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Research article

Simulation of the Mechanical Behavior of the Degradation L4-L5 Lumbar Spine

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A B S T R A C T

Degenerative changes in the lumbar spine significantly reduce the quality of life of people. To fully understand the biomechanics of the affected spine, it is crucial to consider the biomechanical alterations caused by degeneration of the intervertebral disc (IVD). Therefore this study is aimed at the development of a discrete element model of the mechanical behavior of the L4-L5 spinal motion segment, which covers all the degeneration grades from healthy IVD to its severe degeneration, and numerical study of the influence of the IVD degeneration on stress state and biomechanics of the spine. To analyze the effects of IVD degeneration on spine biomechanics we simulated physiological loading conditions using compressive forces.

The results of modeling showed that at the initial stages of degenerative changes, an increase in the amplitude and area of maximum compressive stresses in the disc is observed. At the late stages of disc degradation, a decrease in the value of intradiscal pressure and a shift in the maximum compressive stresses in the dorsal direction are observed. Such an influence of the degradation of the geometric and mechanical parameters of the tissues of the disc leads to the effect of bulging, which in turn will lead to the formation of an intervertebral hernia.

1. INTRODUCTION

Degenerative diseases of the lumbar spine are widespread among the population of different ages, and the problem of their treatment still remains unresolved. The complex structure of the intervertebral disc (IVD) ensures the redistribution of stress in the vertebrae [1, 2]; therefore, degenerative changes in the lumbar spine affect the biomechanics of the spine as a whole. One of the causes of degeneration of the spine is a change in the flow of nutrient fluid to the IVD. The disk is fed through the blood vessels passing through the cartilaginous end plates (CEP), 65% on the surface of the annulus fibrous (AF) 35% [3, 4]. It is known that in osteoarthritis

(OA), the nature of the nutrition of the IVD changes significantly. However, the exact mechanisms of nutrient transfer in the contact layers of the vertebral body-IVD are still not well understood. This information may be useful in the development of methods for the treatment and recovery of OA the spine. Therefore, it is relevant to study the conditions for the regeneration of biological tissues of the spine using computer simulation. Mechanobiological principles postulate that the regeneration of bone tissue is facilitated by stresses with an amplitude <0.15 MPa. Cartilage tissue regeneration is facilitated by compressive stresses with an amplitude of 0.15 to 2 MPa. It was noted that at stresses <0.003 MPa, chondrogenesis and osteogenesis do not occur, and compression stresses of the order of 0.7–0.8 MPa are most favorable for the formation of cartilage tissue. Optimal for the migration of living cells is the fluid pressure in the pores in the range from 20 kPa to 2 MPa [5].

The purpose of this work is developed of numerical model of mechanical behavior of the L4–L5 lumbar spine segment with OA change under physiological exposure.

2. OBJECTIVES

As an object of study, a model sample of the L4-L5 spinal segment in the healthy state and with OA was taken. The influence of degenerative changes in tissues on the creation of conditions for regeneration and the transfer of nutrients under static physiological loads was analyzed.

3. METHODS

We used the method of movable cellular automata (MCA) [6]. In MCA, the simulated material is represented as an group of cellular automata interacting with neighbours according to certain rules. The translations and rotations of automata are governed by the Newton-Euler equations. The interstitial fluid is taken into account by dividing the problem to be solved into two subtasks: 1) definition of the mechanical behaviour of the solid matrix; 2) definition of the fluid transport in a solid matrix. The solid matrix contains a system of interconnected channels and pores, which are implicitly taken into account. The description of the influence of a fluid contained in a solid matrix on the stress state of the medium is carried out on the basis of the Biot linear model of poroelasticity [6,7].

4. MODEL

To study the conditions of tissue regeneration and the redistribution of biological cells through the contact elements of the spine under physiological loads, the model of the L4–L5 lumbar spine segment and verification, validation this model presented in the papers [8], with the corresponding poroelastic parameters presented in Table 1 will be used.

