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BIOMECHANICAL MODEL OF VERTEBRA BASED ON BONE REMODELING

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Summary. *Mechanical load is related to morphology of bone tissue, in a way that bone tissue structure is adapted to load of which influence is exposed to. Process that regulates this relationship is named bone remodeling. Bone remodeling can be mathematically described by bone remodeling equation and integrating this equation with finite element method sequence of bone remodeling can be simulated. Being familiar with mechanisms of bone remodeling is of great importance for implants design because it enables monitoring of bone tissue behavior during post-operative implanted conditions. Post-operative implanted conditions change mechanical load of bone tissue that could be cause of initialization of bone remodeling. Therefore, this paper deals with possibility of biomechanical modeling of lumbar vertebra L_5 based on bone remodeling. Model, formed in accordance with mechanical load caused by every days activities, represents initial model for analysis of bone tissue behavior during post-operative implanted conditions.*

Key words: *Biomechanical model, vertebra, implant, bone remodeling, finite element method – FEM*

Introduction

Research regarding the relationship between mechanical load and morphology of bone tissue can be traced back to work of German anatomist Wolff from 1892 year. Based on his research Wolff suggested a hypothesis, known as Wolff's law, after which structure of bone tissue can adapt under influence of mechanical load to which is exposed. Wolff also suggested that change of bone tissue structure caused by change of mechanical load is optimal, what means that tissue tends to minimal mass needed to bear load. Process, which regulates relationship between mechanical load and structure of bone tissue is usually called bone remodeling. First hypothesis about mechanisms which cause bone remodeling was suggested by German surgeon Roux at 1895, he assumed that cells of bone tissue can "sense" mechanical load and respond to that stimulus at the cell level by initiating bone remodeling.

Starting point of all contemporary theories of bone remodeling is Wolff's and Roux's work. Therefore, it is believed that bone tissue structure adapts to mechanical load to which is exposed. It is also believed that bone tissue contains specialized cells (osteoclasts and osteoblasts), which at the same time act as sensors which "sense" load and as regulators of bone remodeling which increase or decrease bone mass. Change of bone mass during bone remodeling can be achieved by changing density or geometry.

First mathematical model, based on general principles of continuum mechanics, which establishes functional relationship between mechanical load and bone remodeling was suggested by Cowin and Hegedus in 1976 (1). Model, suggested in 1986 by Fyhrie and Carter (2), considers bone remodeling as optimization process during which bone tissue adapts its structure and density to stress-strain state. Recently simulation of bone remodeling based on integration of finite element method, as an effective tool for accurate determination of stresses and strains, and mathematical model of bone remodeling was proposed by many authors (Weinans et al, 1992 (4); Mullender et al, 1994 (5); Xinghua et al, 2002 (7)).

Being familiar with mechanisms of bone remodeling is of great importance for implants design because it enables monitoring of bone tissue behavior during post-operative implanted conditions. Because post-operative implanted conditions change mechanical load of bone tissue that could be cause of initialization of bone remodeling. Application of bone remodeling theory in implants design is object of research conducted by Huiskes et al. during 1987 (3). Researches, conducted during 1998 by Martinez et al. (6) and during 2003 by Waide et al. (9), were investigating behavior of bone tissue during post-operative implanted conditions, which initiate bone remodeling.

Therefore, this paper deals with possibility of biomechanical modeling of lumbar vertebra L_5 based on bone remodeling. Biomechanical model of lumbar vertebra L_5, formed in accordance with mechanical load caused by every days activities, represents initial model for analysis of bone tissue behavior during post-operative implanted conditions.

Methods

Model of bone remodeling

Simulation of bone remodeling, used in this paper, is based on remodeling model of Mullender et al. (5). Regarding this model continuum, which is filled by bone tissue is boiled down to finite elements. Each element contains a sensor cell placed into its centroid. According to model of Mullender sensor cells, after "sensing" mechanical load which initiates bone remodeling, send signals which cause initialization of adaptive process within range extending out of boundaries of elements inside which cells are placed. Effect of this signal to bone remodeling decreases as remoteness from sensor cell location increases. This assumption includes influence of all sensor cells into bone remodeling with respect to its remoteness from location at which bone remodeling takes place.

