Abstract

THE knowledge of mechanical properties of bones plays an important role in medicine and implantology. Two tissues can be distinguished in typical bone: cortical bone and cancellous bone. The latter has a highly complex spatial structure in which number of trabeculae, closely adjacent to one another, are intertwined with pore areas filled with fat, marrow and other soft tissues. It is very important to develop computer models that allow for predicting of the mechanical properties of bone, based on precise non-destructive measurements, so that they can be adapted and used in the future clinical practice.

The aim of the dissertation was to carry out computer simulations of the mechanical properties of bone tissue. Input data for modeling was obtained by means of high resolution microtomographic measurements. Since the main goal was to develop a methodology for modeling of the mechanical properties of bone tissue, animal bones were analyzed during the research. While the choice of slaughter animals has guaranteed easy access to a large number of diverse specimens, and did not require ethical committee approval, the developed methodology remains the same for human bones. Presented methodology is based on finite element method together with the developed specialized biomechanical model of the musculoskeletal system.

The first step was to obtain a digital representation of 6 bovine femurs (proximal end) based on tomographic measurement in lower resolution in macro scale (45.6 µm). Then, 70 statistically representative cubic cancellous bone specimens of 1 cm^3 volume were dissected for the purpose of imaging in 7-times higher resolution in meso scale (6.5 µm). The material parameters were determined experimentally in 3 perpendicular directions for each specimen, using a miniature compression machine, including simultaneous tomographic imaging in selected cases.

At the next stage, a precise digital registration based on local descriptors between cancellous bone specimens and reconstructed femur bones was performed in order to obtain information about their position and orientation in the three-dimensional space. This allowed to juxtapose identical volumes obtained in higher and lower resolution. Thanks to that it was also possible to select the binarization parameters basing on the comparison of determined morphometrical parameters (morphological, topological and textural), as well as to orient spatially the results of mechanical measurements of dissected cubic bone specimens relative to the femoral bone reference system. The sizes of the volumes have been corrected after aligment consistent with the principal axes of anisotropy after analysis conducted for the specimens. Statistical correlations between determined parameters describing the structure and experimental material data were investigated, obtaining values and relationships consistent with the literature data. Femoral bones were subjected to segmentation and binarization using parameters determined after registration of volumes, binary masks covering volumes occupied by bones were also created.

The processed and analyzed data was used for multi-scale computer simulations. After discretization of the volumes of cancellous bone specimens oriented in principal axes of anisotropy, a series of compression and shear tests was performed using finite element method to determine the full form of the stiffness tensor. Input parameters of trabeculae were determined by comparison with material parameters obtained during measurements. Based on the results obtained from simulations and morphometrical analysis (volume fraction and degree of anisotropy), parameters of the Zysset–Curnier model, which averages mechanical properties in orthotropic symmetry, were determined. The relationships obtained this way were used for mapping of the averaged properties within the volumes filled with cancellous bone in the discretized femoral bones, and assignment of the isotropic properties to the cortical bone. The biomechanical model of the musculoskeletal system of cow hind leg, consistent with anatomical values was then used to carry out the simulation of static load condition, using finite element method. Four simplified schemes were used for comparison with the final mapping: isotropic with the same constant value of volume fraction for cortical and cancellous bone, isotropic with two different constant values of volume fraction for cortical and cancellous bone, isotropic with mapping of the actual volume fraction for cancellous bone and orthotropic for cancellous bone without taking into account the actual orientation of the principal axes. It was shown that only full orthotropic mapping with actual volume fraction and orientation for cancellous bone, together with assigning separate properties for cortical bone allows for obtaining the distributions of stresses and strains consistent with the current state of knowledge.

The developed methodology was designed to predict changes in mechanical properties of bones during functional adaptation under external loads. Obtained experimental results and computer models can also constitute a basic source of information for usage in further specialized studies, including data obtained through high resolution *in vivo* imaging of human bones.

Keywords

femoral bone, cancellous bone, microstructure, mechanical properties, anisotropy, FEM

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