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APPARENT YOUNG'S MODULUS OF HUMAN CRANIAL CANCELLOUS BONE

Votava T.[*], Marcián P.[**], Borák L.[***], Fuis V.[†], Zikmund T.[††], Kaiser J.[†††], Wolff J. [‡]

Abstract: *This study investigates the biomechanical behavior of cancellous bone in the os occipitale through finite element modeling. Utilizing micro-computed tomography scans, 47 bone segments were analyzed, and their apparent Young's moduli of each segment were determined in three orthogonal directions. The results revealed strong directional dependencies of Young's modulus on bone volume fractions. In contrast, non-directional dependency exhibited a weaker correlation, indicating an orthotropic elasticity. The derived correlation equations offer an efficient means to describe cancellous bone in cranial biomechanical simulations, especially when a detailed trabecular representation is impractical.*

Keywords: Mechanical properties, skull, cancellous bone tissue, FEM.

1. Introduction

In cases of head injury or disease, irreversible damage to bone tissue can occur. In such circumstances, it becomes necessary to replace the missing bone tissue with a reconstruction plate, which is then secured to the surrounding bone using fixation screws. Biomechanical assessment of the reconstruction plate and fixation screws can be accomplished through computational modelling, often employing the finite element method (FEM) (Marcián et al., 2019). For FEM solutions, understanding the mechanical properties of cranial bone tissue is essential. Currently, when considering the mechanical interaction of a reconstruction plate or fixation screw with cranial bone tissue, cancellous bone tissue is typically modeled as a homogeneous continuum. While it's feasible to create computational models with a more precise representation of cancellous bone trabeculae at the micro level using micro-computed tomography (μCT) imaging, this approach is time-consuming. Utilizing a homogeneous model with a constant apparent Young's modulus serves as a practical compromise, providing satisfactory results. The objective of this study is to establish the correlation between the apparent Young's modulus of the skull's cancellous bone tissue and the bone volume fraction (referred to as BV/TV) through computational modelling.

* Ing. Tomáš Votava, Dis.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, 200956@vutbr.cz

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

*** Ing. Libor Borák, PhD.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, xmborak01@vutbr.cz

† Assoc. Prof. Vladimír Fuis, PhD.: Centre of Mechatronics – Institute of Thermomechanics of the Czech Academy of Sciences – branch Brno and Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, fuis@fme.vutbr.cz

†† Assoc. prof. Tomáš Zikmund, PhD.: Central European Institute of Technology, Brno University of Technology, Kolejní 2906/4; 61 200, Brno; CZ, tomas.zikmund@ceitec.vutbr.cz

††† Prof. Jozef Kaiser, PhD.: Central European Institute of Technology, Brno University of Technology, Kolejní 2906/4; 61 200, Brno; CZ, jozef.kaiser@ceitec.vutbr.cz

‡ Prof. Jan Wolff, PhD.: Department of Dentistry and Oral Health, Aarhus University, Aarhus, Denmark, Vennelyst Boulevard 9; DK-8000 Aarhus C, DK, jan.wolff@dent.au.dk

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2. Methods

The correlation between the Young's modulus of cancellous bone tissue in the skull and the bone volume fraction (BV/TV) can be established by conducting computational tension/compression tests on a series of bone segments. Through these tests, the apparent moduli for each segment are calculated and then correlated with the corresponding BV/TV value (Fleps et al., 2020). Models created for this purpose utilize trabecular structure data acquired from micro-CT scans.

2.1. Model of Geometry

In this study the *os occipitale* of a human skull was cut into 5 block segments (Fig. 1) using surgical saw. Initially, these segments were measured using a micro-computed tomography scanner (GE phoenix v|tome|x L240, GE Sensing & Inspection Technologies GmbH, Wunstorf, Germany) with a voxel size of 25 μm × 25 μm × 25 μm. Subsequently, image processing and thresholding methods were applied to digitize data, capturing the detailed geometry of each segment, including trabecular structures. For the image processing, the STL Model Creator application proposed by Marcián et al. (2011) and scripted in Matlab software (Matlab 2012, MathWorks, USA) was employed. Five block segments were discretized into 47 segments with dimensions of 7.2 mm x 6.75 mm x 3.6 mm (Fig. 1), geometry of each segment was then discretized to generate computational models in Ansys software (ANSYS Academic Research Mechanical, Release 17.2; Swanson Analysis Systems Inc). Based on the digitized data, the BV/TV value was calculated for each segment.

