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BIOMECHANICAL ANALYSIS OF THE INTERVERTEBRAL DISC IMPLANT USING THE FINITE ELEMENT METHOD

ABSTRACT

Dysfunctions of the vertebral column belong to a group of civilisation diseases and they affect approximately 80% of population. The underlying cause is modern (sedentary) lifestyle, low locomotive activity of people and frequent motor vehicle and sports accidents. Despite civilisation's progress, no injury prophylactics or prevention of dysfunctions of the vertebral column have been introduced. The key element influencing function of the vertebral column is the intervertebral disc. It enables multidimensional movements and constitutes a basic connective element between the joints of the vertebral column. It also enables performing basic daily activities. Acting as a ″damper″, it cushions vibrations and transmits loads between the vertebrae. One of the diseases affecting the intervertebral disc is discopathy. This is the most common degenerative disease, which can be treated by both conservative and surgical treatment. After removal of the damaged disc, it can be replaced by an adequate implant, which will assume its function. The implant will be expected to restore the vertebral column motor function, as well as to eliminate the pain resulting from compression of the spine caused by the damaged disc.

This paper presents a biomechanical analysis using the finite element method for the L2-L3 vertebrae system with natural intervertebral disc, and the L2-L3 – implant of the intervertebral disc system. Two cases of the system vertebrae-implant were analysed which differed in the placement of the artificial disc in the intervertebral space. Within the conducted analysis, the state of displacement, strain and stress of reduced analysed systems and their individual elements was determined. A comparative analysis of the results and calculations was performed, also conclusions and observations were formulated, constituting a starting point for building more advanced calculation models and further analyses of such implants.

***Keywords**: biomaterial, intervertebral disc, biomechanical analysis, finite element method*

INTRODUCTION

The indication for surgical treatment of a damaged intervertebral disc is continued presence, despite the conservative treatment, for a period of 3 weeks of severe neurological disorders such as: feet paresis, abirritation of reflexes or sphincter function disorder. In the treatment of the intervertebral disc damage, vertebral distractors and stabilisers are used increasingly often [1-5].

In clinical practice, the stabilisation method has been applied for a long time. It involves immobilisation with the use of stabiliser of the mobile segment, which consists of two vertebrae and the degenerated intervertebral disc. This results in acceleration of the wear process of the discs in the adjacent segments, due to an increase in the range of movement required to compensate for the stiffening. The intervertebral disc implants have become an alternative to stabilisation. Previous studies indicate that in certain dysfunctions of the disc implants appear to be a better solution than stiffening of the vertebrae [6].

Beneficial clinical effects include: pain alleviation, restoration of the function of articulation, avoidance of postsurgical complications, shortening of the convalescence period, easy implantation and safe revision [6]. Biomechanical benefits include: providing the required mobility in the segment, cushioning of any sudden increase in load, reducing the load on the adjacent motor segments, ensuring biomechanical stability and proper adherence of the implant to the bone. Pain is minimised by removal of the degenerated disc and restoration of proper muscle and ligament tone. Proper functioning of the articulation is recreated by enabling movement, and restoration of the adequate distance between the vertebrae, as well as the diameter of the vertebral conduit [6,7].

Considering the fact that in clinical practice implants of the intervertebral disc are used increasingly often in the treatment of disorders of the vertebral column, the paper undertakes the analysis, using the numerical methods, of comparison between stability and transmission of loads generated by the organism on a spine with a natural and an artificial intervertebral disc. The analysis was based on 2 versions of the systems in which model of the artificial intervertebral disc was used. In the first version the disc was introduced to the organism in an appropriate way and was located centrally in the spine whereas in the second version an incorrect implantation of the artificial intervertebral disc was applied. Analysis conducted this way enabled not only to determine the state of displacements and stress of the whole system but also allowed to evaluate areas endangered with damage caused by cooperation and potential overload of the elements involved in the system [8]. Moreover, obtained results enabled to estimate the influence of the placement of the implant on the appointed values of displacements and stress of the analysed system and its particular elements.

