Stress analysis of osteoporotic femur

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Abstract. Osteoporosis and degenerative diseases cause low bone mass that increases fracture risks. This study presents the modelling of osteoporotic femur by employing finite element method (FEM). The loading of femur using FEM tools was performed. The level of degradation was modelled by changing the thickness of cortical shell and using power-law equations, which determine the dependence between apparent density of cancellous bone and its mechanical properties. Obtained results could be useful for both medical diagnosis and bone health check.

Keywords: osteoporosis, finite element method, bone mechanics, femur.

Introduction

Osteoporosis is a disease characterized by low bone mass and micro-architectural deterioration of bone tissue, with a consequent increase in bone fragility and susceptibility to fracture [1]. Osteoporosis is one of the most common health problems affecting both men and women, and it is becoming increasingly prevalent in our aging society. Osteoporosis affects over 200 million people worldwide [2] with an estimated 1.5 million fractures annually in the United States alone [3] and attendant costs exceeding $10 billion per annum [4]. Although osteoporosis affects the entire skeleton, many osteoporotic fractures occur in the femur [5]. It has a high mortality rate: survival is 72% in the first year and only 28% after five years [5].

Due to the complex anatomy of the femur body, the difficulties associated with obtaining bones for in vitro experiments, and the limitations on the control of the experimental parameters, finite element models have been developed in order to analyse the biomechanical properties of bone tissue.

The present study is aimed to determine the stress distribution on cortical shell of femur with verification of various grades of osteoporosis.

Methods

A three-dimensional continuum boundary problem is raised. In order to define the mechanical behaviour of femur model under the compression load, theory of elasticity was applied. Main equations are presented in tensor form:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + f_i = 0, \tag{1}$$

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right), \tag{2}$$

$$\sigma_{ij} = C_{ijkl} \times \varepsilon_{kl}, \tag{3}$$

where σ_{ij} is a tensor of stress, ε_{ij} is a strain tensor, U is a displacement tensor, f_i corresponds to volume forces and C_{ijkl} is a fourth-order tensor of elasticity.

The von Mises-Hencky criterion is chosen to analyse the stressed state of the model. The selection of this criterion is based on mechanical properties of the bone, which seems to behave as a ductile material [6]. Also, the model is continuous and isotropic, so the von Mises stress criterion is applied to the research of stresses, which occur on cortical shell of the model.

The von Mises stress is defined in Eq. (4) below, where σ_1, σ_2 and σ_3 are the maximum, intermediate, and minimum principal stresses respectively; σ_{eq} is a von Mises equivalent stress:

$$\sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} = \sigma_{eq}. \tag{4}$$

The initial geometry of the model was derived from DICOM data files and converted into the numerical body using *SolidWorks* software. The model consists of two basic components – cortical shell and cancellous bone, both modelled as isotropic and elastic. Section view of the model is presented in Fig. 1. Elasticity constants of healthy model were calculated using power-law equations [7]. They are presented in Table 1.
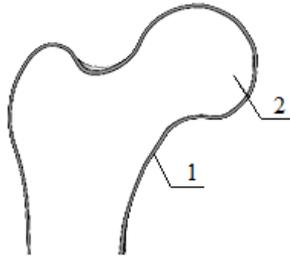

Fig. 1. Section view of numerical femur model: 1 – cortical shell; 2 – cancellous bone

Table 1. Elasticity constants of the healthy model

Component of the model	E, MPa	v
Cortical shell	18000	0.300
Cancellous bone	3260	0.200

The impact of osteoporosis is modelled by decreasing the elasticity modulus of the cancellous bone and thickness of cortical shell, as it is pointed out in Table 2.

Table 2. Varying of parameters of the model

Parameters of the osteoporotic model	Range
Cortical shell thickness, mm	0.5–1.5
Elasticity modulus of cancellous bone	260–3260

The model was rigidly constrained through distal part of femur, and static compressive load collinear to axis of femoral neck in the range of 1000–2000 N was applied. The meshing of the model was performed with volume finite elements due to its curvature. The number of elements and nodes is presented in Table 3.

Table 3. Finite element model

Model component	Number of finite elements	Number of nodes
Cortical shell	4157	7351
Cancellous bone	20560	45139

Results

The stress distribution on the cortical shell of the model was obtained for various grades of osteoporotic degradation and model with 0.5 mm thickness of cortical shell is presented in Fig. 2.
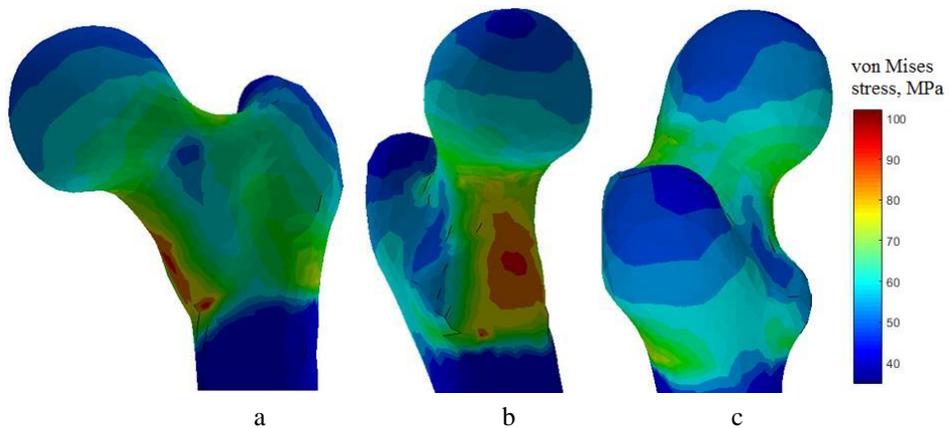

Fig. 2. Stress distribution on the cortical shell of femur model with 0.5 mm cortical shell

As it shown in Fig. 2, the highest von Mises stress appears along the inner area of the neck, near the intertrochanteric line. The difference between the maximal values of stresses in the healthy and osteoporotic model (with 0.5 mm cortical shell thickness) reaches 350%.

Conclusions

We developed the finite element model of human femur, which consisted of the cortical shell and cancellous bone. The model was treated for various grades of degenerative diseases. The distribution of von Mises stress was obtained on the cortical shell of the model. It was found, that value of von Mises stress depends both on quality of cancellous bone and thickness of cortical shell, while the thickness of cortical shell remains critical.

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