According to this model equation of bone remodeling can be expressed:

$$\frac{d\rho(x,t)}{dt} = B \cdot \sum_{i=1}^{n} f_i(x) \cdot \left[\frac{U_i}{\rho_i} - k\right] \qquad (1)$$

$$0 < \rho \le \rho_{cb}$$

where n is number of finite elements, U_i density of strain energy at centroid of finite element, ρ_i density of bone tissue of finite element, k reference stimulus value and B constant of bone remodeling. Remodeling model suggested by Mullender involves function of spatial influence which physically simulates influence of sensor cells on neighboring bone tissue:

$$f_i(x) = e^{-\frac{d_i(x)}{D}} \qquad (2)$$

where $d_i(x)$ is remoteness from sensor cell to location x and D range of sensor cell influence. Young's modulus of finite element can be determined by the following equation:

$$E = C \cdot \rho^{\gamma} \qquad (3)$$

where C and γ are constants.

Mullender converted diferential equation of bone remodeling into an explicit time integration scheme using constant time step Δt, after which the following expression is obtained:

$$\Delta\rho(x,t) = \Delta t \cdot B \cdot \sum_{i=1}^{n} f_i(x) \cdot \left[\frac{U_i}{\rho_i} - k\right]. \qquad (4)$$

$$0 < \rho \le \rho_{cb}$$

New value for density of finite element can be determined from the following expresion:

$$\rho(x, t + \Delta t) = \rho(x,t) + \Delta\rho(x,t) \qquad (5)$$

Bone remodeling in each finite element is considered to be converged if one of the following three conditions is satisfied: (i) reached preset reference stimulus value of ratio between density of strain energy and density of bone tissue k, (ii) reached density of cortical bone tissue $\rho = \rho_{cb}$, (iii) complete resorbtion of bone tissue from finite element $\rho = 0.01$ g/cm^3. Reaching one of the bone remodeling equilibrium conditions can be achieved by changing density of bone tissue in finite element.

Simulation of bone remodeling integrated with finite element method, Figure 1, keep on going iterativly until process would be finished in all finite elements.

The convergence behaviour of bone remodeling can be investigated by objective function F which is defined by the following expresion:

$$F = \frac{1}{m} \cdot \sum_{i=1}^{m} \left| \sum_{i=1}^{m} f_i(x) \cdot \left(\frac{U_i}{\rho_i} - k\right) \right| \qquad (6)$$

where m is number of finite elements inside which bone remodeling keep on going.

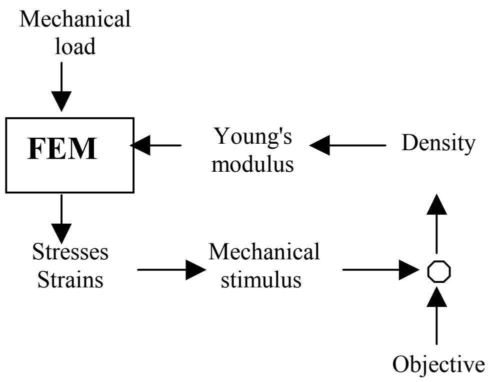

Fig. 1. The iterative feed-back mechanisms of simulation of bone remodeling integrated with finite element method

Values of constant parameters of model used for simulation of bone remodeling (5):

$B = 1$ (g/cm^3)^2/(MPa·time unit)
$\rho_{cb} = 1.74$ g/cm^3
$C = 100$ MPa/(g/cm^3)^2
$\gamma = 2$
$\nu = 0.3$ Poisson's ratio
$\rho_0 = 0.8$ g/cm^3 density of bone tissue in all finite elements at the beging of bone remodeling simulation.

Remaining model parameters were chosen so that stability of bone remodeling would be provided, as well as that final structure of bone tissue would be similar to the real one:

$D = 0.5$ mm
$k = 0.006$ J/g
$\Delta t = 2$ time unit

Physical and geometric model of lumbar vertebra L_5

Lumbar vertebra L_5, shown in Figure 2, was used as basis to generate geometric model.

3D geometric model of vertebra, shown in Figure 2, was generated in environment of comercial geometric modeler Mechanical Desktop 6. Modeling was realized by an automatic generator of geometric models of lumbar vertebrae, which is presented in work of J. Jovanovića i M. Jovanovića (10) in 2002 year.

