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INHOMOGENEOUS MATERIAL PROPERTIES ASSIGNMENT TO FINITE ELEMENT MODELS OF BONE: A SENSITIVITY STUDY

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Abstract: *The present work deals with a strain intensity sensitivity to finite element mesh density in computational models of skull bone sample with an inhomogeneous distribution of Young's modulus. Computational experiments on models with various mesh density were conducted to test the hypothesis that the strain intensity distribution along the bone sample thickness is significantly influenced by the mesh density when material properties of bone obtained from the computer tomography are assigned to the finite element model. The results indicate that the mesh quality matters.*

Keywords: Computer tomography, Finite element method, Material mapping, Patient-specific.

1. Introduction

There are two major features that helps to define the contemporary musculoskeletal biomechanics. "A patient specific approach" and "in silico medicine". The first feature is based on a general trend in today's health-care for personalized medicine (Zadpoor, 2015). In such cases, the patient-specific approach requires additional information pertaining to individual patients. As for bone-related problems, a good start for creating a reliable and effective personalized model is to acquire a set of images from the computer tomography (CT). These images, which differ for each patient, provide not only a necessary insight into the patient's state of health but also the information necessary for building the model. CT systems are based on a principle of measuring X-ray attenuation of tissues which can be transformed into the Hounsfield units (HU). Using an appropriate calibration, HU can provide information on the apparent density (ρ) of bone tissue. It has been proved many times that elastic properties of bones are correlated to ρ (Helgason, 2016); therefore, from the CT-based distribution of ρ, an inhomogeneous Young's modulus (E) distribution in the bone might be obtained as well using an appropriate E-ρ relationship.

The second feature might be defined as the use of computer simulations for medical purposes. Finite element method has become a strong tool for many biomechanicians of today. This tool enables relatively accurate predictions and provides a good insight into behavior of living systems without necessity of invasive procedures. Combining those two features, high-level computational models might be created and used for a wide range of research as well as for helping the treatment of actual clinical cases. However, there is still a big amount of unresolved problems pertaining to the methodology. For instance, the inhomogeneous material assignment to FE models is still not common routine and not all limits of the method have been identified and investigated.

In the most popular approach, a mapping of CT-based ρ into FE models is performed by association of CT-numbers with corresponding nodes of the FE model (Taddei, 2004). A practical implementation is mostly often based on in-house software applications or on publicly available software such as Bonemat (Zannoni, 1998). However, suitability of concrete implementation might depend on the specific problem as no universal approach exists. In any case, the accuracy of the mapping is still questionable and using of FE models with the inhomogeneous material properties distribution is still under scrutiny.

The aim of the work is to present our approach to the material assignment and to study strain intensity sensitivity to mesh density when the inhomogeneous material distribution in a skull bone is assumed.

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2. Material and Methods

2.1. Geometry and material properties

For the purposes of this study, a skull from actual patient (male, 31 yo) was CT-scanned (resolution 0.4 x 0.4 x 0.7 mm). The images were processed using an in-house software application STL Model Creator (Matlab 2010, MathWorks, Natick, MA, USA) to obtain a digitized geometry. The geometry was treated in a CAD software (SolidWorks, Dassault Systems, Velizy-Villacoublay, France) and then imported into a FE software (Ansys 17.2, Swanson Analysis Systems Inc., Houston, PA, USA). Afterwards, positions of nodes of the discretized geometry along with the CT images were imported into another in-house software application CTPixelMapper (Python 3.4) to perform a mapping of CT-numbers into the FE model and a conversion into Young's moduli (Fig. 1 and 2). For the conversion, a general eq. (1) was used for three different types of material assumed to be contained in the CT data depending on specific CT-numbers. Material coefficients for those tissues are listed in Tab. 1. Eq. (1) combines a CT-ρ conversion based on a phantom calibration of CT device with E-ρ conversion taken from literature (Helgason et al., 2008). Poisson's ratio for bone was assumed to be 0.3.

$$E = a \cdot (b \cdot CT^c + d)^e + f \quad (1)$$

Tab. 1: Material coefficients associated with Eq. 1.

