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DETERMINATION OF ULTIMATE STRENGTH OF BONES FOR THE NEED OF FORENSIC MEDICINE USING COMPUTER TOMOGRAPHY DATA

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Abstract

For the needs of forensic medicine the knowledge of mechanical behavior of the whole bones is of high importance. Mechanical properties, such as Young's modulus of elasticity and Poisson's ratio have already been measured using small pieces of bones, which is for the needs of forensic medicine useless. Moreover, these characteristics are age-dependent and therefore usually considered as the average comparative values. The aim of the work is to describe the possible relationship between the mechanical fracture of the bone in relation to age and sex for different bones and types of mechanical loading. For the assessment we use both mechanical testing in vitro and mathematical modeling.

1 Introduction

The "traditional" concept in bone biomechanics is to assess material properties of bone tissue experimentally using small specimens. Bone tissue is then considered to be homogeneous, isotropic material with only two material parameters to be described: Young's modulus of elasticity E and Poisson's ratio μ. This approach, however, is neglecting two important aspects of the bone tissue: its very high inhomogeneity and anisotropy, that could be described as material orthotropy. While it is very difficult to include the material orthotropy in the mathematical models, there is a possibility to use at least varying isotropic material properties throughout the bone according to the varying density of the bone tissue.

The information on the bone tissue density is easy to obtain directly from the Computer Tomography scans or there is also a better possibility with the help of bone densitometry.

Forensic medicine is looking for another information: what is the ultimate strength in accordance to different type of loading, different type of bone, age, sex and various other parameters. Therefore, the approach of considering only one parameter to describe such a variety of bones would be just useless and another approach has to be established. Experimental modeling is very expensive and because we are seeking the ultimate values of strength (therefore every specimen is destroyed during the experiment) we decided to use so called "mixed-method". The procedure includes experimental modeling using three-point bending test and numerical

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modeling of several other loading conditions that would be difficult to model experimentally, e.g. torque.

2 Methods

To assess the mechanical properties of a bone we use both experimental and numerical modeling. The cadaveric material for the experimenal study was obtained from the Institute of Forensic Medicine, 2^{nd} Faculty of Medicine, Charles University in Prague. Immidiately after extraction the bones were wrapped into a towel wet with saline solution and frozen to the temperature of -18°C. Before the experiment, the specimens were thawed to the room temperature. The testing masine used was Instron 4301 adjusted to the range of 1000N. Experiments proceeded with the crosshead velocity set to 5mm/min.

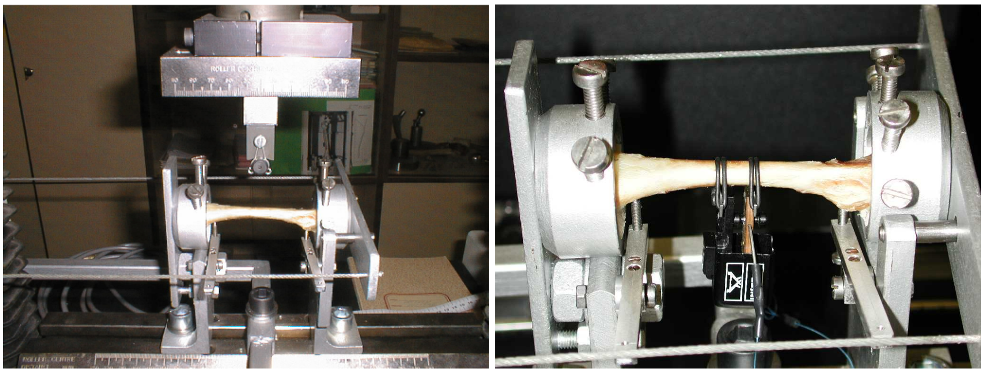

Figure 1: Three-point bending test of a specimen

Three-point bending test is carried out for every specimen. The loading conditions are shown in the Fig. 1. Both the proximal and distal ends of the bone are fixed in a special device enabling small elastic deformations of the supports in the direction of the load. The elastic deformations of the supports are measured. The specimen is also prestressed in the axial direction accordingly to the body weight. Every specimen is preconditioned for several compression cycles and then fully loaded up to the failure to eliminate the initial yeilding involving microstructural damage[1]. To find out the places of strain concentration leading to the tissue damage we use strain gauge measurement. For every specimen we evaluate the stress-strain relationship to be included in the numerical modeling.