Fig. 2. Physical model of vertebra L_5

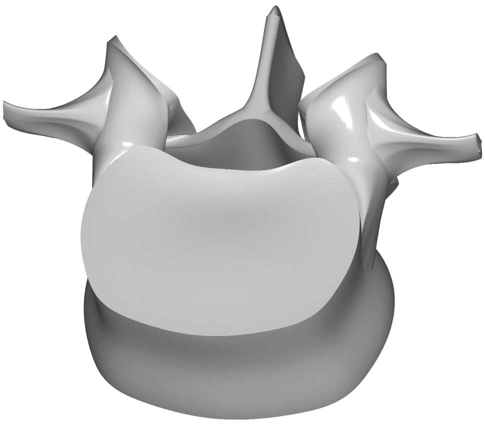

Fig. 3. 3D geometric model of vertebra L_5

3D geometric model of vertebra, shown in Figure 3, was used as basis to generate 2D geometric model of vertical section of vertebral body, which is shown in Figure 4.

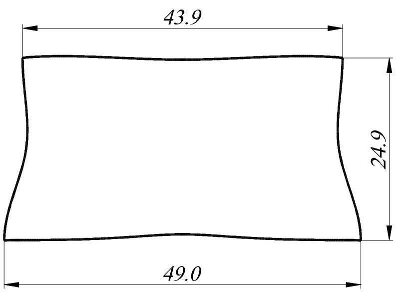

Fig. 4. 2D geometric model of vertebra L_5

FEM model of lumbar vertebra L_5

2D geometric model of vertebra, shown in Figure 4, is used as basis to generate mesh of plane linear isoparametric elements with nodes at each corner (11). Generated mesh is consisted of 110x70 finite elements, which make structure with 15762 degrees of freedom (dof).

Load of vertebral body section, which is caused by every days activities, of young person is shown in Figure 5. According to research that is conducted by Xinghua et al. (7) shape of load distribution is symmetrically concave parabola, and total magnitude of vertical load is 117.3 N.

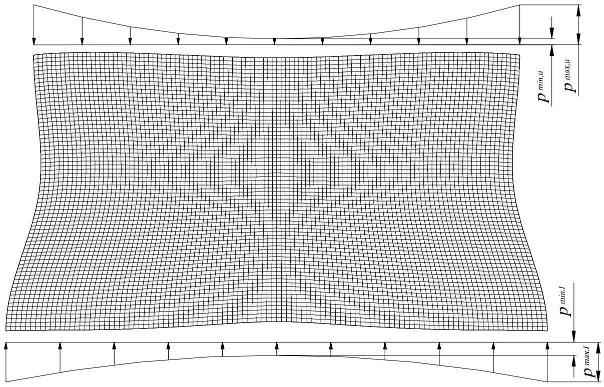

Fig. 5. 2D FEM model of vertebra L_5

Parameters of load distribution of upper and lower vertebral body endplate were chosen so that shape and magnitude of vertebral load from mentioned research would be satisfied. Values of load distributions parameters are: $p_{max,u} = 4.8$ N/mm^2, $p_{min,u} = 1.6$ N/mm^2, $p_{max,l} = 4.525$ N/mm^2 and $p_{max,u} = 1.325$ N/mm^2.

Results

Results of simulation of bone remodeling of lumbar vertebra L_5 are shown in Figure 6. Process was monitored until bone remodeling was finished in each finite element. There is a distribution of density of strain energy shown in Figure 7, which was mechanical stimulus in a model used to simulate bone remodeling.

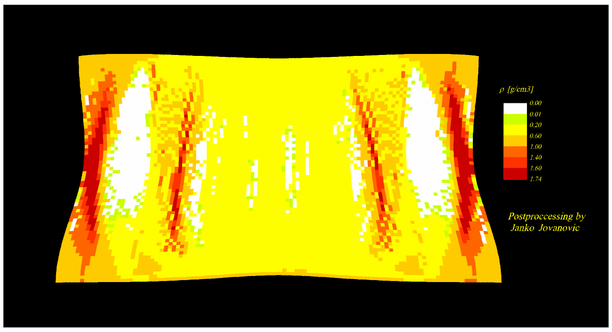

Fig. 6. Distribution of density of bone tissue after ending of bone remodeling

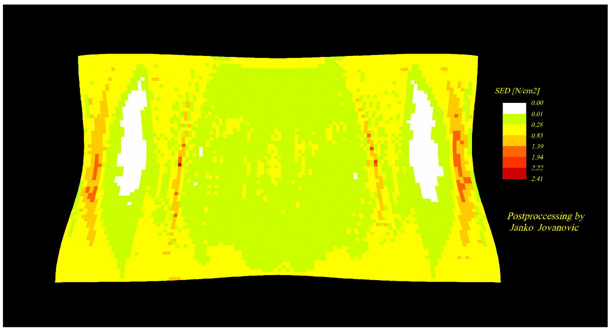

Fig. 7. Distribution of density of strain energy after ending of bone remodeling

Adaptive process ended after 170 iterations, during which change of vertebral mass was investigated, as well as objective function as indicator of convergency of bone remodeling. Obtained dependencies of ratio between current m and initial mass of vertebra m_0, as well as objective function F during bone remodeling are shown in Figures 8 and 9.