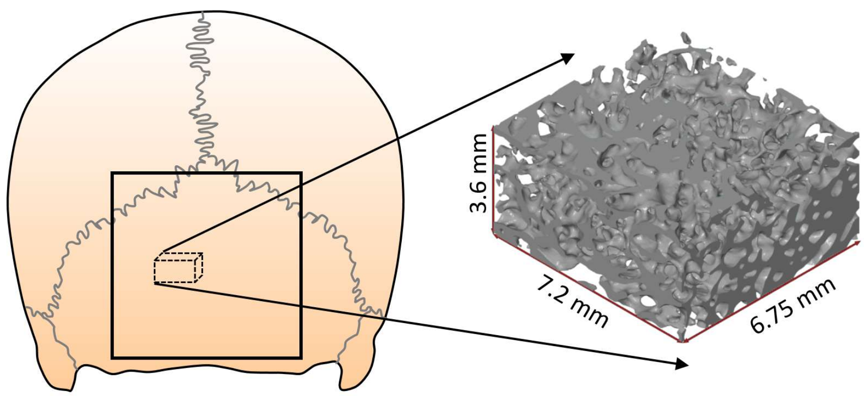

Fig. 1: a) Solved area on the cranial bone - os occipitale; b) micro structure of cancellous bone tissue.

Each segment consisted exclusively of cancellous bone tissue (i.e. no cortical bone was included). Due to limitations in image processing, certain trabeculae within the modeled segments appeared disconnected from the remaining cancellous bone tissue. These small isolated parts were removed and not considered in subsequent calculations or in the measurements of bone volume fraction. For discretization tetrahedron quadratic element was used, each segment was discretized into approximately 1 200 000 elements. The approximate number of nodes was 2 500 000 for each segment.

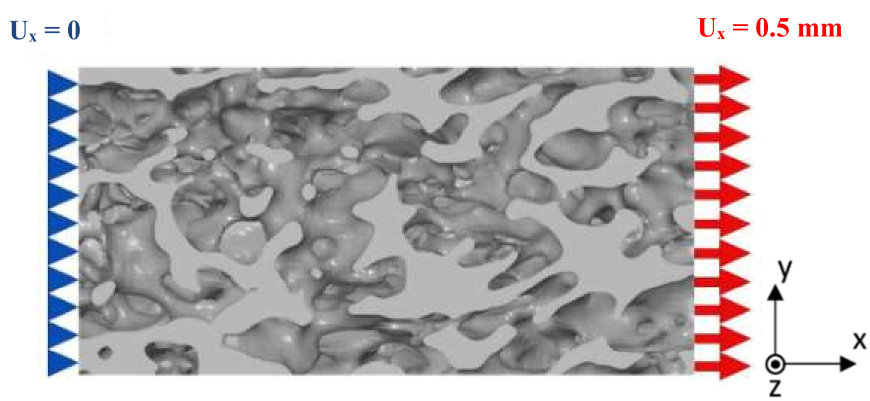

Fig. 2: Boundary and load conditions (Note: Conditions only for the tensile test in X-direction is shown. Conditions for the tests in Y- and Z-directions are analogous.).

2.2. Boundary conditions

To simulate a tensile test, each segment was subjected to loading in three directions parallel to the coordinate axes shown in Fig. 2 (Ševeček et al., 2019). The load was displacement-driven; specifically, one side of the segment was elongated in a particular direction by 0.5 mm while the other side was fixed in the same direction (u = 0 mm) as shown in Fig. 2.

2.3. Material model

In this study, trabeculae in the cancellous bone tissue were modeled as a homogeneous, isotropic, linear-elastic material represented by two material parameters: Young modulus (E) and Poisson ratio (μ). The applied values are $E = 15$ *GPa* (Rho, 1993) and $\mu = 0.3$ *[-]*.

2.4. Determination of apparent Young's modulus

The apparent Young's modulus of cancellous bone represents its effective stiffness. It is determined by applying Hooke's law, considering a homogeneous distribution of the bone tissue within the bone volume:

$$\sigma = E \cdot \epsilon \Rightarrow E = \frac{F \cdot l}{S \cdot u}, \tag{1}$$

where F is the normal force acting in the volume in the loaded direction (calculated as a resultant reaction force in constraints in the FE model), l is the length of the segment in the loaded direction, S is the area of the cross section parallel to the loaded direction and u is the given displacement.

Apparent Young's moduli for all segments in all three directions are presented in Fig. 3 (blue symbols). Using the least square method, four relationships in a commonly-used power form $E = b + c \cdot (BV/TV)^d$ were determined; specifically, three sets of constants b, c and d were calculated to derive three direction-dependent equations (Eqs. (2) through (4)), along with one set of constants for a non-directional dependency (5). For each relationship, coefficient of determination R^2 was calculated. The relationships are visualized in Fig. 3 as well. Data are available at the link: 10.5281/zenodo.10635546.

