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# MICROSTRUCTURAL MODELS OF TRABECULAR BONE - COMPARISON OF CT-BASED FE MODELS

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**Abstract:** *In the article a detailed comparison of techniques used to develop detailed FE models of trabecular bone microstructure is presented. The FE models are built using a stack of microtomographic images of trabecular bone of 35μm$^3$ spatial resolution. Compression test of a cylindrical sample taken from human proximal femur is virtually performed using FE models developed using different procedures. Effect of improper segmentation (deficiency/excess of bone volume), mesh smoothing, mesh density, use of hexahedral/tetrahedral elements, linear/quadratic shape functions is evaluated in a parametric study. Material model used in the study is based on results from nanoindentation. Obtained elastic properties of the sample are compared to experimental results from compression test.*

**Keywords:** ***Microstructural FE model, mesh quality, segmentation, trabecular bone.***

## 1. Introduction

Precise measurement of bone quality in vivo is important for early diagnosis of osteoporosis and other bone diseases that lead to increase of fracture risk. One of the traditional and widely used methods of diagnosis of osteoporosis is DEXA (Dual-energy X-ray absorptiometry). Although DEXA is the most widely used technique for clinical bone quality measurements, the method itself has serious limitations and it has been shown to be inaccurate. DEXA is not an accurate measurement of true bone mineral density, it is rather a measurement that reflects bone area. Therefore DEXA can overestimate the bone mineral density for taller subjects and underestimate the bone mineral density of smaller subjects. Moreover, bone strength is not influenced only by the density of the tissue, but also by the spatial arrangement of the individual trabeculae and the quality of their interconnections.

It has been shown (Verhulp et al., 2008, Bourne et al., 2004) that accurate micro-FE models of trabecular bone structure are a promising technique that accounts for the spatial arrangement of trabeculae and the quality of their interconnection and can be used for precise bone quality assessment. The ability of the microstructural models to predict the overall mechanical properties is influenced by several factors, namely the tissue material model and precision of the techniques used in the process of development of the FE model. This article aims at investigation of the influence of segmentation methods, methods used to develop the micro-FE models, used finite elements, quality of the FE mesh on resulting overall mechanical properties as a measure of bone quality.

## 2. Materials and methods

The FE models were developed based on a sample of human trabecular bone scanned in a micro computed tomography (μCT) scanner. A cylindrical trabecular bone specimen (5 mm diameter, 10 mm length) was drilled from a human femoral head (70 year old male) and then cleaned of marrow by washing in ultrasonic cleaner (Bandelin Sonorex Digitex, Berlin, Germany). Ends of the sample were impregnated with epoxy resin. The sample was fixed in a special micro loading devices with a frame made of a material with very low X-ray absorption. The loading device with the mounted sample was placed on a rotating table in a shielded case of μCT device. Tomographic scanning was performed using X-ray tungsten microfocus tube with divergent cone beam and a hybrid silicon pixel detector

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(Medipix-2). For the measurement a 80 μA tube current and 45 kV acceleration voltage were used. Tomography of the undeformed specimen was acquired with 0.5º increments up to total 360º rotation.

After the first tomography the sample was loaded up to 4% overall strain in 0.5% increments. Between the strain increments the specimen was allowed to relax for 20 min. Applied force was measured during the whole experiment using a 100 N load cell (U9B, HBM GmbH, Darmstadt (Germany). Every strain increment has been tomographically captured using 180 projections in 1º increments.

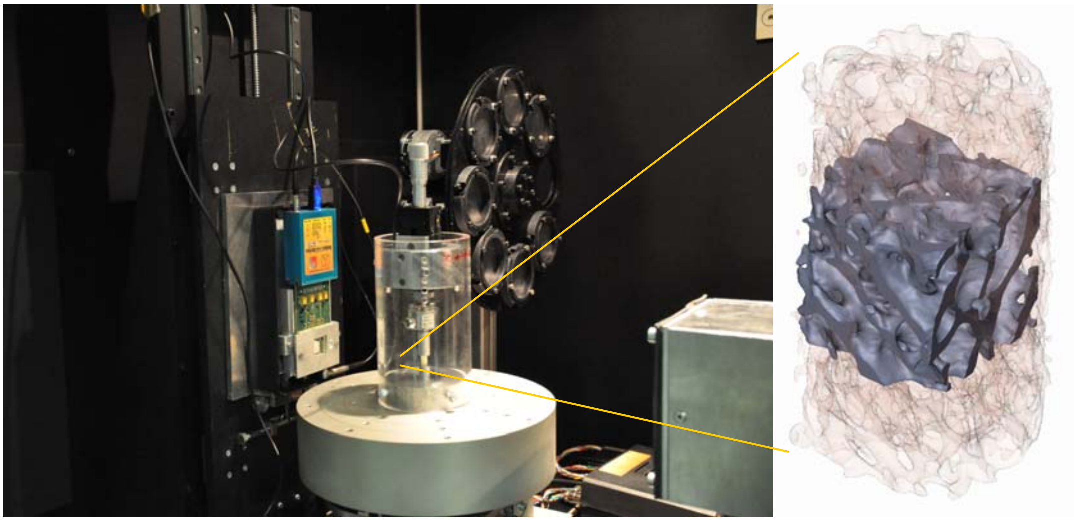

*Fig. 1: Experimental setup in the micro-CT and developed FE model of the microstructure.*

Stress-strain curve of the experiment has been developed. Stress has been calculated as the applied force divided by the full-size cross-sectional area and strain has been assessed from the displacement of the loading platens computed from the X-ray projections. From the stress-strain curve Young's modulus of elasticity in the direction of the applied load has been computed: $E_{z.meas}$ = 2.102 GPa.