Based on multiple physical and mathematical models, adequate biomechanical systems can be built, whereas the finite element method enables to determine the state of stress and displacement in conditions similar to real ones. The results provide a basis for optimisation of structural characteristics of the system’s individual elements, as well as for selection of proper mechanical properties of the biomaterial [9-14].

MATERIALS AND METHODS

The model of the intervertebral disc implant used in the analysis is one of the most commonly used implants for cervical and lumbar spine. It consists of three components creating a ball joint. Between two skid plates made of Co-Cr-Mo alloy there is an insert made of ultra-high molecular weight polyethylene PE-UHMW (UHMWPE). The modular structure of ProDisc allows adjusting it to individual characteristics of a patient’s vertebral column (Fig. 1).

Fig. 1. Pro Disc II intervertebral disc implant [15]

This paper contains a biomechanical analysis of three models, using the finite element method and performed in the ANSYS programme:

- model I – L2-L3 segment of the vertebral column with a healthy intervertebral disc,
- model II – L2-L3 segment – ProDisc II implant of the intervertebral disc (Fig. 2a).
- model III – L2-L3 segment – implant of the intervertebral disc ProDisc II incorrectly applied and dislocated in regards to the axis of the spine (Fig. 2b).

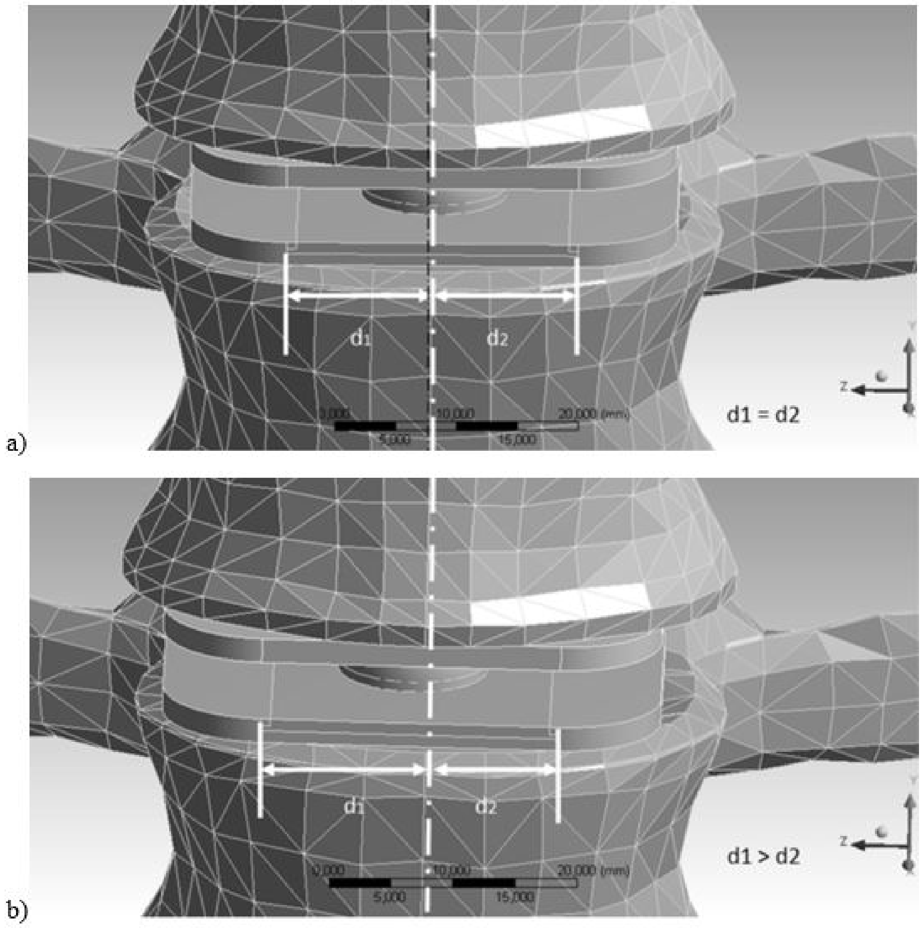


Fig. 2. The placement of the intervertebral disc implant: a) model II, b) model III

The material properties assumed for the elements in the calculation system are presented in Table 1.

