22nd International Conference
ENGINEERING MECHANICS 2016
Svratka, Czech Republic, 9 – 12 May 2016

ESTIMATION OF ORTHOTROPIC MECHANICAL PROPERTIES OF HUMAN ALVEOLAR BONE

P. Marcián*, P. Lošák, J. Kaiser***, L. Borák******

Abstract: *In computational simulations of biomechanical problems, cancellous bone has often been modeled as a homogeneous, linear isotropic or orthotropic continuum. However, a need for higher modeling level is topical when it comes to simulations related to the dental implantology. The purpose of this study is to analyze cancellous bone specimens from alveolar bone, to estimate their apparent mechanical properties (assuming linear orthotropy) and to discuss their applicability in computational simulations of dental implantology problems. For this purpose, four cancellous bone segments from the first premolar region of human mandible were scanned on μCT device and subsequently analyzed using methods of biomechanical finite element simulations. In combination with the standard equations of mechanics of materials for calculating beam stiffness, nine independent elastic constants of linear orthotropic material model were determined for all analyzed segments. The results confirmed that the elastic constants are strongly dependent on the quality of the analyzed segment and its topology. It was concluded that this type of material model should be used only in cases where the stresses and strains in the bone itself are not of main concern. Otherwise, the information about the histomorphometry data should be inseparable part of each such model.*

Keywords: Bone, Mandible, FEM, micro-CT.

1. Introduction

Bone tissue is a complex living structure that undergoes a continual change of topology during the lifetime. The change of topology (known as a bone modeling or remodeling) is believed to be driven by a mechanical stimulus and a typical example of this phenomena is the gradual resorption of underloaded alveolar ridge in the mandible. The underloading is usually caused by the absence of tooth or teeth in this region and might be eliminated by a dental implant therapy. After the implant is placed into the bone, the surrounding tissue will be stimulated by the mechanical loading and the affected bone will start to remodel.

Dental implant therapy is an interdisciplinary task that includes not only medical treatment itself but also pre-medical planning and preparations, among others using methods of biomechanics. A powerful tool that can be used for development of dental implants, analysis of the treatment prospects or estimation of the dental implant performance is the computational simulation. Nowadays, the most frequent way of the computational simulation is based on the finite element method. This method itself became routine; however, the input data and some components of the computational models in biomechanics are still debatable, not fully established or even unknown. Widely discussed is the model of material of living tissues. For instance, the bone in the aforementioned example, and especially its cancellous part, has often been modeled as a homogeneous, linear and isotropic or orthotropic continuum. Such approach may be fully sufficient and justifiable in some cases; however, in case of simulations related to the dental

* Ing. Petr Marcián, PhD.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic; CZ, marcian@fme.vutbr.cz

** Ing. Petr Lošák, PhD.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic; CZ, losak@fme.vutbr.cz

*** Prof. Jozef Kaiser, PhD.: Institute of Physical Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic; CZ, kaiser@fme.vutbr.cz

**** Ing. Libor Borák, PhD.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic; CZ, liborborak@seznam.cz

implantology (e.g. including implant performance analyses, bone remodeling predictions etc.), the level of cancellous bone modeling is extremely important and using such simplifications might be inappropriate. Efforts to increase this level is evident and highly topical.

The aim of this study is to analyze mandibular cancellous bone specimens, estimate their apparent mechanical properties (assuming linear orthotropy) and discuss their applicability in the computational simulations of dental implantology problems.

2. Methods

Four cancellous bone segments from the first premolar regions of four human mandibles were subjected to the micro-computed tomography (μCT; GE vtomexL240 μCT device, General Electric, USA). The bone segments were selected to represent typical location for dental implant placements. The segments were of maximum possible cubic shape (5x5x5 mm) with the orientation as indicated in Figure 1.

The μCT images (voxel size of 20 μm) were first analyzed in Image J software (Schneider et al., 2012) using software extension Bone J (Dougherty et al., 2007) and basic histomorphometric parameters were obtained. Bone volume fraction (BVF), mean trabecular thickness (Tb.Th) and mean trabecular spacing (Tb.Sp) were adopted as representative characteristics of the segments. The images were further processed in STL Model Creator software (Marcián et al., 2011) to obtain 3D models of the segments (Fig. 2). The models were subsequently imported into the FEM software ANSYS 16.2. The models were meshed by quadratic tetrahedral elements SOLID187 with a general element size of 0.02 mm. At the micro level, the bone is assumed to be homogeneous, linear and isotropic with a typical values of Young's modulus (E) and Poisson's ratio (μ) of 15 GPa and 0.3, respectively (Shefelbine et al., 2005).

