SOLID MODELING AND STATIC FINITE ELEMENT ANALYSIS OF THE HUMAN TIBIA

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INTRODUCTION

Currently many finite element (FE) models of human bones and joints exist. Computer Tomography (CT) Scans or Magnetic Resonance Imaging (MRI) constitute the input data for a variety of software that will produce a solid model of the object. A finite element model (FEM) is superimposed on the geometrical one; material properties are assigned and loading conditions are prescribed. The needed analysis is then performed. Depending on the level of sophistication of the software used and the requirements of the specific research, the geometry and the FE mesh are more or less detailed and accurate.

Most FE analyses performed up to the present date for the human tibia consider the bone as an isotropic homogeneous medium. A reasonable approximation of bone is to consider it an orthotropic linear elastic solid governed by Hooke's law. Knets [1] measured the material parameters of the human tibial cortical bone. Ashman et al. [2] and Rho et al. [3] correlated the orthotropic elastic moduli of the tibial cancellous bone to the bone density. Ford and Keaveny [4] determined the regression equations to be used for the longitudinal and transverse shear moduli. No study of the correlation of Poisson's ratio to the density was found in the literature.

In 2001, Cattaneo et al. [5] created an orthotropic FE model of the glenoid part of a scapula based on the data retrieved from CT and Belluci et al. [6] constructed an orthotropic but homogeneous FE model of a human femur, in which the cancellous bone is partitioned into three regions of different material properties. In 2002, Hull et al. [7] developed a very complex FE model of the human knee joint in which the cortical bone of both femur and tibia is assigned orthotropic properties but the cancellous bone is considered isotropic.

In this paper, using current modeling methods, starting from CT retrieved data; several orthotropic FE models of the whole tibia are described and compared. For the same static loading conditions, the loading that occurs during normal gait, with different sets of material properties assigned to the tibial cancellous bone and FE meshes the differences in results are registered and constitute the object of an ongoing work.

MODELING

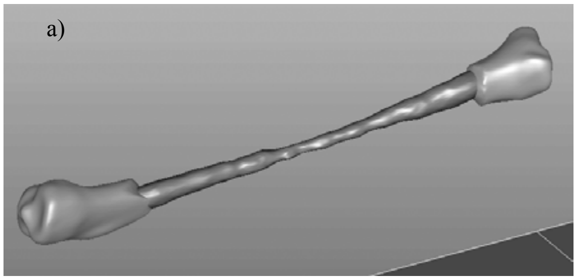
A CT scan of a cadaveric human tibia was used as the basis of this present research. A total of 201 CT scan slices of the tibia were taken; the distances between the scans varying along the length of the bone with a higher density at the proximal and distal ends, as those were the regions of interest.

The data was imported into MIMICS (Materialise), and the threshold method was used to differentiate between the cortical bone region, cancellous bone region and the bone marrow cavity. The individual elements of a CT image are called voxels and each has a value referred to in Hounsfield units based on the density of the structure (the value for water is 0). The threshold used in the present work for cortical bone was: 1990 – 3127 (upper limit of the scanned data), and for cancellous bone: 1100 – 1990 (both coarse and fine trabecular bone, as the trabeculae of tibial cancellous bone are almost longitudinal). The epiphyseal line was considered as part of the cancellous bone since the Hounsfield values associated did not pass the cortical bone threshold, most probably due to the age of the specimen. The values lower than 1100 were used to construct the bone marrow cavity.

Each slice was manually edited: the external and internal contours were smoothed out and internal cortical bone cavities removed. The density numbers throughout the cortical and cancellous regions were recorded in separate files to be used in determining the numerical values of the elastic and shear moduli based on the correlation equations determined in [3,4].