***Table 1**. Mechanical properties of materials used for numerical analysis [16-18]*

Material	Young's modulus E, MPa	Possion ratio
Co-Cr-Mo alloy	200 000	0,3
vertebra	12 000	0,3
natural intervertebral disc	500	0,4
cardrige UHMWPE	830	0,4

In the analysis, a geometric model of the lumbar part of the vertebral column was used, particularly the L2-L3 segment (FIG. 3a) and a geometric form of the intervertebral disc implant, developed on the basis of the Pro Disc II prosthetic, using the Inventor software. (Fig. 3b).

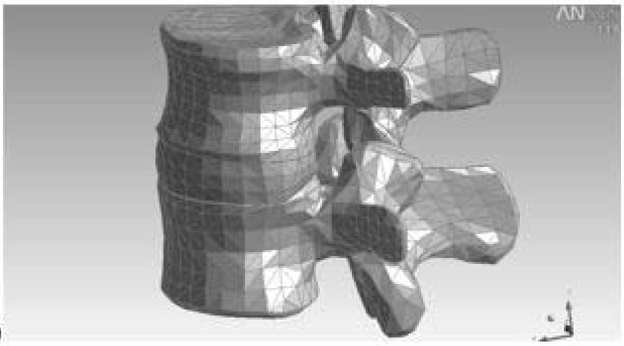
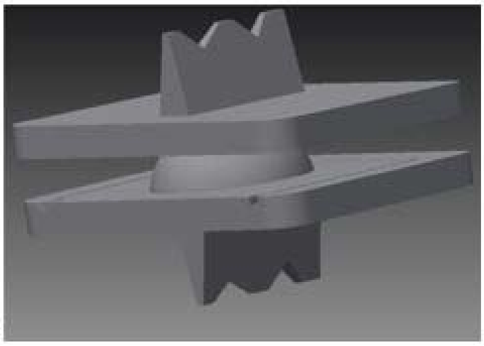
a)

b)


Fig. 3. Geometrical model of the system: a) L2-L3 section of spine, b) Pro Disc II intervertebral disc implant

Based on the geometric models, a network of finite elements was generated. The SOLID 187-type finite element for the analysis of three-dimensional forms was used for discretisation.

In the course of the study, the state of reduced displacement, strain and stress was determined. To perform calculations it was necessary to establish and determine the initial and boundary conditions. For the purposes of the model I and model II, the following assumptions were made:

- L3 vertebra was immobilised by divesting all the nodes on the lower joint surface of the vertebral corpus of all the levels of freedom, which disabled its displacement or possible rotation (Fig. 4a)
- L2 vertebra was evenly loaded on the whole upper joint surface of the corpus with the force F acting towards the y axis and the loading moment M causing the spine to bend forward in the saggital plane (Fig. 4b).

