DEVELOPMENT OF VISCO-ELASTO-PLASTIC MATERIAL MODEL FOR HUMAN TRABECULAR BONE USING NANOINDENTATION

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1. Introduction

Knowledge of trabecular bone behaviour under loading is very important for bone quality assessment. For numerical modelling of deformation behaviour of trabecular tissue it is necessary to establish a material model for single trabeculae. For visco-elasto-plastic material model used in this study have to determine eight material constants. Two elastic constants were obtained directly from nanoindentation test by Oliver-Pharr method [1]. Remaining material constants were identified from a Finite Element (FE) simulation of nanoindentation test [2].

2. Material and Methods

2.1 Nanoindentation test

A 3mm thick sample for the nanoindentation experiment was prepared from human (male donor, 72 ages) femoral head using precision saw (Isomet 1000, Buehler). The sample was cleaned in 1% Alconox detergent lotion and then grinded using polishing machine (LaboPol-4, Struers) with diamond grinding discs. The grinding procedure was finished with monocrystale diamond suspension and final polishing was done using aluminum-oxide suspension with 0.05 μm grain size.

During the nanoindentation test a diamond indenter (Berkovich type) was pressed down into the sample surface. Load and penetration depth of the indenter was measured. Different loading rates, holding times and peak loads were applied. Various loading parameters were chosen for statistically significant fitting procedure of the FE simulation. About 300 indents with 10 μm grid size (fig. 1) were performed at different places of the sample (about 20 indents from the same location).

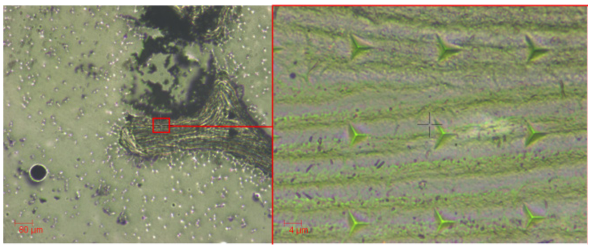

Fig. 1: Trabecular bone indentation area (left), grid of indents (right).

2.2 FE simulation of nanoindentation test

For FE simulation of the nanoindentation test a rotationally axisymmetric plane model was developed. The sharp Bercovich tip was replaced with equivalent cone and rounded due to use of nonlinear contact between the indenter and the sample. For the diamond indenter a pure elastic model with known Young's modulus (E_i=1140GPa) and Poisson's ratio (μ_i=0.04) was used. For trabecular bone material model with von Mises yield criterion and bilinear isotropic hardening with implicit creep was chosen. The model requires determining of eight material constants. Young's modulus (E_{trab}) and Poisson's ratio (μ_{trab}) for elastic part yield stress (σ_y), tangent modulus (E_{tan}) for plastic part and coefficients C_1, C_2 ,C_3, C_4 for implicit time hardening creep using Eq. 1.

$$\dot{\varepsilon}_{cr} = C_1 \sigma^{C_2} t^{C_3} e^{-C_4/T} \qquad (1)$$

Where ε_{cr} is equivalent creep strain, σ is equivalent stress, T is temperature and t is time at the end of a substep. Elastic constants were established directly from experiment, remaining six constants were determined by fitting procedure of nanoindentation curves.

2.3 Fitting procedure

Nanoindentation curves from experiment ware sampled and obtained load values were prescribed to model of indenter in each loadstep. Results of the FE simulation were compared with experimental ones by least squares method and R^2 error was calculated. Initial values of material constants were chosen and modified in each simulation using custom grid optimisation algorithm (described in the flowchart in fig. 2.) to minimalize R^2.

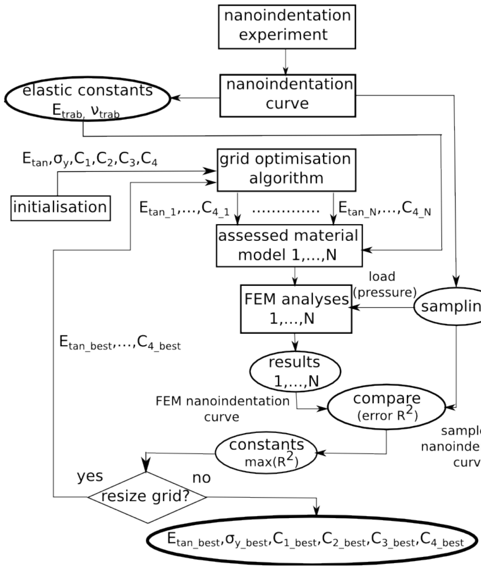

Fig. 2: Flowchart of fitting procedure

3. Results a discussion

Best material constants (E_{tan_best},.,C_{4_best}) for each indentation curve obtained from the optimisation procedure were compared with other resulting constants from curves of same indentation area. Although the indents came from a similar area (10 µm grid size), the identified constant weren't exactly the same and determined appropriate ranges for material model of single trabecular are shown in Tab. 1. This discrepancy can be attributed to several influences (material, experimental, numerical). Trabecular bone is inhomogeneous biological material and its material properties in different locations can significantly vary. Influence should also simplify the numerical model due to countability. Nevertheless, presented optimization scheme is suitable for determination of parameters of visco-elasto-plastic material model for trabecular bone. This material model is needed for large-deformation analyses of trabecular bone [3].

Tab. 1: Resulting constant's ranges

	#1(10/10/20)*	#2(10/10/240)	#3(20/40/20)
E_{avg} [GPa]	13.840	14.486	15.875
μ_{avg} [-]	0.2	0.2	0.2
σ_y [MPa]	110-205	180-240	120-220
E_{tan} [MPa]	1070-1340	950-1300	1100-1600
C_1 * e-13	5.2-8.57	6.2-8.39	7.9-8.3
C_2	3.98-4.87	2.95-3.83	1.54-2.5
C_3	0.65-0.9	0.3-0.54	0.45-0.62
C_4	0.32-0.37	0.36-0.38	0.21-0.27
*#area(peak force [mN]/ holding time [s]/ loading rate [mN/min])			

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