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CORRELATION OF TRABECULAR BONE MECHANICAL PROPERTIES TO ITS MICROSTRUCTURE USING µCT-BASED FE MODELING

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Summary: *FE models of trabecular bone microstructure are used in to assess its apparent mechanical properties. Material model used in FE simulation of compression and tension test is based on Young's modulus of elasticity of the trabecular tissue obtained by nanoindentation of single trabecula. Anisotropic plasticity with kinematic hardening is used in the modeling, where yield stress is calculated according to yield strains of the trabecular bone and Young's modulus given by nanoindentation results. Frictionless boundary conditions are applied to the sample and stress-strain diagram is calculated for each of the sample. Apparent strain of 2% is applied to the free end (both in tension and compression). Results obtained from numerical simulation of the compressive and tensile testing are close to the results obtained experimentally. Importance of proper segmentation of the bone tissue from CT-images as well as quality of the tetrahedral elements, need for use of quadratic shape functions is underlined in the paper. Choice of proper yield criteria, need for anisotropic plasticity and large deformation analysis is discussed as well.*

1. Introduction

To study trabecular bone morphological and material properties it is possible to use high resolution micro Computed Tomography (micro-CT). Material properties of trabecular bone are strongly dependent on the connectivity between the individual trabeculae and their spatial arrangement (Mulder, 2007). Degree of mineralization of trabecular bone increases during development and also plays an important role in its apparent mechanical properties. To study the influence of the structural parameters on mechanical properties of the bone is one of the key issues in bone tissue engineering. Nanoindentation is successfully used to determine Young's modulus of elasticity at the level of single trabecula with high confidence (Chevalier, 2007, Zysset, 1999).

Micro-CT data can be used to reconstruct the complex geometry of the trabecular bone inner structure. The geometry is then discretized using either tetrahedral or hexahedral elements. Voxel FE models, i.e. models where every voxel (cube with vertices defined by four and four pixels in two successive CT-slices) is converted in one hexahedral element have been recently used to assess the uniaxial apparent modulus of trabecular bone (Chevalier, 2007). It is also possible to use these FE models for optimal design of pourous scaffold microstructure

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(Adachi, 2006). These micro-FE models of trabecular inner structure use linear elastic material model for the tissue with Young's modulus of elasticity based on nanoindentation (Zysset, 1999) and therefore are not able to address the post-yield behavior of trabecular bone. There exist only few studies of trabecular bone post-yield bahavior based on micro-CT data and only one was compared to experimental data (van Rietbergen, 1998). In this study, we present a detailed FE model of trabecular bone, based on micro-CT data, with anisotropic plasticity with yield condition based on Young's modulus of elasticity of the tissue obtained from nanoindentation and values of yield strains in compression and tension. This model combined with geometric nonlinearity is capable to reflect the post-yield softening of trabecular bone particularly seen in compression.

2. Methods

Cylindrical samples of trabecular bone from porcine proximal femurs (3 and 5 mm in diameter, n=4) were scanned using in-house micro-CT system (Fig. 1), consisting of X-ray Hamamatsu tungsten microfocus tube (divergent cone beam), rotating table on which the sample is placed and Medipix-2 detector (Platkevic, 2008 and Jakubek, 2008) (300 µm thick Si sensors arranged into 256x256 square matrix).

