A femur model was constructed using 197 images, spaced every mm at the epiphisis and every 4mm in the diaphisis. The images were 211x211 pixels, with a resolution of 0.7 mm/pixel, calibrated with a phamton.

Segmentation of the images produced a wire model that was imported to ANSYS. This FE software was programmed for the automatic construction of the solid model. Using 10 nodes tetrahedrons, various meshes were created for a convergence study. Plots of von Mises stresses, equivalent deformation and energy of deformation were evaluated for twenty points of all models. Then, a mesh of 43125 elements was choseen. The load condition used was the same as the one presented by Doblaré and Garcia [2]. Assignment of mechanical heterogeneous properties was computed at every centroid of the elements using a program developed by the authors.

If the bone behaves as an object with ortotropic symmetry, it is necessary to determine nine non-zero elastic constants of the flexibility matrix: three Young modules E_1, E_2, E_3; three shear modules G_{12}, G_{13}, G_{23}; and six Poisson ratios ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, ν_{32}, of which only 3 are independent. Young modulus in the axial direccion (E_3) is related to density estimated from the CT using known equations. To obtain the remaining elastic constants, information of previous studies that have determined these properties by mechanical tests [4] was used. Resulting the following relations:

$$\begin{array}{lll} E_3 = 1 & E_2 = 0.67 * E_3 & E_1 = 0.67 * E_3 \\ G_{32} = 0.3 * E_3 & G_{13} = 0.27 * E_3 & G_{12} = 0.22 * E_3 \\ \upsilon_{21} = 0.3 & \upsilon_{31} = 0.95 * \upsilon_{21} & \upsilon_{32} = 0.79 * \upsilon_{21} \end{array} \quad (1)$$

The FEM analysis provides the stress components of the three coordinated planes for each element. These are then used to solve the eigenvalue and eigenvector problem of the Stress Matrix, in order to obtain the principal directions for every element of the model. The principal directions obtained for a heterogeneous and isotropic model are used as seed for an iterative process to find the actual direction of the mechanical properties. Convergence is verified for the three angles of every element.

To define local coordinate system in FEM programs the Euler angles (α, β, χ) are required. These are obtained from the principal stresses vectors with a rotation matrix.

RESULTS AND DISCUSSION

A comparison between isotropic and anisotropic models of the femur is performed. Results indicate that it is necessary to consider anisotropy to model bone tissue. Figure 1 shows results for a heterogeneous and anisotropic model.

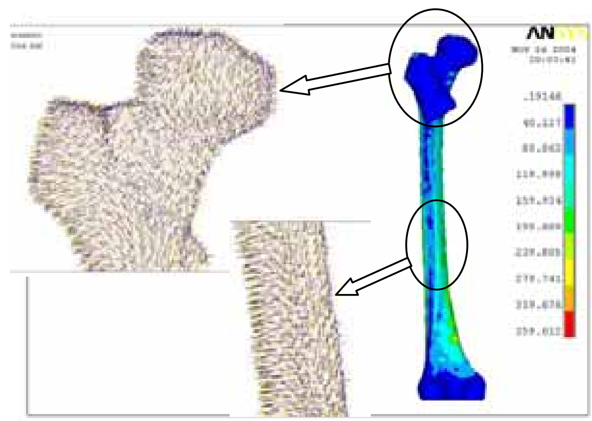

Figure 1: Orientations of the coordinates systems are shown for the epiphisis and diaphisis. Plot of von Misses stress is for the whole model.

CONCLUSIONS

We developed methodology to represent a bone model with a mechanical property and a material symmetry system for every model element. Numerical results indicate that even models with a relatively small number of elements leads to reliable results. The model reflects the highly heterogeneous and anisotropic characteristics of the bone, and operates at very low computacional cost, using normal CT. The model is not intended as a substitute of microscopic bone models [3].

REFERENCES

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