### 2.1. Influence of excessive tissue segmentation

Apart from the modulus of elasticity at the tissue level, segmentation plays an important role on resulting mechanical properties of the sample. As a reference, properly segmented images (half-maximum height protocol and the automatic and adaptive iterative thresholding procedure) were taken. As improperly segmented images the binary images containing the properly segmented tissue were volumetrically grown to make the total TB/TV ratio larger. Three increments were tested to give four FE models (base, grow1, grow2, grow3). The difference in the volume of the FE models is depicted in Fig. 2.

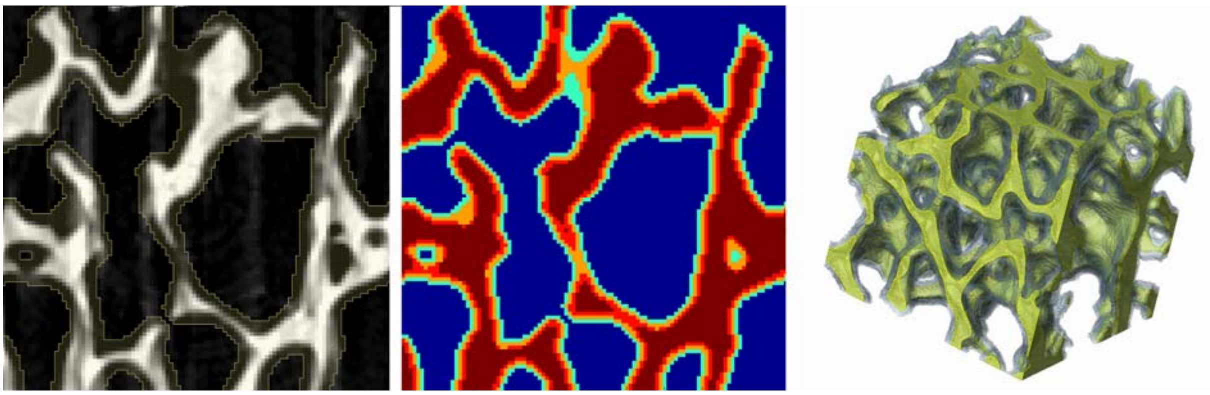

*Fig. 2: Effect of inaccurate segmentation shown in a selected micro-CT image and resulting model.*

### 2.2. Tetrahedral vs hexahedral models

The properly segmented images were taken as the base for development of all the FE models. To compare hexahedral and tetrahedral elements used to fill the volume of the sample four voxel models with different size of the voxels (1x1x1, 2x2x2, 4x4x4 and 8x8x8 pixels were used to define a single voxel) and five tetrahedral models with different density of the FE mesh (total number of nodes

65938, 83122, 150183, 222071, 321748). Apart from the linear tetrahedral elements, models discretized using quadratic tetrahedral elements were tested (total number of nodes 449853, 559125, 980689, 1510082, 2194965).

### 2.3. Small deformation vs large deformation analysis

Selected models (voxel_1x1x1, lin_tetra_222071, quad_tetra_559125) were compared in both small deformation and large deformation analysis. Since the material properties at the tissue level were considered linear elastic, small deformation analyses were computed in one load step.

### 2.4. Comparative simulation

To assess the influence of the abovementioned parameters on the ability of the resulting FE models to predict the overall elastic material properties of the trabecular bone a virtual compression test of the micro-FE models have been carried out. Young's modulus of the trabecular bone tissue (15 GPa) was assessed previously by nanoindentation. The sample was loaded in three perpendicular directions to assess the orthotropic elastic constants. The z-direction was assumed to be the direction of loading, y-axis was in the direction of the X-ray beam and x-direction was perpendicular to the direction of the X-ray beam.

The bottom side of the specimen was fixed in all spatial directions and the upper side was prescribed a uniform displacement in z-direction. Magnitude of the applied strain was 1%. Elastic properties were calculated as the applied force (calculated as the sum of reactions at the fixed end) divided by the cross-sectional area of the sample.

Apart from the orthotropic elastic properties ($E_x$, $E_y$, $E_z$) also the maximal values of principal stresses were compared for all the load cases.