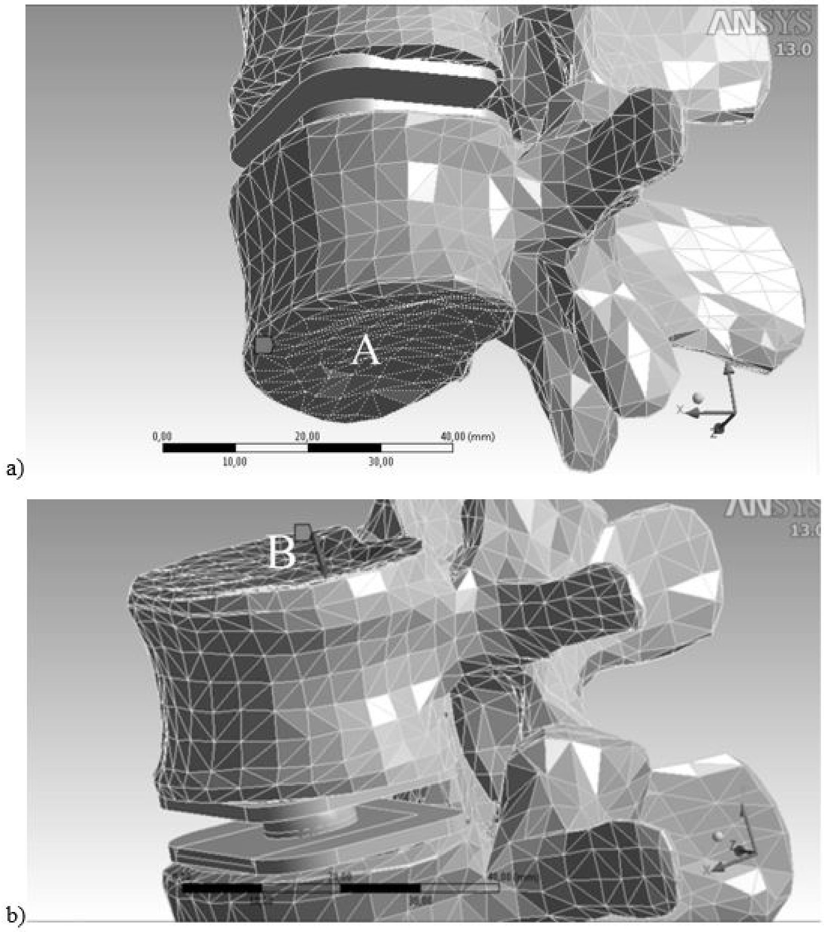


Fig. 4. Schematic presentation of the boundary conditions used in numerical analysis: a) place “A” of attaching fixed support, b) place “B” of attaching loading force F

In the analysis a loading force F 1500 N and loading moment M = 7,5 Nm was used. The compressive forces acting on the vertebral column are significantly increased when lever mechanism is applied. Together with the corpus, arms create the long part of the lever. The weight of the lifted object is balanced with constriction of the erector spine, which acts along the short arm of the lever. Value of the load assumed in the analysis is the value transmitted through the lumbar section of a person weighing 154.3 lbs (70 kg) during ordinary daily activities, such as standing in a vertical position [19].

In the prepared calculation model simplifications based on omission of cancellous bone were used. Furthermore, uniform type of intervertebral disc was applied in the model I and ligaments were omitted. Such simplifications of the model resulted in the transmission of all the loads to the disc or the implant of the intervertebral disc, which allowed to determine areas where occurs accumulation of stain at the moment of the contact between implant and the bone in the conditions of its loading, which can become a basis to the optimization of the implant.

For the prepared calculation models a state of displacement, strain and stress (reduced according to the Huber-Misses strength hypothesis) was determined. Those quantities were determined particularly for the whole calculation system, as well as for its individual elements.

RESULTS

The obtained values for reduced displacement, strain and stress are presented in Table 2 and in figures 5-7.

Presently, intensive research is being conducted in the world with relation to finding new methods of treating intervertebral disc dysfunctions, both using the traditional methods of stabilisation and modern intervertebral implants. The focuses on the lumbar and cervical section of the vertebral column, as well as on finding modern materials which are expected to replace the damaged intervertebral discs with regard to their function in a manner as similar as possible to the real ones [20]. The studies use both traditional, experimental research techniques and computational methods [21-23]. Authors concentrate mainly on determining states of strain and stress in the natural disc structures, as well as in implants, searching for optimal solutions and verifying clinical experience. The studies contribute to development of new indications in injuries of the vertebral column [24, 25].