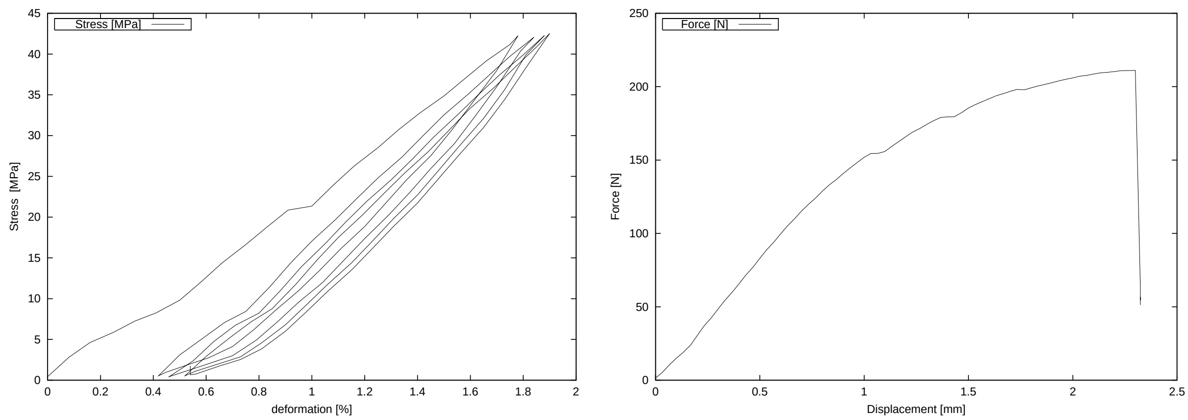

Figure 2: Preconditioning and force vs. displacement diagram

Every tested specimen is scanned using computer tomography device (Somatom Plus) and a geometrical model of that specimen is reconstructed. Then we conduct a simple finite element analysis with the 3-D model to obtain a prediction of the failure load. These steps are conducted prior the experiment. In the numerical part of the work, we reconstruct the geometrical model of every tested specimen using the computer tomography scans and algorithms such as Marching Cubes Algorithm [2] and Delaunay space triangulation. Marching Cubes Algorithm is capable of reconstruction of any organ surface represented by a set of triangles. Because this algorithm produces very large amount of triangles for a simple organ (millions), we need to reduce the number of the vertices by applying Decimation algorithm. This algorithm reduces the number of triangles eliminating the triangles that are co-planar and retriangulating the new gap. Then the volume of the organ (represented by the set of triangles) is filled with tetrahedral elements using the Delaunay triangulation. Because the mechanical properties of the bone are depen-

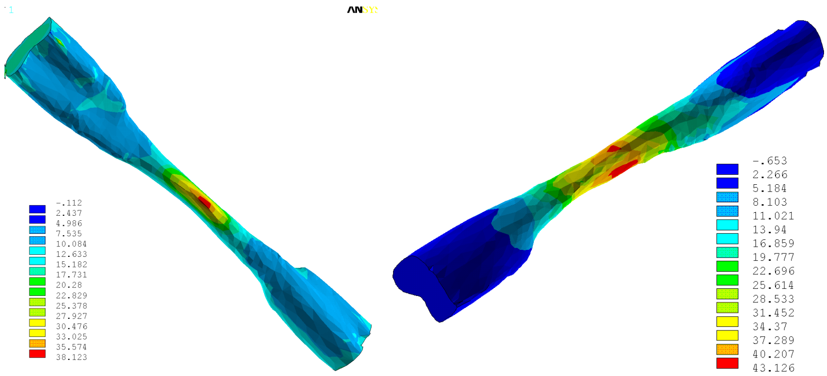

Figure 3: Example of the numerical results (three-point bendig and torque - σ_I)

