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Numerical Elastoplastic Analysis of Trabeculae in Lumbar Vertebral Body

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This paper presents a numerical modelling of lumbar vertebrae L1 by employing the finite element method. The three-dimensional model of vertebral body is derived by processing CT data and DICOM format files. The model includes cortical shell, trabecular bone and posterior elements. The formation of trabecular structure was performed by script-controlled ellipsoidal cut-outs. In order to define the nonlinear relationship between the stress and the strain, the Ramberg-Osgood equation was applied. Therefore, the von Mises stress was assumed to characterise the stressed state of bone tissue due to 1 and 7 MPa compression load. According to specific difficulties for "in vitro" and "in vivo" investigation methods, this "in silico" technique may provide new insight for further understanding of the trabecular bone behaviour in terms of plastic deformation.

Key words: lumbar vertebra, finite element method, elastoplasticity, trabeculae.

1. Introduction

The multidisciplinary difficulties of spine modelling have been studied by different researchers involved in investigation of biomechanical processes, e.g., such as the age-related spinal degeneration [1, 2]. In vitro experimental measurements of spinal components or segments tested in the laboratory conditions are limited by the availability of samples and the variability between specimens. In vivo measurements provide information on the bone tissue in its natural state, but they are restricted by limited invasiveness. More recently, a third method, a computer analysis, often referred to as the "in silico" analysis, has become more widespread in the assessment of the spine and its segments.

The finite element numerical simulation could serve as an effective tool for the "in silico" analysis that cannot be clarified by experimental methods. Moreover, numerical simulation techniques have the potential to reduce costs and time during the development of effective bone tissue treatment methods or implants. Consequently, there is a need to obtain more and more realistic and correct numerical models that reflect the anatomical geometry and mechanical properties of bone tissue.

Regarding extremely large difficulties in forming of the real geometry of the spine, most of the studies focus on the simplified models. Recent developments are limited to smaller fragments of vertebrae [3, 4], and majority of the studies concern vertebral body in isolation [5–8] using the simplified shape by excluding the posterior elements, while the trabecular structure is not verified [9, 10]. In most of the applications, the investigations were restricted to the linear elastic material behaviour, and consideration of the nonlinear effect of plasticity is limited [10, 11].

The purpose of this study is the numerical elastoplastic investigation of a lumbar body with an introduction of the trabecular structure formed by ellipsoidal cuts. This method has been adopted to deal with the complex anatomical form of a trabecular tissue. Numerical studies assuming plastic deformation of the bone are aimed to produce new results allowing to better knowledge of the trabecular bone behaviour.

2. Methods and initial data

2.1. Problem description

The bone tissue is modelled as elastoplastic continuum. As no strength theory for bone has been validated at this time [12], the von Mises yield criterion (2.1) was applied to assess the stress state. The von Mises criterion equation is defined by the following equation:

$$\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}}=\sigma_y, \tag{2.1}$$

where σ_1, σ_2 and σ_3 are maximum, intermediate and minimum stresses respectively, and σ_y is the yield stress. The von Mises criterion has also been selected because of its compatibility with the Ramberg-Osgood material model.

2.2. Description of the model

The inhomogeneous lumbar vertebral body model is presented in Fig. 1. It consists of two basic structural members: outer cortical shell encircling inner bone tissue. In this study, the DICOM data of human CT was used for the initial geometry definition. The trabecular tissue was obtained by *Python* script-controlled ellipsoidal cut-outs in the open source CAD software *SALOME 7*. This method allows us to represent the inner structure of vertebrae consisting of plate-like and rod-like trabeculaes.

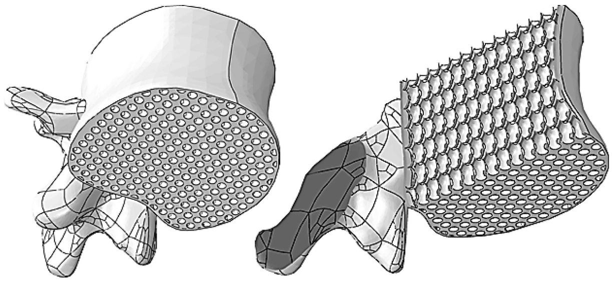

FIG. 1. The model of lumbar vertebrae.

2.3. Mechanical properties

Following Timothy and Brandeau [13] the Ramberg-Osgood equation was applied for the stress-strain behaviour. The Ramberg-Osgood model is defined by the following equation:

$$\varepsilon = \frac{\sigma}{E} + \alpha \left(\frac{\sigma}{\sigma_y} \right)^n, \tag{2.2}$$

where ε is the strain, σ is the ultimate strength, E is the modulus of elasticity, n is the strain-hardening exponent, α is the yield offset, and σ_y is the yield stress. The stress-strain curve is presented in Fig. 2.