The analysis of the results indicates that in with the used loading force F and loading moment M of the model I of the L2-L3 spinal segment containing a natural intervertebral disc, the maximum reduced displacement is LI = 0.13 mm (Fig. 5), and corresponding reduced stress is σmax I = 3 MPa, and does not exceed the limit value for compressive strength of the bone tissue cortex in the vertebral corpus, that is Rc = 192 MPa (Fig. 6). As a result of loading the system compressive force F and loading moment M causing bend forward the L2 vertebra was displaced and rotated in the posterior direction in the sagittal plane. This has caused location of the maximum values of the reduced stress values in the front part of the stems. Replacement of the natural disc with an implant in model II did not affect the way in which the system was displaced and rotated, and, similarly to model I, as a result of loading, the L2 vertebra moved forward in the sagittal plane. In model II slightly higher values of reduced displacement were observed, and with maximum loading it was LII = 0,19 mm. The corresponding reduced stress for the whole system was $\sigma_{max\ II}$ = 56 MPa, and did not exceed the plasticity limit value for metallic biomaterial, that is $R_{p0.2}$ = 450 MPa, at the same time exceeding the compressive strength value of the vertebral corpus cortex R_c = 192 MPa (Fig. 6 a, b, c). The determined maximum stresses were occurred in certain points and resulted from accumulation of stresses related to the size of the finite element used in the calculation model and the cooperation between vertebra and the implant. In the model III, in which the implant of the intervertebral disc was introduced incorrectly, the increase of the obtained values of displacements and reduced stress were observed in the comparison with model II. Appropriately maximum displacement of the vertebra L2 for model III was LIII = 0,43 mm, maximum appointed stress was assigned to metal biomaterial of the implant and reached σIII = 67 MPa (Fig 5 and 6). Conducted analysis of the distribution of displacement of the upper disc of the implant for the analysed model indicated their asymmetrical placement in the traverse plane in regards to sagittal plane crossing the axis of the spine in case of model III (Fig 7).

Table 2. *Results of numerical analysis for solution model I and II*

	F, N/ M, Nm	Model I			Model II			Model III		
		L_I, mm	ε_I, %	σ_I, MPa	L_{II}, mm	ε_{II}, %	σ_{II}, MPa	L_{III}, mm	ε_{III}, %	σ_{III}, MPa
vertebra	1500/ 7,5	0,13	0,41	3	0,19	0,16	19	0,43	0,23	27
intervertebral disc		0,08	0,65	3	-	-	-	-	-	-
Co-Cr-Mo alloy		-	-	-	0,16	0,02	56	0,33	0,03	67
UHMWPE cardrige		-	-	-	0,11	2,20	18	0,14	2,70	23
F – loading force, M – loading moment, L – displacement, ε – von Misses strains, σ – von Misses stress										