Note	CT number range	a [mm^2/s^2]	b [g/cm^3]	c [-]	d [g/cm^3]	e [-]	f [MPa]
Soft tissue	(0-1280>	0	1	1	1	1	5
Cancellous bone	(1280-1500>	$2.5x10^{-7}$	0.9756	1	-975.6	3	0
Cortical bone	(1500-4095>	$1.25x10^{-6}$	0.9756	1	-975.6	3	0

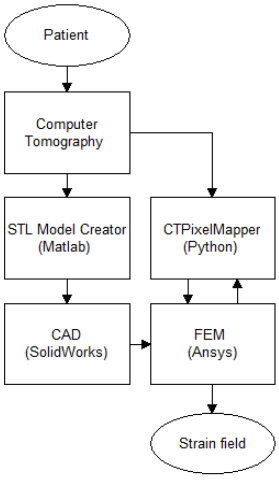


Fig. 1: Procedure flowchart.

2.2. FE Model

For the study, only a beam-like sample was retrieved from the whole skull (Fig. 3). The sample with dimensions of 5x7x25 mm and with the assigned material was encastered and loaded by an arbitrary linear force of 15 N/mm concentrated in the middle of the sample length (Fig. 4). Seven variants of the FE mesh were tested to show how the combination of the mesh density and the inhomogeneous material assignment affects the strain fields in the regions of interest. In these variants, uniform free mesh consisted of tetrahedral quadratic elements (SOLID187) sized 0.1; 0.2; 0.4; 0.7; 1.0; 1.5; 2.0 mm. Therefore, the geometry discretization as well as the material mapping were carried out seven-times to obtain seven FE models of "testing" bone sample. See Fig. 4 for exemplification of the finest and roughest meshes. To confirm that the governing factor in the presumed strain variability is the material assignment, seven "control" FE models were recalculated under the same condition as the testing ones with the only exception that a homogeneous Young's modulus of 5 GPa was assumed.

2.3. Sensitivity study

Strain intensity distributions were evaluated along four paths indicated in Fig. 4. Preliminary testing calculations proved that the paths were in a sufficient distance from the constraints or loading and were not influenced by them. The finest mesh was considered as a reference one and results from models with this mesh were compared to results from models of other mesh densities. The non-parametric Wilcoxon rank-sum test was used for the comparison.

3. Results and Discussion

Typical strain intensity distributions along the paths are shown in Fig. 5. The control models did not account for the presence of less stiff cancellous bone; therefore, the total strains were generally lower than those at the same position when more accurate inhomogeneous material properties were used. The comparisons of control model results prove that even the roughest mesh is sufficient to provide satisfactory results when the homogeneous material properties are assumed. Fig. 6 shows typical result of

such comparison. The results of different mesh densities are virtually the same (correlation of R^2 = 0.96 to 1.00) and small deviations might be attributed to the free mesh variability and related numerical issues.

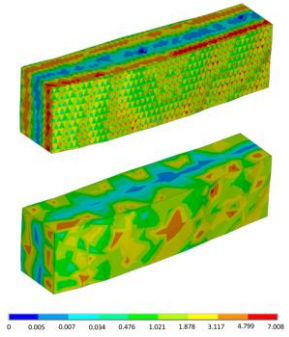


Fig. 2: Typical distribution of E within the sample (in GPa). Up: The finest mesh. Down: The roughest mesh.

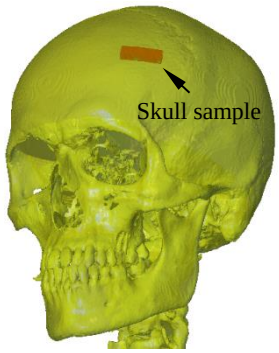


Fig. 3: CT-scanned human skull and the position of the sample.