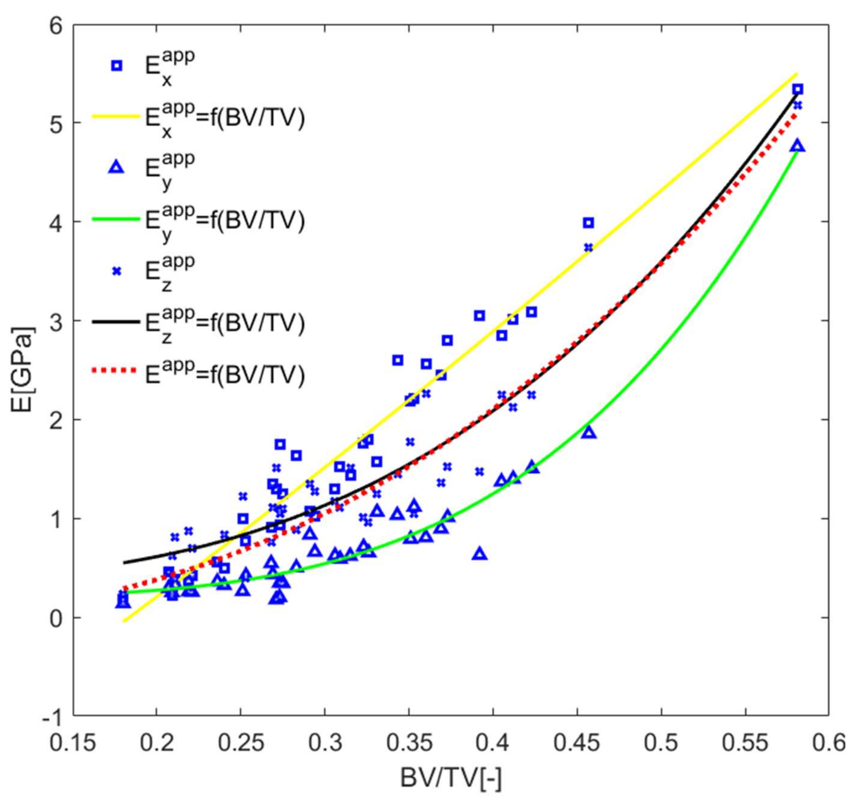

Fig. 3: Relationship between apparent Young's modulus and BV/TV.

$$E_x^{app} = 13.98 \cdot \left(\frac{BV}{TV}\right)^{1.14} - 2.02\,[GPa];\ R^2 = 0.95 \quad (2)$$

$$E_y^{app} = 37.86 \cdot \left(\frac{BV}{TV}\right)^{3.92} - 0.20\,[GPa];\ R^2 = 0.96 \quad (3)$$

$$E_z^{app} = 22.81 \cdot \left(\frac{BV}{TV}\right)^{2.82} - 0.37\,[GPa];\ R^2 = 0.87 \quad (4)$$

$$E^{app} = 18.41 \cdot \left(\frac{BV}{TV}\right)^{2.35} - 0.04[GPa];R^2 = 0.68 \quad (5)$$

While substituting BV/TV values near zero into Eqs. (2) through (5) would produce negative Young's moduli, practical calculations necessitate constraining the validity of these equations. Thus, realistic values of Young's modulus can be obtained by applying the equations only within the BV/TV range of *(0.18; 0.58)*.

3. Conclusions

Strong correlations ($R^2 > 0.85$) were observed between the apparent moduli in each direction and BV/TV. When Eqs. (2) through (5) are compared to the similar study published by van Ruijven et al. (2003), a similar slope can be observed. If same Young's modulus is substituted into dependencies published by van Ruijven, comparable values of apparent Young's modulus will be returned. On the contrary, non-directional dependency showed a much weaker correlation, indicating an orthotropic elasticity of cancellous bone in the *os occipitale*. The derived equations can effectively describe trabecular structure in biomechanical simulations of cranial bone using the FEM, especially when a more detailed trabecular finite element representation is impractical due to its time-consuming nature.

The derived equations hold significant clinical implications. They can steer optimal implant design and placement in the cranial region, underscore the importance of considering orthotropic elasticity in surgical planning, and present a time-efficient approach for biomechanical simulations in clinical research. In emergency cases, these equations offer a practical and prompt means of assessing cancellous bone properties, assisting clinicians in making informed decisions swiftly.

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