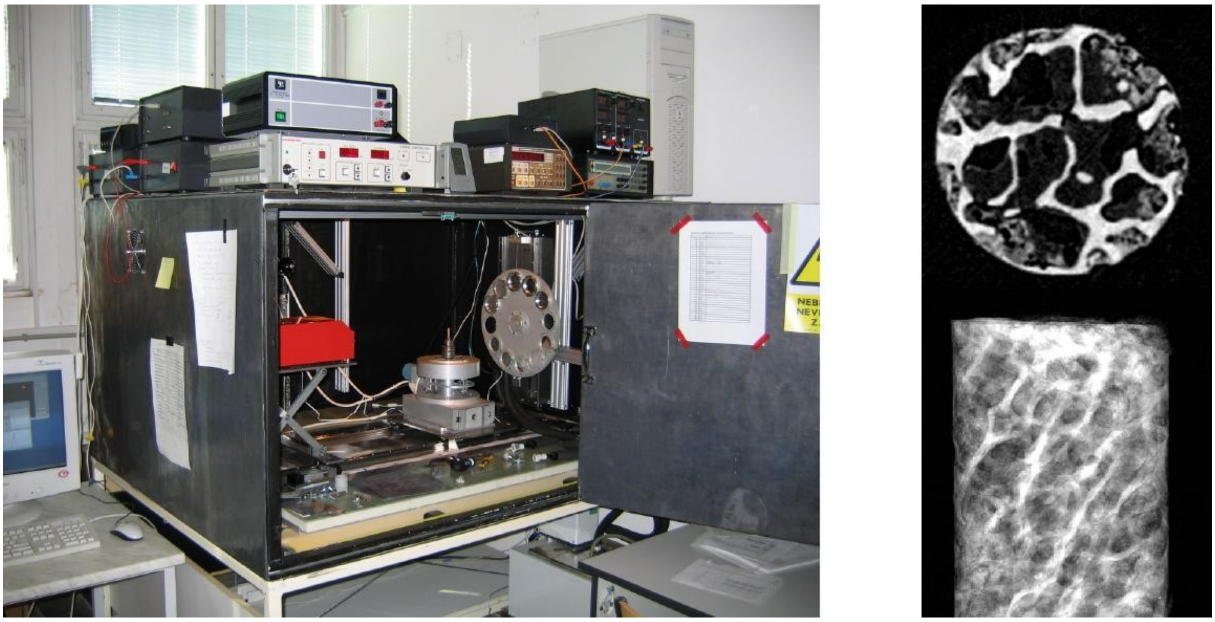

Figure 1.: micro-CT experimental setup and recontruction of bone microstructure

Finite element models of trabecular microstructure were constructed based on the micro-CT images. A fully-automated segmentation algorithm was developed in order to ensure the same procedure for all samples. FE models of the trabecular bone microstructure are developed using either hexahedral (voxel) elements or tetrahedral elements. At this level of structural detail the trabecular bone is isotropic and homogeneous and therefore the material properties in the FE models are same for all the elements in the entire mesh.

Modulus of elasticity of the tissue is determined by nanoindentation. The surface of the sample is prepared by mechanical polishing using a combination of diamond and carbide papers with sub-micron accuracy. Compliance method is used to assess elastic modulus of the tissue from the unloading part of load displacement curve. Because of the viscoelastic material properties the loading is followed by a hold at peak load for 30 s time interval to avoid the creep of the material which is initially higher than the unloading rate.

Region of interest (ROI) with cubic volume 100x100x100 pixels is selected from the volumetric image data. Marching Cubes Algorithm is used to detect the surface of the structure and two comparable FE models are developed for each of the sample from the same ROI: i) tetrahedral FE model, ii) hexahedral FE model. Volumes of the FE models are calculated and compared to get the deviation caused by discretization. Example of the FE mesh using tetrahedral and hexahedral elements is given in Fig. 2.