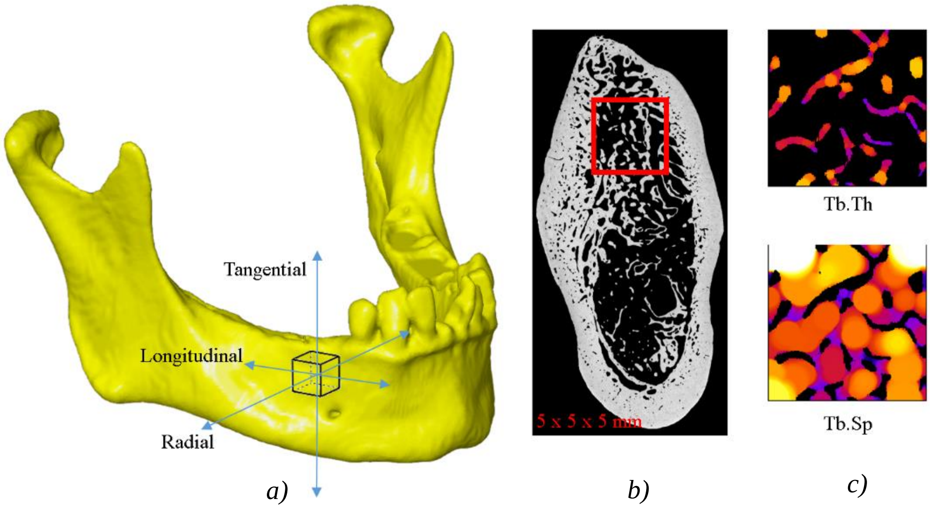

Fig. 1: Bone histomorphometry analysis: a) Segment position and orientation; b) μCT image of the mandible section with highlighted position of the segment; c) Typical image from the analysis in Image J.

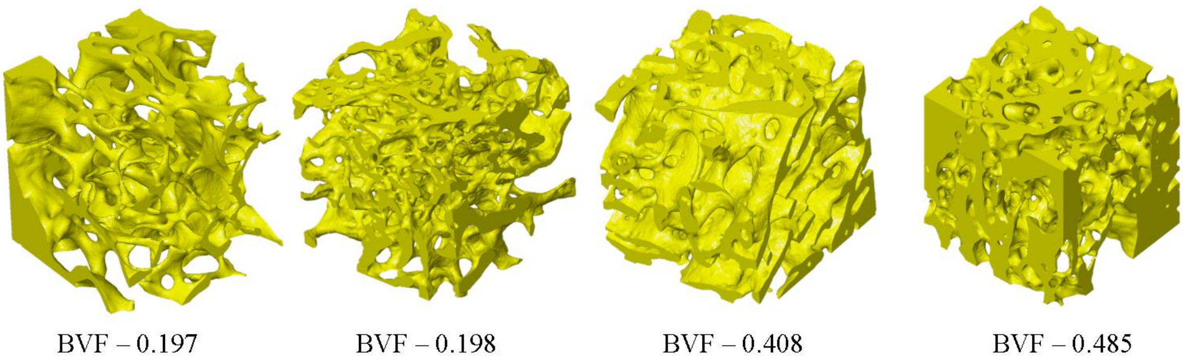

Fig. 2: Bone segment models created from the μCT images.

Nine independent elastic constants of the orthotropic material representing the apparent mechanical properties of each cancellous bone segment were estimated from six computational experiments: 1. Three tensile tests for the estimation of the Young's moduli and major Poisson's ratios (E_x, E_y, E_z, μ_{xy}, μ_{yz}, μ_{zx}); 2.