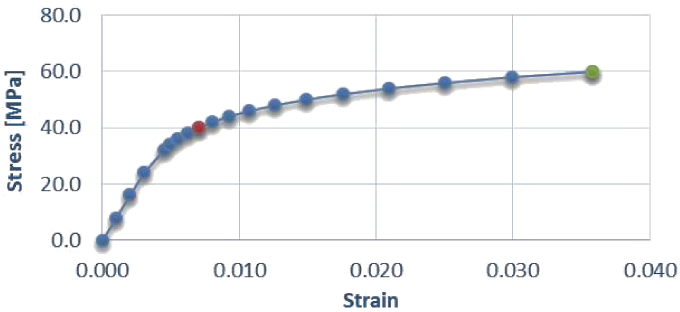

FIG. 2. The stress-strain curve of bone tissue.

The mechanical properties of the cortical shell and the cancellous bone, taken from [13, 14] are given in Table 1.

Table 1. Mechanical properties of the model components.

E [MPa]	σ_y [MPa]	σ [MPa]	n	α	Poisson's ratio
8000	40	60	6.534	0.002	0.30

2.4. Mesh and boundary conditions

The bone is subjected to the physiological loads, which occur through daily activities and atmospheric pressure. Generally, this represents normally directed pressure on the upper surface of the model. The bottom of the model was constrained from any motion. Finally, the model was meshed with tetrahedral grid which consisted of 9.2 million elements. The fragment of the mesh is presented in Fig. 3. The calculations took 5.2 h on Xeon E5-2690x14 with 2.9 GHz and 32 GB RAM.

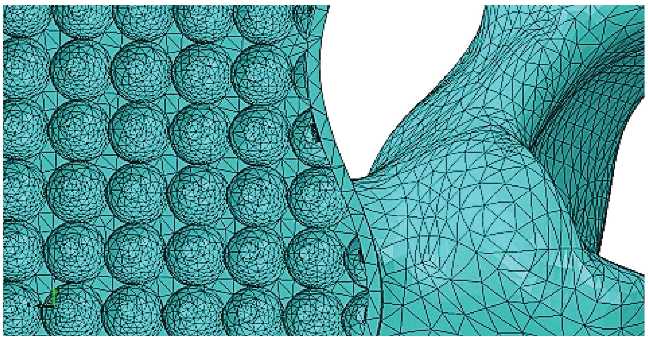

Fig. 3. The fragment of meshed model (top view).

3. Numerical results and discussion

The distribution of von Mises stress, presented in Fig. 4, was obtained for 1 and 7 MPa compression load.

The results showed that yield stress was not reached under the 1 MPa load. The extremum stress values are concentrated on the cortical shell. It can be seen that the cortical shell of lumbar vertebra is clearly divided into two zones, the upper one with higher stress values (30 MPa) and the lower zone with lower stress values (20 MPa), while trabecular structure remains relatively unloaded (the maximum values of stress are in the range of 10–15 MPa).

Under the 7 MPa load, the yield stress is exceeded and stress redistributes firstly on the cortical shell. Then, the extremum values of stress (60 MPa) appear

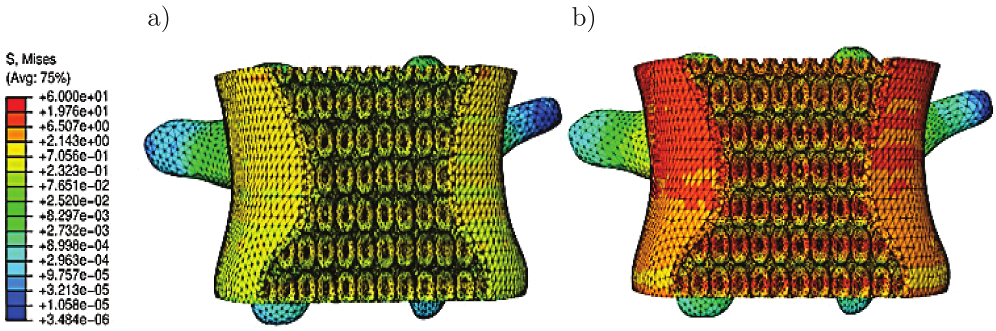

FIG. 4. a) Stress distribution due to 1 MPa load, b) stress distribution due to the 7 MPa load.

on the porous structure throughout all vertebrae volume: mostly on horizontal plate-like trabeculae.

This proves that the cortical shell performs the primary role in load carrying and in the case of its plastic deformation the trabecular structure appears to be overloaded. Therefore, this also explains a quicker degradation of horizontal trabeculae.

4. Conclusions

We developed the L1 vertebra model, which consisted of the cortical shell, trabecular bone and posterior elements. The model was analyzed for different load values and the nonlinear mechanical properties were supplied. The results showed that in terms of elastic deformation the larger part of the load is carried by the cortical shell, but in the case of plastic deformation the load redistributes and concentrates on horizontal trabeculae. The developed technique could be applied to further investigate mechanical behaviour of the bone and the results may find the application in treatment of degenerative diseases.

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