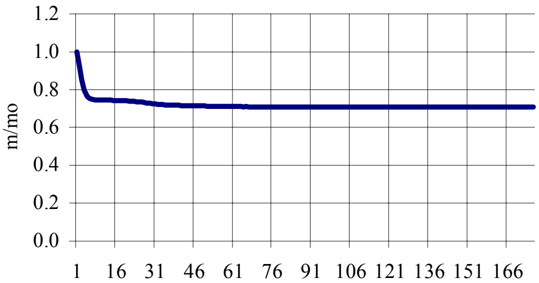

Fig. 8. Mass change during bone remodeling

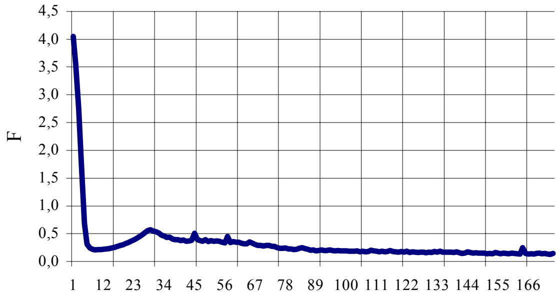

Fig. 9. Objective function change during bone remodeling

Conclusion

Regarding the fact that used FEM model was based on number of assumptions and simplifications distribution of density of bone tissue obtained according to bone remodeling model is surprisingly similar to reality. Model of vertebra is two-dimensional, relationship between Young's modulus and density is expresed by crude approximation. Choice of density of strain energy, as mechanical stimulus of bone remodeling, was also more or less based on the fact that it is an easily interpretable physical scalar which is related to stress and strain.

Obtained biomechanical model of vertebra can be used as an initial model for investigation of bone tissue behavior in changed mechanical load conditions. One of the possible resons for change of mechanical load is post-operative implanted conditions.

Analysis of influence of different types of hip-implants on change of mechanical load of proximal femur and bone remodeling caused by that change was object of research conducted by Wiade et al. at 2003 (9). This research experimentaly and theoreticaly proved that different adaptive process caused by post-operative implanted conditions of different types of hip-implants was cause of less clinical succes of Muller-Curved implant compared to Lubinus SPII implant.

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BIOMEHANIČKI MODEL PRŠLJENA BAZIRAN NA PROCESU ADAPTACIJE KOŠTANOG TKIVA NA MEHANIČKO OPTEREĆENJE

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Kratak sadržaj: *Mehaničko opterećenje je povezano sa strukturom koštanog tkiva, tako što se ista prilagođava opterećenju čijem je uticaju izložena. Proces koji reguliše ovu vezu poznat je kao proces adaptacije koštanog tkiva. Proces adaptacije koštanog tkiva na mehaničko opterećenje je moguće matematički opisati jednačinom adaptacije i integrisanjem iste sa metodom konačnih elemenata simulirati tok adaptivnog procesa. Poznavanje mehanizama procesa adaptacije koštanog tkiva od izuzetnog je značaja za projektovanje implantata jer omogućava praćenje ponašanja koštanog tkiva nakon njihove ugradnje. Ugradnjom implantata dolazi do promjene mehaničkog opterećenja koštanog tkiva što može biti uzročnik pokretanja adaptivnog procesa. Stoga se u ovom radu razmatra mogućnost biomehaničkog modeliranja slabinskog pršljena L_5 baziranog na procesu adaptacije koštanog tkiva na mehaničko opterećenje. Model, formiran prema mehaničkom opterećenju koje odgovara svakodnevnim aktivnostima, predstavljao bi polazni model za analizu ponašanja koštanog tkiva pršljena nakon ugradnje implantata.*

Ključne reči: *Biomehanički model, pršljen, implantat, adaptacija koštanog tkiva, metoda konačnih elemenata - FEM*