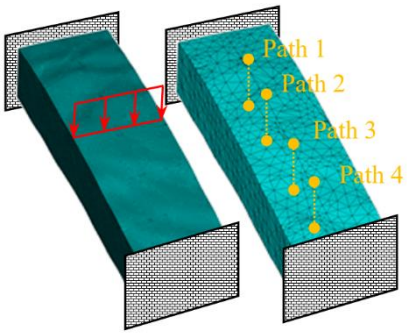


Fig. 4: FE Models of skull bone samples. Left: The finest mesh with depicted boundary conditions and loading. Right: The roughest mesh with depicted evaluation paths.

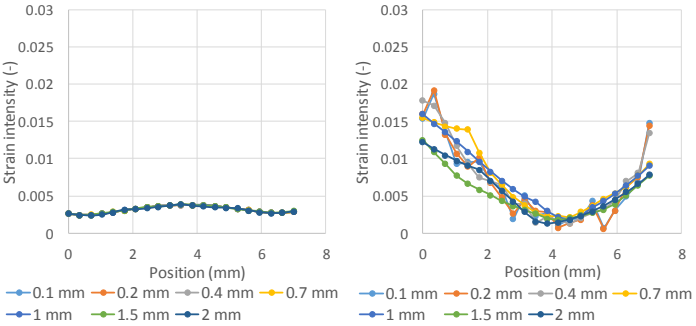


Fig. 5: Typical distribution of strain intensity along the path. Left: Results on Path 4 of control models (homogeneous distribution of E). Right: Results on Path 4 of testing models (inhomogeneous distribution of E).

The testing models show much greater result differences than the control models. This was due to strong dependency of material assignment on the mesh density. From Fig. 7 it is evident that linear trends in the comparisons deviate from the identity when the element size increases. While the worst correlation between models with the fine meshes was observed to be R^2 = 0.97, the worst finest vs. roughest mesh result correlation was R^2 = 0.43. In order to decide what deviation is already unacceptable, the Wilcoxon test was used to test a null hypothesis that the median difference between pairs of the calculated strain intensity distributions is zero. For all pairs, the z-score was calculated and the results are listed in Tab. 2. The critical z-score for a 95 % confidence interval is +/- 1.96. Therefore, if the calculated z-score is outside the +/- 1.96 interval, the null hypothesis must be rejected. Results in Tab. 2 indicate that all meshes with the element sizes lower than 1.0 mm (i.e. =< image voxel size) produce strain intensity distributions that are not significantly different from those of the reference one. Finer mesh with element size similar or smaller than CT voxel satisfactorily reproduce the source images. Whether this accuracy is beneficial in terms of biomechanical simulation should be further investigated. However, it seems that the mesh quality is a significant factor that affect the results from models with the inhomogeneous material properties.

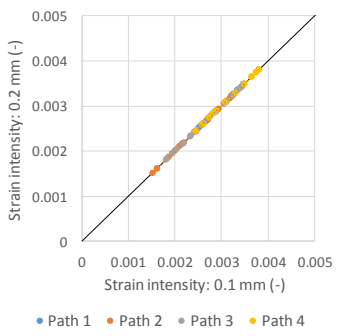
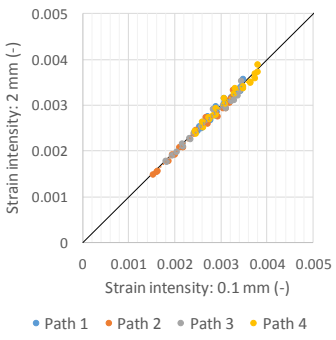


Fig. 6: Comparison of strain intensity distribution between the control models (homogeneous distribution of E).