Three shear tests for the estimation of the shear moduli (G_{xy}, G_{yz}, G_{zx}). Each computational test was performed as indicated in Figure 3 and the elastic constants were calculated using Eq. (1) through (3). In those equations, F_i is a calculated reaction force [N], F_j is a loading force [N], u_i is a predefined displacement [mm], u_j is a calculated displacement [mm], l_i is the segment dimension [mm], S_i is the segment cross-section area [mm^2] and J_i is the segment second moment of area [mm^4]. Indices i and j represent directions x, y and z. As for the shear modulus and Poisson's ratio, index ij represent any combination of directions x, y and z. Therefore, G_{ij} is the shear modulus in direction j on the plane with the normal in direction i and μ_{ij} corresponds to the contraction in direction j when the extension is applied in direction i. Eq. (1) and (2) follow the classical mechanics of materials method for calculation of bar elongation and transverse contraction. Eq. (3) is derived from the formula for calculating the deflection of the Timoshenko cantilever beam. The shear coefficient κ_{ij} for the rectangular section is dependent on the Poisson's ratio and can be calculated using Timoshenko's expression (Eq. (4)).

$$E_i = \frac{F_i \cdot l_i}{S_i \cdot u_i} \qquad (1) \qquad \mu_{ij} = \frac{u_j \cdot E_i \cdot S_i}{l_i \cdot F_i} \qquad (2) \qquad G_{ij} = \frac{F_j \cdot l_i}{\kappa_{ij} \cdot S_i \cdot \left(u_j - \dfrac{F_j \cdot l_i^3}{3 \cdot E_i \cdot J_i} \right)} \qquad (3)$$

$$\kappa_{ij} = \frac{5 \cdot (1 + \mu_{ij})}{6 + 5 \cdot \mu_{ij}} \qquad (4) \qquad \frac{\mu_{ij}}{E_i} = \frac{\mu_{ji}}{E_j} \qquad (5)$$

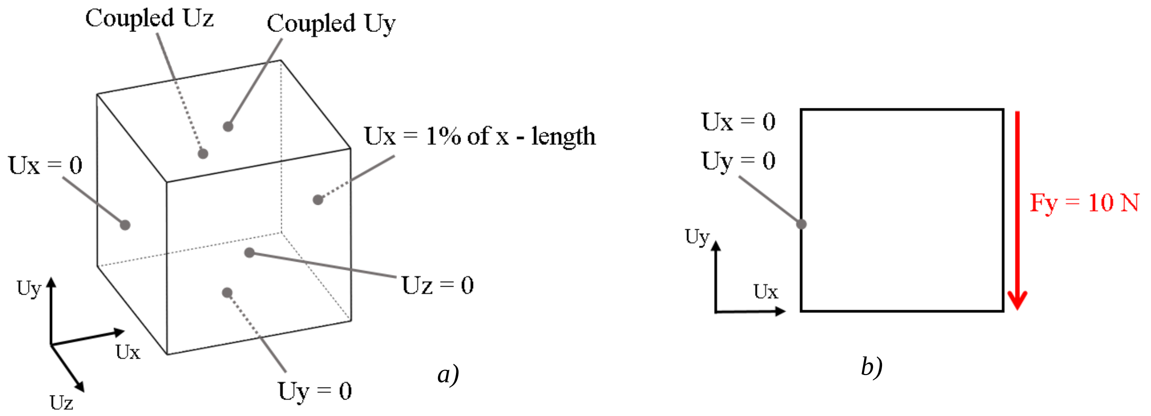

Fig. 3: Computational experiment setting: a) E_x and μ_{xy} calculation; b) G_{xy} calculation.

Prior the computational experiments on the cancellous bone segments, the methodology (especially the calculation of the shear moduli) were tested on the fully homogeneous cube with an acceptable accuracy (maximum error of 5%). To increase the credibility of the results, the minor Poisson's ratios (μ_{yx}, μ_{zy}, μ_{xz}) are also calculated and tested whether the relations in Eq. (5) is satisfied.

3. Results

Results of the histomorphometry analysis are shown in Figures 4. The Young's moduli, major Poisson's ratios and shear moduli for all bone segments are presented in Figures 5. The minor Poisson's ratios were checked using the expression in Eq. (5) and the calculated values differ from the theoretical ones by a maximum of 0.5 %.

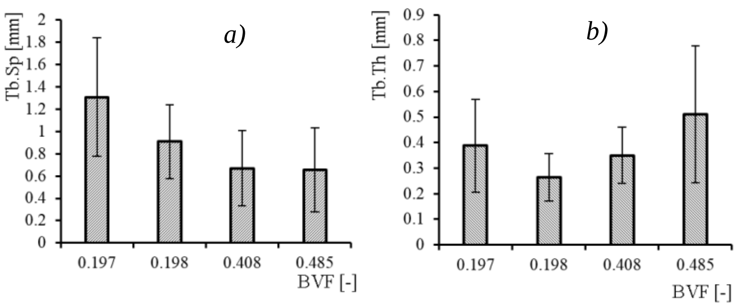

Fig. 4: Histomorphometry analysis results: a) Trabecular bone spacing; b) Trabecular bone spacing.

