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Research article

Simulation of the Mechanical Behaviour of the Degenerated L4-L5 Lumbar Spine Segment

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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 considers the healthy state and early-stage degenerative changes of the L4–L5 intervertebral disc, 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 modelling results showed that, at the initial stages of degenerative changes, the amplitude and area of maximum compressive stresses in the intervertebral disc increased. In the degenerated model, a decrease in intradiscal pressure and a dorsal shift of the maximum compressive stresses were observed. These changes in the geometrical and mechanical properties of the disc tissues may contribute to disc bulging, which can further promote the development of an intervertebral hernia.

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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. Nutrient transport to the intervertebral disc occurs mainly through the cartilaginous endplates and, to a lesser extent, through the annulus fibrosus [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 osteoarthritic changes in 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 to develop a numerical model of the mechanical behaviour of the L4–L5 lumbar spine segment with degenerative changes under physiological loading.

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, together with its verification and validation, was previously presented in Ref. [8]. In the present study, this model was used with the poroelastic parameters listed in Table 1.

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	$3*10^{-19}$

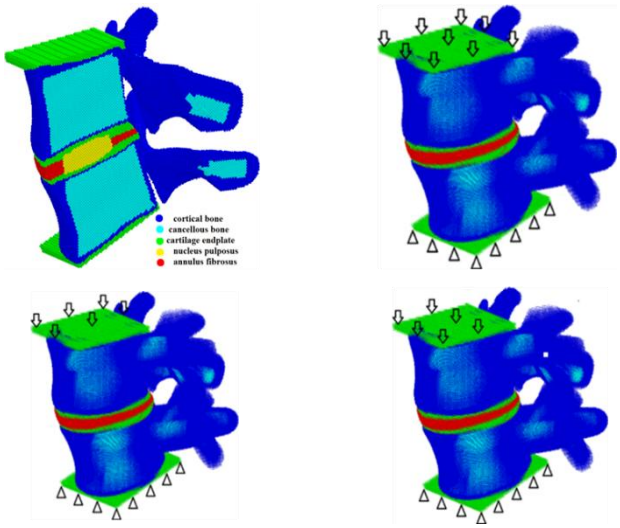


Fig. 1. Model of the section L4-L5 lumbar spine at different physiological load: (a) cross-section, (b) standing, (c) bending, (d) flexion.

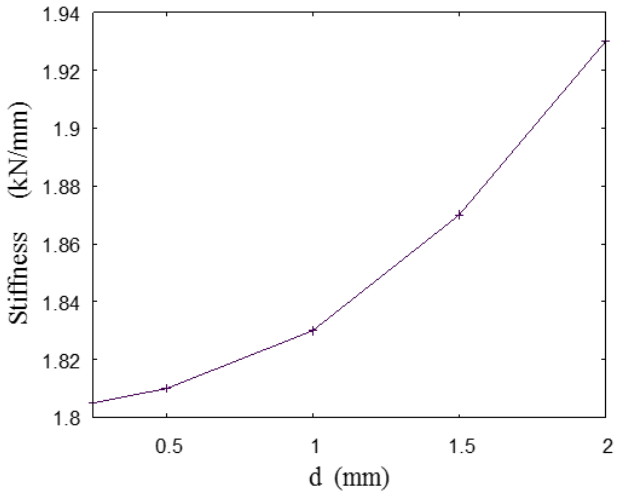


Fig. 2. Stiffness versus size of automata in the model sample.

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 2). Thus, further numerical studies were performed on the models with an automata size of 0.5 mm.

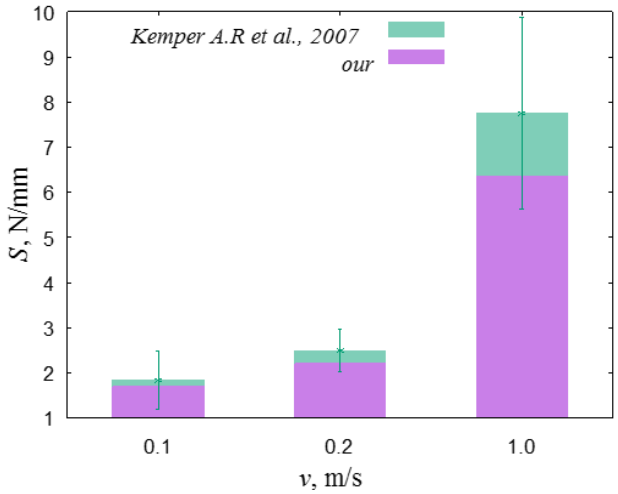


Fig. 3. Histogram of stiffness versus different loading rates.