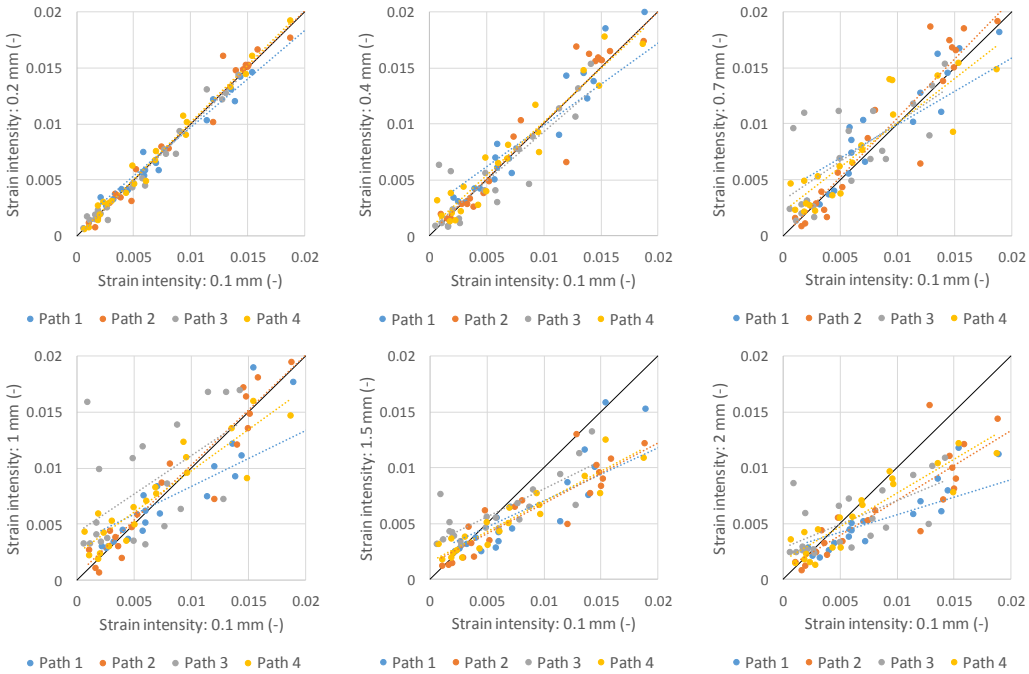


Fig. 7: Comparison of strain intensity distribution between testing models.

4. Conclusion

The calculations indicated that FE mesh quality matters when it comes to material properties assignment to the FE models, especially when a free mesh of tetrahedral elements is used. Unfortunately, many questions remain and further detailed investigations should be performed to find an optimal methodology that would ensure reliable patient-specific models. In any case, the difference between homogeneous and inhomogeneous distribution of material properties is evident and it should be preferable to use the second one for patient-specific models if strain fields within the bone is in question.

Tab. 2: Z-scores of Wilcoxon test.

Element size	Path 1	Path 2	Path 3	Path 4
0.2 mm	-1.13	-0.05	-1.20	-0.61
0.4 mm	-0.19	-0.50	-0.85	-0.85
0.7 mm	-0.16	-0.89	-1.76	-1.86
1.0 mm	-2.00♠	-0.57	-2.17♠	-2.07♠
1.5 mm	-3.53♠	-3.25♠	-0.40	-2.21♠
2.0 mm	-3.94♠	-3.08♠	-0.92	-1.48

♠ Null hypothesis is rejected.

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References

Helgason, B., Gilchirst, S., Ariza, O., Vogt, P., Enns-Bray, W., Widmer, R.P., Fitze, T., Palsson, H., Pauchard, Y., Guy, P., Fergusson, S.J. and Cripton, P.A. (2016) The influence of the modulus-density relationship and the material mapping method on the simulated mechanical response of the proximal femur in side-ways fall loading configuration. Medical Engineering and Physics, 38, pp. 679-689.

Marcián, P., Konečný, O., Borák, L., Valášek, J., Řehák, K., Krpalek, D. and 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.

Taddei, F., Pancanti, Al. and Viceconti, M. (2004) An improved method for the automatic mapping of computed tomography numbers onto finite element models. Medical Engineering & Physics, 26, pp. 61-69.

Zadpoor, A.A. and Weinans, H. (2015) Patient-specific bone modeling and analysis: The role of integration and automation in clinical adoption. Journal of Biomechanics, 48, pp. 750-760.

Zannoni C., Mantovani, R. and Viceconti, M. (1998) Material properties assignment to finite element models of bone structures: A new method. Medical Engineering & Physics, 20, pp. 735-740.