Table 1. Mechanical properties of biological tissues healthy and with OA.

tissue	ρ_m, kg/m^3	G_m, MPa	K_m, MPa	φ, %	k, m^2
Cortical	1850	3600	8000	4	$5*10^{-18}$
Cortical(OA)	1950	3970	8600	3	$1*10^{-19}$
Cancellous	1000	1600	3600	80	$5*10^{-15}$
Cancellous(OA)	1100	1750	3800	75	$1*10^{-16}$
CEP	1000	1	5	80	$7*10^{-18}$
CEP(OA)	1100	1.3	6	75	$1*10^{-19}$
AF	1060	0.5	2.5	80	$3*10^{-19}$
NP	1060	0.3	1.6	80	$3*10^{-19}$

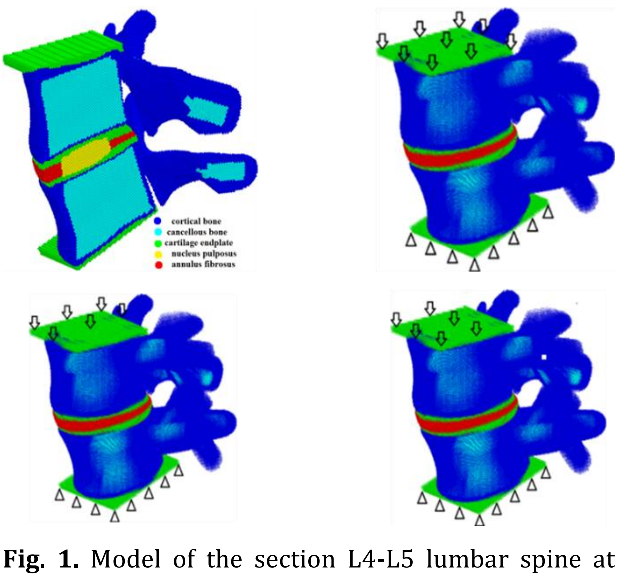

Fig. 1. Model of the section L4-L5 lumbar spine at different physiological load: (a) cross-section, (b) standing, (c) bending, (d) flexion.

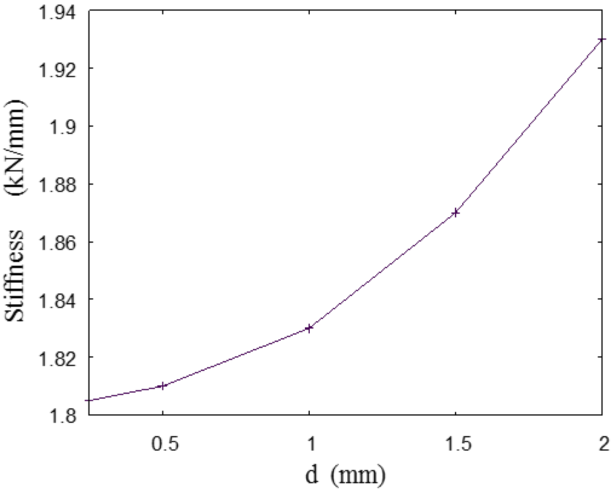

Fig. 2. Stiffness versus size of automata in the model sample.

The results on the convergence of the model stiffness showed that the dependence is nonlinear, and the total scatter between the values for the minimum and maximum size of elements does not exceed 10 % (Figure 3). Thus, further numerical studies were performed on the models with an automata size of 0.5 mm.

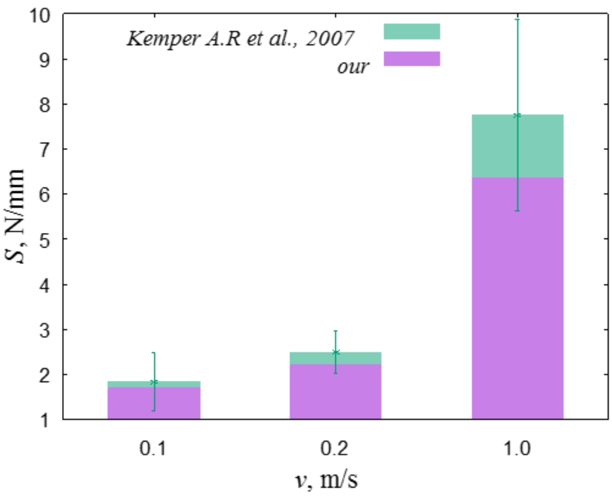

Fig. 3. Histogram of stiffness versus different loading rates.

In this work, the saccordancetiffness parameter of the lumbar spine model was validated in with the available experimental data [8].

5. RESULTS

It has been shown in the literature that during OA changes in CEP, the pressure in the NP and AF increases [9]. The fluid pressure in the NP increased as the CEP calcified, while its permeability and porosity decreased. These calculated predictions confirm the hypothesis that sclerotic CEP will lead to a decrease in the nutrient fluid in the mandible and protrusion of the mandible through the AF under compression and rotational loads. Lack of nutrient fluid and accumulation of waste metabolites can lead to excessive apoptosis of NP cells and loss of extracellular matrix [10].

To study the effect of osteoarthritis on the processes of regeneration of biological tissues, the patterns of distribution of hydrostatic pressure in a healthy segment of the spine (figure 4) and with OA changes (figure 5) were analyzed.