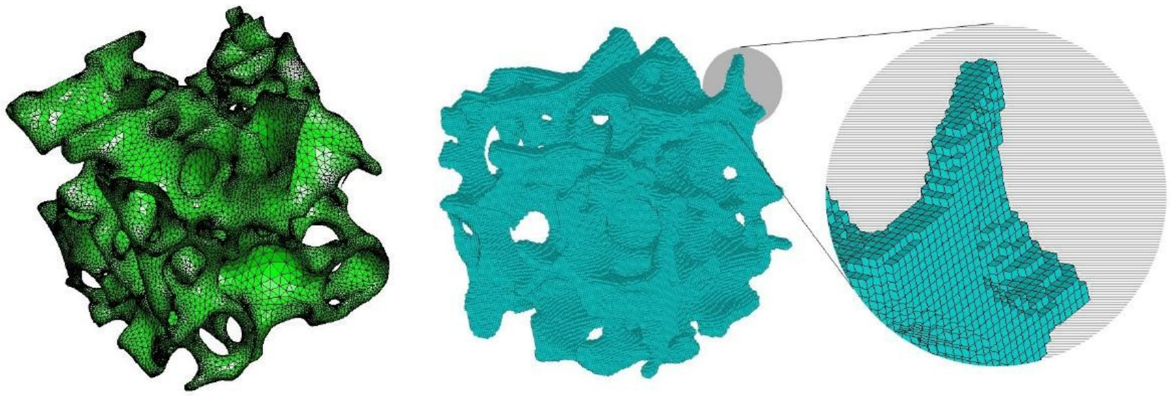

Figure 2.: detailed FE models of trabecular bone microstructure: i) tetrahedral ii) voxel

The FE models are subjected to loading representing 2% compression and 2% tension and overall response is calculated. Stress–strain diagram obtained from the numerical analysis is compared to experimentally determined one. Apparent stress is given by the sum of nodal forces at the fixed end of the specimen (reactions) divided by the cross–sectional area of the sample. Apparent strain is defined by the applied displacement divided by the total height of the sample. These values are calculated at each iteration time which enables for comparison with the experimentally determined stress–strain diagram.

Plasticity model with anisotropic hardening is used with tissue yield stress based on the modulus of elasticity obtained by nanoindentation, yield strains in tension and compression. Values of the yield strains in compression and tension are 0.41% and 0.83% respectively, based on (Kopperdahl, 1999). Hardening slope defined as 5% of the elastic modulus is assumed equal in compression and tension.

Tissue yield stress is calculated based on the elastic modulus assessed by nanoindentation and values of the yield strain (different in compression and tension) according to the formula:

$$\sigma_{yield} = \sqrt{\frac{2}{3} E_{nano}^{trab} \varepsilon_{yield}}$$

where E_{nano} is the modulus of elasticity measured by nanoindentation and ε_{yield} is yield strain. Mean values of the yield stress obtained using this relationship for all the models is 50 MPa in tension and 110 MPa in compression.

3. Results

Numerical analysis considering 2% nominal strain in tension and compression was performed. At this level of strain contact between individual trabeculae does not have to be considered. Displacement controlled analysis was performed with frictionless boundary conditions. Geometrical nonlinearity (large strains) is considered and relationship between apparent stress vs. apparent strain is plotted for each of the sample. The yield strains obtained numerically are compared to experimentally determined values, when the cylindrical samples are mechanically tested using the loading device. Total displacement is applied in 10 load steps and plastic stress increment is monitored. Response of the FE models is calculated for 2% compression and 2% tension.

Computed values are close to the measured values, both in tension and compression. The same stress analysis was also performed without geometrical nonlinearity considered and results clearly show the importance of large deformations to be considered when calculating the yield behavior of trabecular bone. Analysis of the results obtained using either quadratic tetrahedral (10-noded), linear hexahedral (8-noded) and quadratic hexahedral (20-noded) elements was performed.

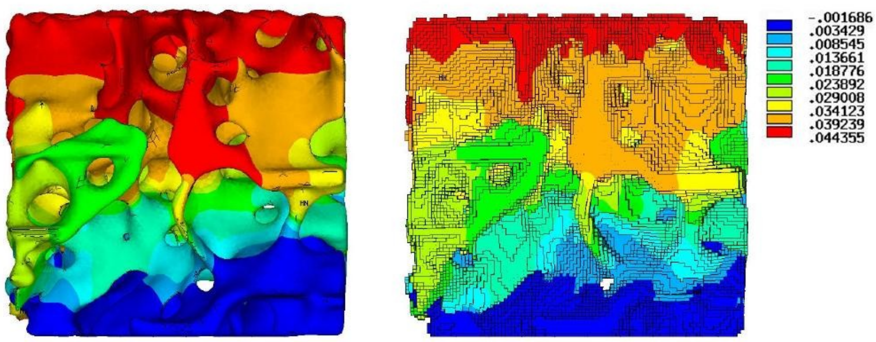

Figure 3.: Quadratic tetrahedral and linear hexahedral models: vertical displacements