## 3. Results

As the most appropriate model the most dense tetrahedral model with quadratic shape based on the original image data (no downsampling) was taken. The orthotropic material properties were computed using the reaction forces computed in the constrained part of the sample. Resulting Young's modulus of elasticity in the direction of applied load was computed for this reference model as $E_{z.FEM.}$=.1.925 GPa (SD.=.0.177 GPa). The elastic constants predicted by the voxel models were in good correspondence with the experimentally assessed value in case of the voxel model with no downsampling used. The base model underestimates the Young's modulus ($E_{z.voxel.}$=.1.858 GPa, SD = 0.244 GPa). All FE models give good results for estimation of elastic properties up to 4x4x4 downsampling of the original volumetric image data.

*Tab. 1: Overall material properties for selected FE models.*

| *Model name* | *$E_x$ [GPa]* | *$E_y$ [GPa]* | *$E_z$ [GPa]* | *$\sigma_{1.max}$ [MPa]* | *$\sigma_{3.min}$ [MPa]* |
|---|---|---|---|---|---|
| *voxel shrink* | *0.6328* | *1.286* | *1.225* | *98.657* | *-49.154* |
| *voxel base* | *1.063* | *1.971* | ***1.858*** | *76.142* | *-44.113* |
| *voxel grow 2x2x2* | *1.615* | *2.268* | *2.530* | *42.173* | *-39.628* |
| *voxel grow 4x4x4* | *1.902* | *2.840* | *3.178* | *34.123* | *-33.143* |
| *150183_linear_tetra* | *1.160* | *2.221* | *1.911* | *118.576* | *-64.154* |
| *980689_quadratic_tetra* | *1.167* | *2.231* | *1.813* | *125.225* | *-77.321* |
| *222071_linear_tetra* | *1.186* | *2.267* | *1.931* | *124.341* | *-77.123* |
| ***1510082_quadratic_tetra*** | ***1.153*** | ***2.231*** | ***1.925*** | ***128.875*** | ***-79.342*** |

Stresses predicted by the FE models varies more significantly that the predicted elastic properties. To make the postprocessing easier to compare only the central part of the FE model was taken into account and stresses were computed at the same trabecula. Taking as the reference model again the largest tetrahedral model with quadratic shape functions we can see that the voxel models significantly underestimate the stresses in the trabecular structure.

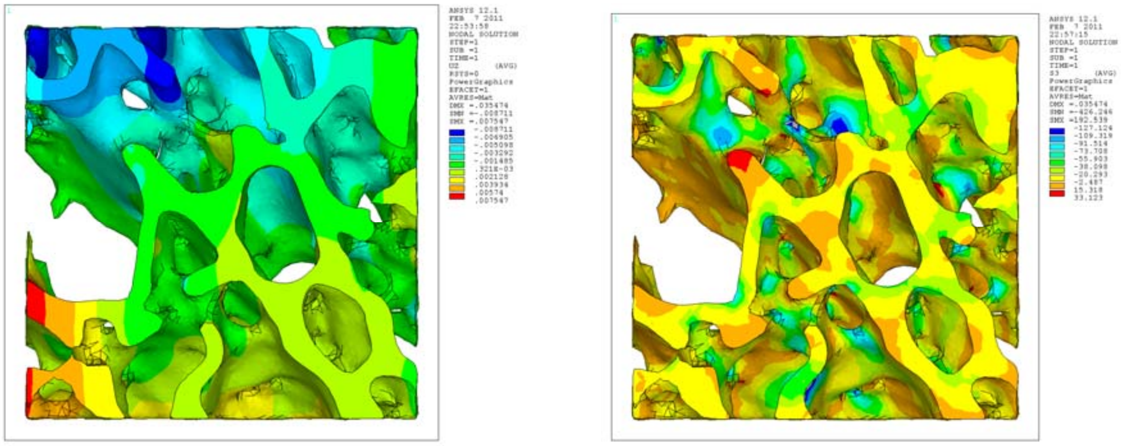

*Fig. 3: Exemplary results of μFE analysis – linear tetrahedral model (150183 nodes) showing displacements in the vertical direction and third principal stresses in medial plane of the cubic sample.*

## 4. Conclusions

Microstructural FE models provide an excellent tool for prediction of elastic properties of trabecular bone. This study shows that effective elastic modulus of trabecular bone can be predicted using micro-FE models with tissue properties obtained from nanoindentation. Also the deformed mesh for the tetrahedral elements showed a good correspondence with the reconstructed CT scans with the same applied deformation.

As the best predictor of the deformation behavior of trabecular bone, FE models developed using tetrahedral elements with quadratic shape function should be considered. The density of the FE mesh should be evaluated first in a parametric study. The voxel models provide good results for orthotropic elastic properties, however, a great care must be paid to proper segmentation. Under or over segmentation can affect the results significantly.

On the other hand, for estimation of the elastic properties only, the models can be developed based on downsampled images. However, if stresses and strains in the microstructure are to be evaluated this downsampling is not desirable. In this case, again, the quadratic tetrahedral elements give the best results.

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Medipix collaboration at: http://medipix.web.cern.ch/MEDIPIX.