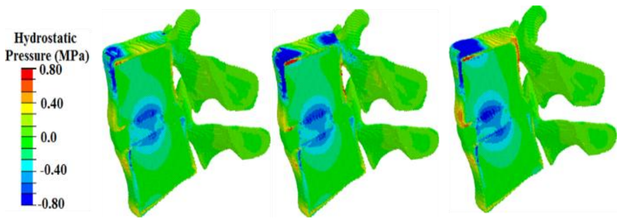

Fig. 4. Fields of hydrostatic pressure in the healthy spinal segment at different loading: standing (a), bending (b), flexion (c)

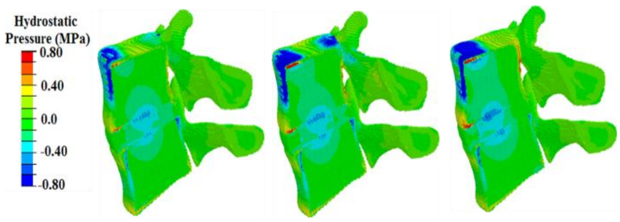

Fig. 5. Fields of hydrostatic pressure in the spinal segment with OA at different loading: standing (a), bending (b), flexion (c)

The obtained results (figure 6) indicate that under all types of physical activity in a healthy joint, conditions for the processes of chondrogenesis and osteogenesis are observed in the cortical layer. In the cancellous bone, conditions are created mainly for osteognosis; in CEP and NP optimal conditions for chondrogenesis are observed.

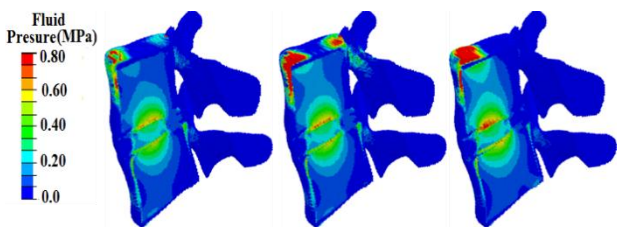

Fig. 6. Fields of Fluid pressure in the healthy spinal segment at different loading: standing (a), bending (b), flexion (c)

An analysis of the fluid pressure fields in the pores showed that when modeling the oropharyngeal joint in the area of the cortical and spongy tissue, an amplitude of the fluid pressure is observed that corresponds to the optimal values for the transfer of biological cells through the entire volume of the vertebra. At the same time, in the contact area "vertebral body-IVD", the maximum amplitude of pressure is observed and promotes the transfer of nutrients through this zone to the NP. In the AF the pressure level is below the optimal value, but at the same time lies in the range conducive to cell transfer.

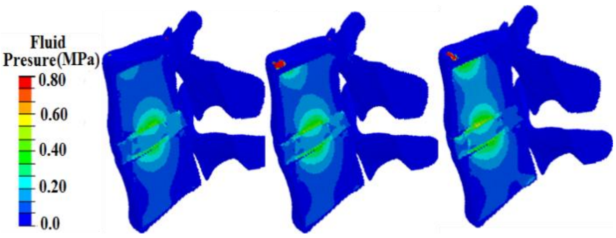

Fig. 7. Fields of Fluid pressure in the spinal segment with OA at different loading: standing (a), bending (b), flexion (c)

Analysis of fluid pressure distribution fields in the pores of the spinal segment with OA changes (figure 7) shows that the required level for osteogenesis and chondrogenesis of pressure is observed in a significantly smaller volume of cortical and cancellous tissue. At the same time, the maximum values of the parameter under study are concentrated (as in the case of the healthy joint) on the contact surface, which in turn contributes to the transfer of nutrients through the VB and CEP to the NP. At the same time, a level of fluid pressure in the pores is reached in the AF, which promotes the transfer of biological cells.

6. CONCLUSIONS

This work presents the results of a numerical study of the mechanical behaviour of the L4–L5 lumbar spine segment at healthy and light osteoarthritis degenerative changes. The simulation results showed that in OA, degenerative changes in the conditions for the activation of the processes of osteogenesis and chondrogenesis are preserved. However, the conditions for the transfer of biological cells (nourishment of the disk) change: thus, in the sore sample, the nutrition of the disk occurs mainly through cartilaginous platinum, while in the fibrous rings, the conditions for the transfer of biological cells are observed in a small volume. In osteoarthritis, the conditions for the intake of nutrients are also observed in the entire volume of the fibrous rings. This fact indicates a change in the nutritional regime of the intervertebral disc during degenerative changes, which, in turn, is likely to significantly affect the processes of disc degradation.

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