APPLICATION OF VISCO-ELASTO PLASTIC MODEL TO HUMAN TRABECULAR BONE BASED ON RESULTS FROM NANOINDENTATION AND VERIFIED BY TIME LAPSE X-RAY MICROTMOTOMOGRAPHY

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SUMMARY
This paper deals with development of a numerical visco-elasto plastic material model for a single human trabeculae and its application on a complex sample. The elastic constants for this model were obtained directly from nanoindentation, remaining ones were determined indirectly from Finite Element Analysis (FEA). Identified material model was used for a Finite Element (FE) model of complex cylindrical sample of human trabecular bone. The geometry of the FE model was obtained from X-ray micro Computed Tomography (µCT). To verify the ability of the material model to describe deformation behavior of trabecular bone a cylindrical sample was incrementally loaded in compression and the deformed microstructure repetitively scanned µCT.

INTRODUCTION
Knowledge of trabecular bone behaviour under loading on macroscopic and microscopic level is very important for the bone quality assessment. For investigation of deformation behaviour of trabecular bone a combination of modern computational method and advanced experimental device can be successfully used. In this study elastic material properties of human single trabeculae were obtained from nanoindentation test by Oliver-Pharr method [1]. Experimentally determined Young’s modulus for single trabeculae should be in range 13-18 GPa [2,3]. Elastic constants obtained from nanoindentation fell into this range and served as the basis for numerical visco-elasto-plastic material model. Remaining material constants were determined by fitting the experimental load-displacement curve to results from the FE model [4]. Identified material model for the single trabeculae was used for a model of trabecular tissue. Geometry of the tissue sample was developed from µCT data of zero deformation state. FE model and real specimen were subjected to loading test with the same boundary conditions (load increments, total load etc.). Deformation behaviour between FEM and experiment was compared.

METHODS
A sample of trabecular bone for the nanoindentation, a 3 mm thick slice was prepared from a human femoral head using a precision saw (Isomet 1000, Buehler). The sample was cleaned in 1% Alconox detergent lotion and grinded using a polishing machine (LaboPol-4, Struers) and diamond grinding discs with grain size 35 and 15 μm and finished with monocrystale diamond suspension with grain size 9, 6, 3 and 1 μm. Final polishing was done using aluminum-oxide suspension with 0.05 μm grain size. For verification of the loading test a cylindrical trabecular bone specimen (3 mm diameter, 10 mm length) was drilled from femoral head. The sample was cleaned of marrow by washing in ultrasonic cleaner and its ends were impregnated with epoxy resin. During the nanoindentation a load and penetration depth of the diamond indenter is measured. Three different loading rates (20, 120, 240 mN/min), three holding times (10, 20, 40 s) and two peak loads (10, 20 mN) were used. The indents with 10 μm grid size (Figure 1) were performed.

Figure 1: Trabecular bone indentation area (left), grid of indents (right).

Multiple indents were made for statistically significant fitting procedure of the FE simulation of nanoindentation. For FE simulations of the nanoindentation test a rotationally axisymmetric plane model was used. The Berkovich pyramid indenter used in the experiment was replaced with an equivalent cone. The sharp tip of the cone was rounded due to the use of nonlinear contact between indenter and specimen. For the diamond nanoindenter a pure elastic material model with known Young’s modulus E=1140GPa and Poisson ratio ν=0.07 was used. The material model with von Mises yield criterion and bilinear isotropic hardening with implicit creep was chosen. For this model remaining material constants must be determined, namely yield stress (σy), tangent modulus (Etan) for plastic properties and four constants for creep properties. These material constants were evaluated by fitting the nanoindentation curves obtained from the FE simulation to experimental ones.
The experimental nanoindentation curves were sampled to obtain values of force and penetration depth to set up individual load steps of the FE simulation. Nanoindentation curves determined from the FE simulation were compared with experimental ones by least squares method.

A special loading device was developed to load the sample incrementally directly in the X-ray shielded case (Figure 2). The sample was loaded up to 4% overall total strain in 0.5% increments. Every deformation state was scanned to obtain the deformed microstructure of the loaded sample. Loading force was recorded using 100 N load cell (U9B, HBM).

Voxel FE model of sample was developed from the projections of the zero deformation state. Because of the computational complexity the model was created using a representative volume (1.5 x 1.5 x 2 mm) from the center of the sample. This model was equipped with the material model obtained from simulation of the nanoindentation.

Table 1: Loading rates and peak forces used in the experiments and resulting elastic constants.

<table>
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<th>curve</th>
<th>loading [mN/min]</th>
<th>force [mN]</th>
<th>E [GPa]</th>
<th>ν [-]</th>
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<td>10</td>
<td>240</td>
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<tr>
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<tr>
<td>8</td>
<td>20</td>
<td>120</td>
<td>18.144</td>
<td>0.2</td>
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</table>

Remaining constants were obtained from FEA of the nanoindentation test. Identified material model for the single trabeculae was used for complex model of trabecular bone sample. Both the model and the sample were compressed up to 4% deformation. Results (field of strains and stresses) from FEA (Figure 3) were compared with results from compression test using µCT scans reconstructed in each load step and image correlation technique.

RESULTS AND DISCUSSION

The material model for the trabecular bone was determined from nanoindentation. Elastic constants (E, ν) directly obtained from the experiment are shown in Table 1.

CONCLUSIONS

Combination of experimental approach and FE modeling enables to investigate the trabecular bone behaviour under loading at micro structural level. Visco-elasto/plastic constitutive model was used to describe deformation behavior of trabecular bone. Constants needed for the material model were determined from nanoindentation curves using FEA. Established material model is suitable for simulation of trabecular bone yielding at different loading conditions; however, more experiments are needed to validate this material model. Real time tomography can be successfully used for the development of complex micro structural FE models and to capture the inner structure collapse during loading test. Knowledge of internal structure deformation in each load step enables to validate the computational analyses.

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REFERENCES