dent on the tissue density, it is possible to define Young's modulus for every finite element of the model as a function of apparent density obtained from the appropriate CT-scan in the form $E = E(x, y, z, \rho)$. We consider the material of the bone to be non-linearly elastic, but with material properties varying throughout the bone. It is also known that the material properties of the cancellous bone can also vary according to the strain rate [3], but this feature is not yet included in our models. The models provide good prediction of the critical load according to the experimentally measured values, but for better understanding of the failure mode a better material model is neccessary to be considered. The most important thing on the mathematical modeling is the fact, that we are able to conduct several loading conditions on the same specimen (FE model) so we are able to specify different loading conditions that would be difficult or even impossible to model experimentally.

3 Results

Procedures for both experimental and numerical assessment of the material properties of bone has been shortly described in the paper. The described algorithms enables us to conduct really broad range of experimental and numerical tests and to derive huge amount of data needed to specify relationship between the ultimate stress of bone in accordance to the type of loading (and several other important characteristics as mentioned earlier in the paper). We are able to adapt the numerical model to fit the experimental results from the three-point bending test (especially the boundary conditions) and to apply the other load steps.

So far we are able to test large number of bones required for the statistical evolution and to conduct the numerical analyses with required speed thanks to the described reconstruction algorithms. As another example, the field of the first principal stresses in case of uniaxial compression test is presented on Fig. 4. The results from the numerical analysis of the femur well correspond to the experimental analysis done by Jírová et al [4]. We can conclude that computer tomography-based finite element modelling can be successfully used in prediction of the failute of single bone under broad range of loading conditions.

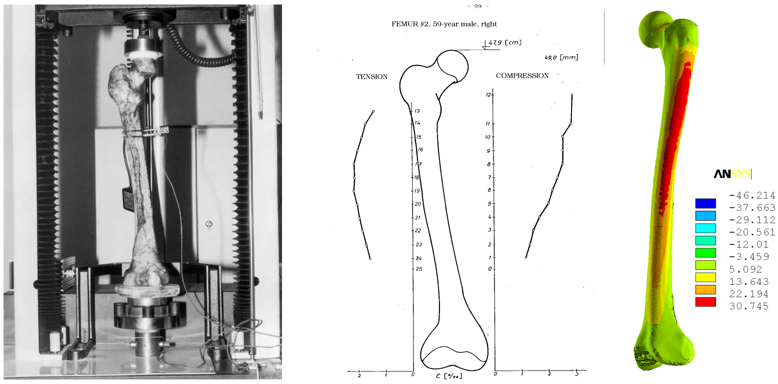

Figure 4: Principal strains and stresses in the femur (uniaxial compression) experimental vs. FEA results

What as for the future, we would like to improve the mathematical description of the bone material, especially the material orthotropy should be included, but it is very difficult to define the directions of the orthotrophy. We are also aware of the shortcoming of the tests as it is not possible to test the same specimen under several loading conditions as we are seeking for the ultimate values and therefore every specimen is damaged during the test.

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References

[1] Keaveny T.M., Guo X.E., Wachtel E.F., McMahon T.A., and Hayes W.C.: Trabecular bone exhibits fully elastic behavior and yields at low strains. Journal of Biomechanics, 27:1127-1136, 1994

[2] Lorensen, W.E. and Cline, H.E., "Marching Cubes: A High Resolution 3D Surface Construction Algorithm", Computer Graphics, vol. 21, no. 3, pp. 163-169, July 1987.

[3] Rice, J.C., Cowin, S.C., Bowman, J.A., "On the dependence of the elasticity and strength of cancellous bone on apparent density", Journal of Biomechanics, 21, 2, pp. 155-168.

[4] Jírová J., Slavík M., Karpíšek M., "Experimental Investigation of Quasistatic Behaviour of System Femur - Hip-Joint Prosthesis". Proc. of 2^{nd} Bilateral Symposium CSFR-NSR, Bad Honnef 1989.