A Semi-Automatic Procedure to Develop Specimen-Specific Finite Element Models from Micro Computer Tomography Images of Implanted Bones

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Introduction

The mechanical stimuli play an important role in the complex process that regulates the bone tissue growth and its integration around prosthesis. Finite Elements Models (FEM) can be important tools to investigate the mechanical behavior and evolution of the bone structure, but the bio-diversity between different specimens and conditions make it difficult to generate statistically representative numerical models. The present work aims at developing a semi-automatic procedure to generate specimen-specific FEM of a series of rat bone specimens with osseo-integrated titanium implants, with the goal of regrouping each sample-based result in a more complete statistical analysis accounting for biovariability.

Materials and Methods

The development of the procedure is part of a mixed experimental-numerical research project that aims at establishing a link between the in-vivo mechanical stimulation of the rat tibia and the bone regeneration around prosthesis. The experiment consists in implanting two titanium implants in the tibia of Sprague-Dawley rats and activating them with known force after two weeks of integration in order to stimulate bone growth [1]. After the sacrifice, the samples composed of the rat tibia and the osseo-integrated implants are processed by Micro Computer Tomography (μCT) with a resolution of 20 μm (Fig. 1a).

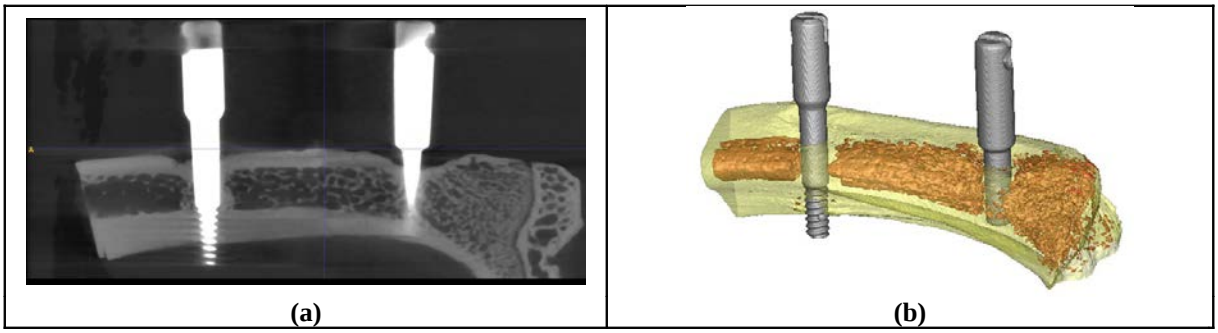

Figure 1: (a) a μCT image of the sample; (b) a 3D segmentation with differentiation of materials.

A semi-automatic segmentation procedure, implemented in a custom version of the software ITK-Snap, allows to reconstruct the 3D geometry and the Bone Mineral Density (BMD) of each specimen from the μCT images. A statistical analysis of the grayscale histogram of each specimen permits to define the optimal thresholds for the implants and the bone tissues, with differentiation between the cortical and trabecular bones. These specimen-specific thresholds

are used as input for the segmentation in order to obtain the 3D geometry of the sample (Fig. 1b). Even though the biodiversity prevents the use of the same thresholds for all specimens, this statistical procedure guides the user and ensures the reproducibility of the end results.

The FEM mesh is generated with a custom tool based on an advanced iso-surface meshing algorithm [2], an octree domain decomposition method and a quality Delaunay tetrahedralization algorithm [3]. To take into consideration the heterogeneity of the bone tissue, each element of the model is assigned an homogenized set of material properties using a voxel-based adaptive integration rule. Based on a gray scale calibration phantom, the voxel values are converted into BMD and consequently in Young Modulus through the empirical relation presented in [4]. The FEM is finally exported and computations are carried out with *Simulia Abaqus 6.10*.

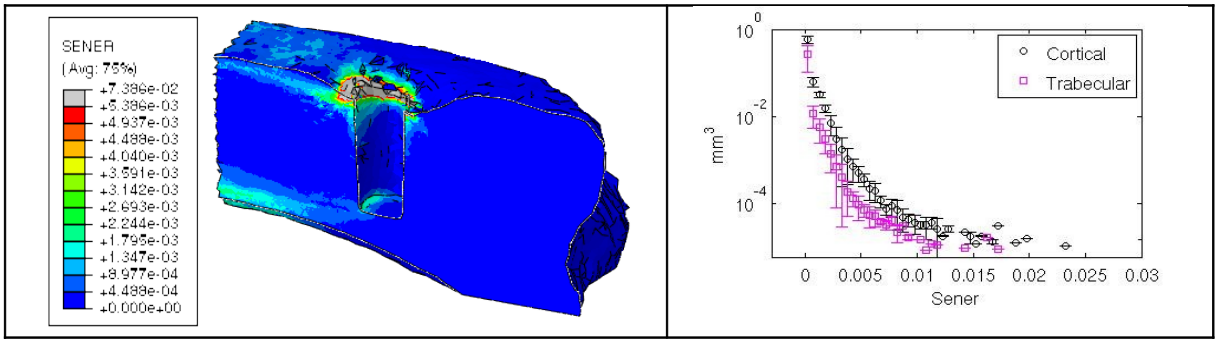

Figure 2: (a) strain energy density field on a section passing through the proximal implant axis; (b) cortical and trabecular volume histograms associated to strain energy density (b).

Results

Using the developed methodology, an accurate and reproducible specimen-specific FE model can be constructed and analyzed from a μCT scan in just a few hours of work, most of which is spent correcting the segmentation for local artifacts. As an example, Fig. 2a shows the Strain Energy density distribution (SENER) around the proximal implant. The differentiation of the material properties clearly indicates the different reaction of the bone structure to the external load. Figure 2b represents the volume histograms of strain energy density of four specimens with differentiation of cortical and trabecular bone.

Discussion

Works involving experimental research on living tissues have to deal with the difficulties of generating models that can be representative of biovariability. The present methodology can be an important tool to extend the use of FEM analysis to large series of samples, thus accounting for biodiversity. The experimental validation of the obtained numerical models is an important task that is currently being undertaken based on three point bending tests and inter-implant stiffness measurements.

References

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