The geometry data for the cortical and cancellous bone regions were imported individually into GeoMagic Studio (Raindrop Geomagic, Inc.) as point clouds. GeoMagic Studio was used to process the data in order to create Non-uniform Rational B-Splines (NURBS) surfaces, which are easily handled by FE software. After editing the data (de-noising, smoothing, filling of gaps), the curves or points were wrapped as closed manifold surfaces. A manifold surface is a triangle-based surface in which all the triangles are continuously connected by their edges, the closed kind bounds volumes.

Four surfaces were created corresponding to the outer cortical shell, the internal bone marrow cavity and two surfaces delimiting the epiphyseal cancellous bone. The very thin layer of cancellous bone along the diaphysis has been neglected. Figure 1 presents the NURBS surfaces created.



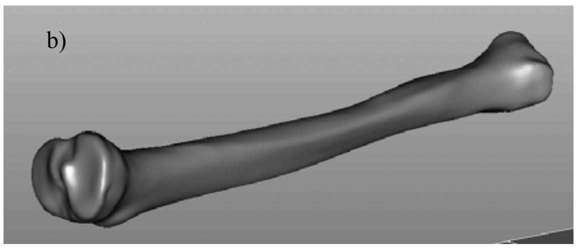


Figure 1. NURBS surfaces: a) the epiphyseal cancellous bone and the bone marrow cavity; b) the outer cortical surface.

Finally, all data have been exported as STEP files into SDRC – IDEAS (Version 8) software.

ANALYSIS

Three orthotropic FE models of the whole tibia have been created and constitute the object of an ongoing research. The effect of the fibula was neglected. Table 1 contains the sets of material properties assigned to the cortical and cancellous bone partitions. As bone marrow is mostly fat and does not have a support function the material properties assigned to it are the properties of air.

Material Property (MPa)	Cortical bone	Cancellous bone		
		1	2	3
E_1	6.91	4.48	$-98+1.52\rho$	$0.06\rho^{1.51}$
E_2	8.51	4.48	$-124+1.81\rho$	$0.06\rho^{1.55}$
E_3	18.4	9.64	$-326+5.54\rho$	$0.51\rho^{1.37}$
G_{12}	2.41	1.41	931ρ	931ρ
G_{13}	3.56	1.28	$775\rho -158$	$775\rho -158$
G_{23}	4.91	1.28	$775\rho -158$	$775\rho -158$
ν_{12}	0.49	0.35	0.35	0.35
ν_{13}	0.12	0.12	0.12	0.12
ν_{23}	0.14	0.12	0.12	0.12

Table 1. Material properties of the human tibia

The cortical bone layer was considered homogeneous for all the models, as the properties vary only slightly through thickness. Three sets of properties for the cancellous bone layer were considered. The numerical material properties included in Table 1 are averaged between the values taken from the literature [1,2,5,6]. The regression equations used belong to Rho et al. [3] and Ford and Keaveny [4]. The numerical values of the density are retrieved from the CT numbers of the actual tibia used in this research, as mentioned in the previous section.

The static loading conditions were considered to be the ones occurring during normal gait at the stance phase in near full extension. The loading value of 2450 N was taken from Harrington [8]. This compressive force was distributed over the nodes at the top of the tibial plateau, with the highest loads in the approximate centers of medial and lateral areas. The total loaded area represented a fraction of 20% of the total tibial plateau area, with the medial loaded area larger than the lateral loaded area, to reproduce a real loading situation. The degrees of freedom of the nodes in the distal epiphysis were totally constrained.

EXPECTED RESULTS

The work on this project is ongoing but the preliminary results obtained for a simplified model for deflection and stresses are in the same range with the ones found in the literature. The region of interest is the proximal epiphysis of the tibia and the expected results should show compressive stresses significantly greater in the popliteal area than in the corresponding anterior area and small, by comparison, in the tibial plateau. Also high stresses should be registered in the distal epiphysis. An extensive analysis of the stresses is still under work, and it is expected to underline the differences between the three models considered.

The results obtained so far are encouraging and give a little more insight into how to optimally model a human bone geometry and material behavior.

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