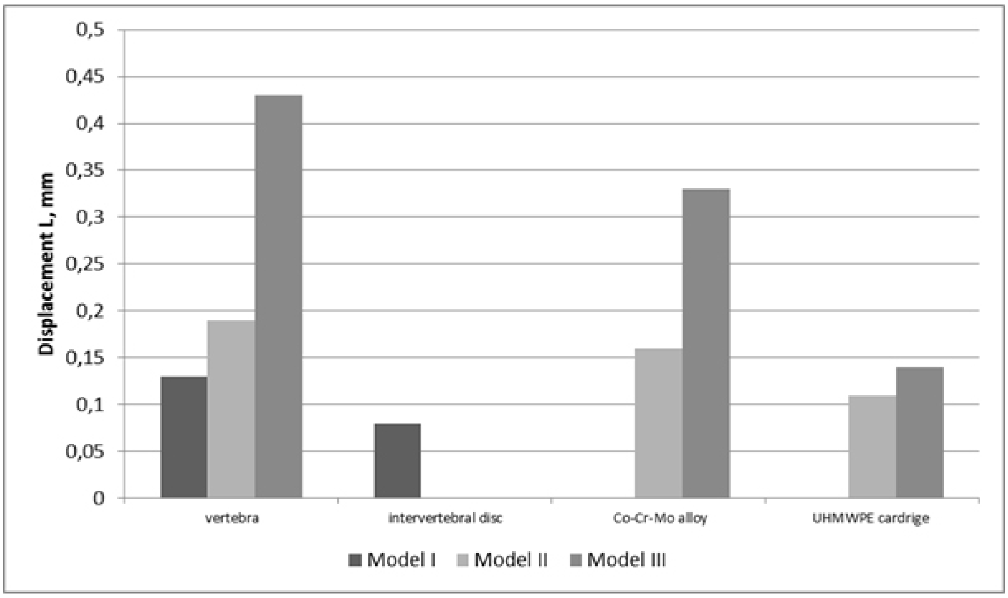


Fig. 5. Values of displacement in the system element's

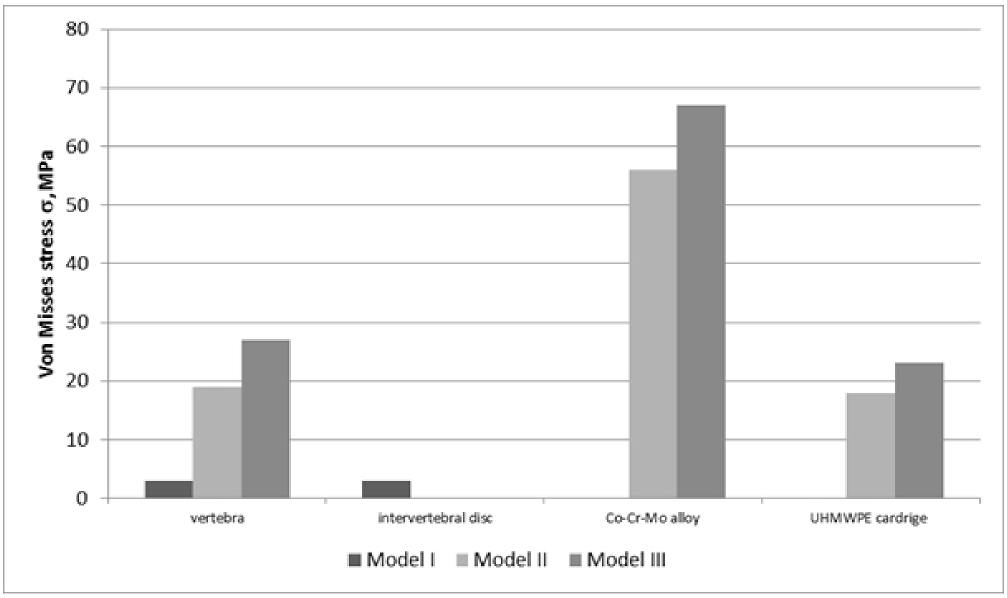


Fig. 6. Values of von Misses stress in the system element's

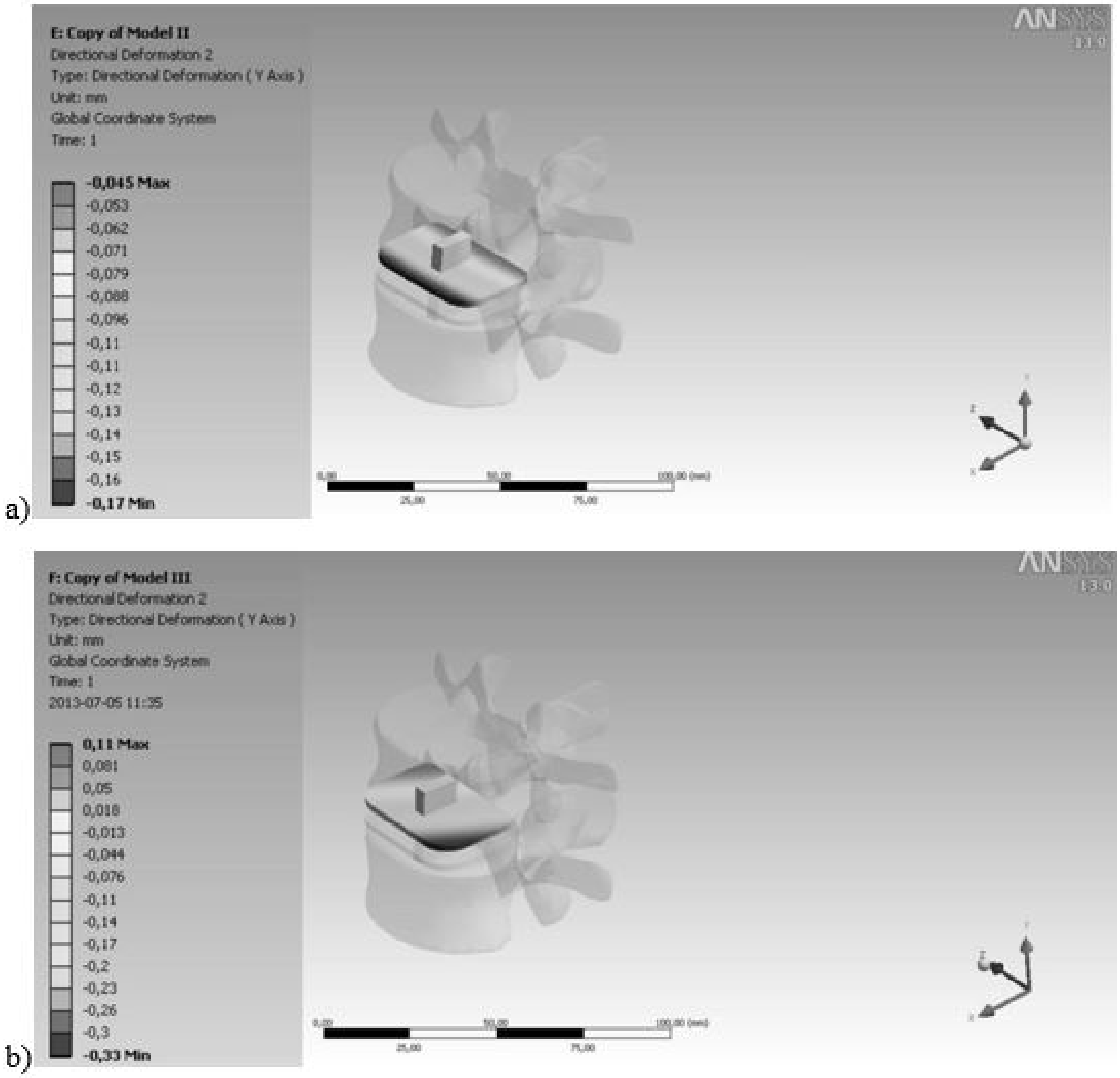


Fig. 7. Comparison of displacement in sagittal plane for models: a) II, b) III

CONCLUSIONS

The results of the numerical analysis using the finite element method of the lumbar L2-L3 section of the vertebral column with natural intervertebral disc and with an implant revealed that replacing the natural disc with an implant introduced correctly into the axis of a spine does not affect the functioning of the whole system, and with loading both systems act similarly. Simultaneously, an minimally increased mobility of the L2-L3 segment containing the implant was reported. The assumed in model III incorrect position of the implant characterized by dislocation with regard to the axis of the spine in the front plane resulted in the change in the way of functioning of the analysed system in the comparison to model I and II. Higher values of displacements and stress in the system were observed, and the vertebre L2 in regards to L3 was displaced and rotated in the sagittal and front plane.

Increased movement of the models with the implant of the intervertebral disc It resulted from the structure of the implant, especially the structure of the polyethylene insert, its shape and geometrical properties. Mechanical properties of the biomaterial the insert is made of are also important and worth considering while designing such implants. The material should provide proper resilience, elasticity and strength similar to that of a natural intervertebral disc. Using materials with similar characteristics will contribute to proper restoration of the motor function in the injured section of the vertebral column.

Moreover, proper preparation of the metallic biomaterial elements is very important, as well as precise choice of the implant's geometry and its placement centrally where the removed natural disc was. Inadequate size of the elements may lead to local overload of the bone structures, resulting in a damage to the vertebral segment, recurrence of the pain symptoms, and to eventual loosening of the implant. Wrong placement of the implant will lead to changes in the loading transmission, resulting in disturbing of the biomechanical balance of the skeletal system and contributing to a significant worsening in the patient's quality of life.

Summing up the numerical analysis, it needs to be emphasised that assumed boundary conditions significantly influenced the obtained results. In natural conditions the vertebrae in the mobile segments of the vertebral column are joined with intervertebral discs made of annulus fibrosus and nucleus pulposus. Additionally, the vertebrae are stabilised by a system of very strong ligaments and muscles which enable movements [16]. In the presented analysis a simplified loading model was used, ignoring the ligaments and muscles. Thus, the obtained results are preliminary and constitute a starting point for further analyses using a more developed loading system, considering the specificity of the function of the lumbar spine in real conditions, at the same time creating conditions for better optimisation of the structural characteristics of the intervertebral disc implant.

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