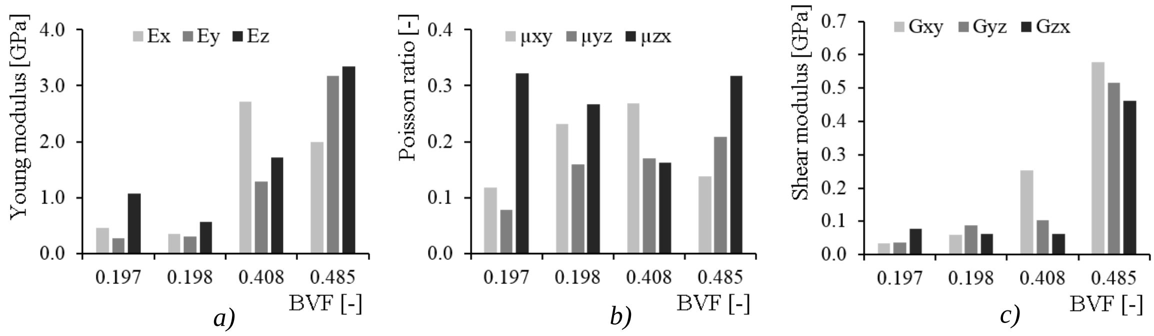

Fig. 5: Computational experiment results: a) Young's moduli E_i; b) Major Poisson's ratios μ_{ij}; c) Shear moduli G_{ij}.

4. Discussion

The calculated elastic constants are strongly dependent on the quality of the analyzed segment. The specific values are consistent with those presented in (van Eijden et al., 2006); however, authors of the referred paper studied different part of human mandible (mandibular condyle) and did not provide constants for bone in the vicinity of teeth. The results indicate that the higher the BVF, the higher the apparent Young's modulus. Alternatively, similar link might be seen between the apparent Young's modulus and Tb.Th. For the precise quantification of these relationships, much larger statistical data set would be required. This faces difficulties with suitable specimen acquisition. However, the variability of the results that depend on various histomorphometric parameters indicates that using homogeneous, linear and orthotropic material model in computational simulations related to mandibular cancellous bone might be extremely untrustworthy if the information about the histomorphometry data are not provided (and if they do not correspond with the actual bone under consideration). The segments were not analyzed for the principal material directions in this study; however, the necessity of having information about the principal material directions for the computational simulation using the orthotropy is obvious.

5. Conclusion

It is evident that using homogeneous, linear and orthotropic material model in the computational simulations related to cancellous bone is precarious and should be used only when the cancellous bone is not of the main concern. If the cancellous bone is analyzed for the effect of the interaction with dental implants, higher level of modeling is strongly advised to be adopted. Typical example of higher level in this case might be using detailed 3-dimensional model of the cancellous bone structure. Although this approach is more complex in terms of topology definition and much more computational time consuming, the results would be much more trustworthy than using simplified continuum. This approach is becoming powerful part of the patient-specific concept not only in biomechanics but in general.

Acknowledgement

The research was supported by the Czech Science Foundation by grant No. 16-08944S.

References

Dougherty, R. & Kunzelmann, K. (2007) Computing local thickness of 3D structures with ImageJ. Microscopy and Microanalysis, 13, pp. 1678-1679.

Marcián, P., Konečný, O., Borák, L., Valášek, J., Řehák, K., Krpalek, D. & Florian, Z. (2011) On the Level of Computational Models in Biomechanics Depending on Gained Data from Ct/Mri and Micro- Ct, in: MENDEL 2011 - 17th International Conference on Soft Computing. 1. Brno: Brno University of Technology, pp. 255-267.

Schneider, C.A., Rasband, W.S. & Eliceiri, K.W. (2012) "NIH Image to ImageJ: 25 years of image analysis". Nature Methods, 9, pp. 671-675.

Shefelbine, S.J., Simon, U., Claes, L., Gold, A., Gabet, Y., Bab, I., Müller, R. & Augat, P. (2005) Prediction of fracture callus mechanical properties using micro-CT images and voxel-based finite element analysis. Bone, 36, 3, pp. 480-488.

van Eijden, T. M., van der Helm, P. N. , van Ruijven, L. J. & Mulder, L. (2006) Structural and mechanical properties of mandibular condylar bone. Journal of Dentistry Research, 85, 1, pp. 33-37.