The most common criterion used to study failure behavior of trabecular bone is the von Mises criterion (Nagaraja, 2005 and Niebur, 2000). However, trabecular bone possess very distinct yield strains in compression and tension. Therefore, it is essential to apply anisotropic plasticity for failure analysis of trabecular bone. The only publication which uses high-resolution FE model of trabecular bone and refers to the phenomena is work of Niebur et al. Up to now, comparison of different plasticity criteria applied to failure analysis of trabecular bone has not been published.

Apart from the anisotropic plasticity model described earlier von Mises criterion was used and results compared to values obtained using anisotropic plasticity model. Isotropic plasticity is often used for failure analysis of trabecular bone, however, our results show importance of the yield anisotropy of trabecular bone. When using von Mises plasticity with yield stress computed according to plastic strain in tension, results differ by more than 50% for the 2% loading, see Fig. 4.

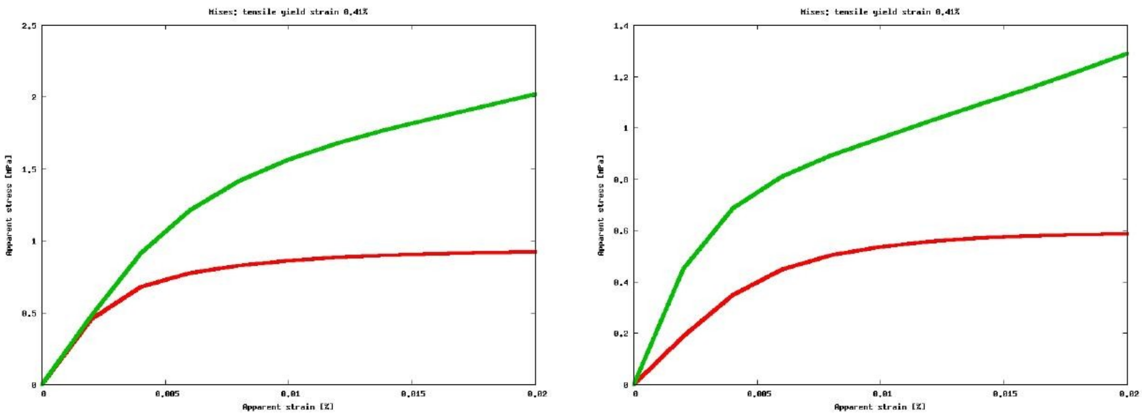

Figure 4.: Apparent stress-strain diagram for 2% compression and vonMises plasticity with yield stress based on yield strain in tension compared to anisotropic plasticity (tetrahedral el)

4. Conclusions

Microfocus X-ray computed tomography is used to create high–resolution FE models of trabecular bone microstructure. Response of the FE model is compared to apparent material properties obtained experimentally using a special loading device. In conclusion, adopted procedures are found to be a robust and precise method to predict the material properties of trabecular bone; provided the trabecular bone structure is segmented properly from the tomographic images. Described procedures are promising for detail analysis of deformation behavior of materials with complex inner structure, e.g. trabecular bone. Results obtained by FE modeling indicate a great importance of the quality of tetrahedral elements, need for second-order elements and proper surface detection when converting the μCT data into surface mesh. In both voxel and tetrahedral meshes the strain distribution is very localized imposing special requirements on the mesh quality. One has to bear in mind that the analyzes were performed considering only 2% strain. For larger strains it would be necessary to consider the self contact between close trabeculae. Considering anisotropic plasticity with kinematic hardening is of great importance even for smaller strain values.

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