In this work, the stiffness parameter of the lumbar spine model was validated against 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 nucleus pulposus and protrusion of the nucleus pulposus through the annulus fibrosus 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.

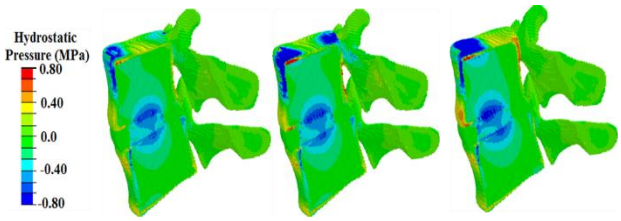


Fig. 4. Fields of hydrostatic pressure in the healthy spinal segment at different loading: standing (a), bending (b), flexion (c).

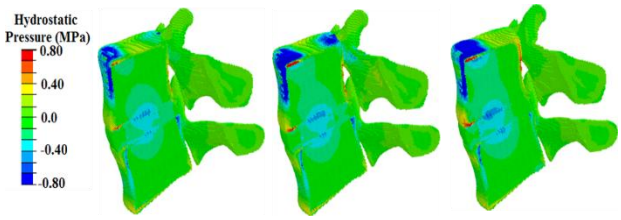


Fig. 5. Fields of hydrostatic pressure in the spinal segment with OA at different loading: standing (a), bending (b), flexion (c).

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 osteogenesis; in CEP and NP optimal conditions for chondrogenesis are observed.

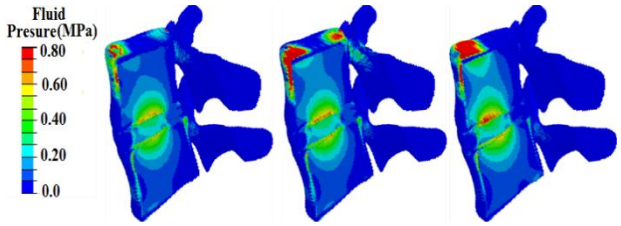


Fig. 6. Fields of Fluid pressure in the healthy spinal segment at different loading: standing (a), bending (b), flexion (c).

An analysis of the fluid pressure fields in the pores showed that when modeling the spinal segment 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.

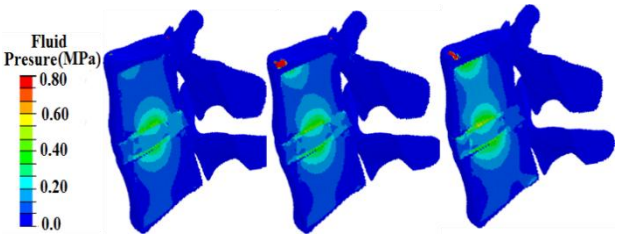


Fig. 7. Fields of Fluid pressure in the spinal segment with OA at different loading: standing (a), bending (b), flexion (c)

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 a numerical study of the mechanical behaviour of the L4–L5 lumbar spine segment in healthy and early degenerative states. The simulation results showed that degenerative changes alter the distribution of hydrostatic and fluid pressure in the intervertebral disc and adjacent tissues. In the healthy model, conditions favourable for osteogenesis and chondrogenesis were observed in larger regions of cortical bone, cancellous bone, cartilaginous endplates, and nucleus pulposus. In the degenerated model, these favourable conditions were reduced and shifted, indicating changes in nutrient transport and tissue regeneration potential. The results suggest that disc degeneration affects the nutritional regime of the intervertebral disc, which may contribute to further degradation and possible disc bulging.

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