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The biomechanical analysis of the traumatic cervical spinal cord injury using Finite Element approach

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According to up-to-date knowledge only mathematical modelling of the spinal cord injury (SCI) may provide real insight into a spatial location of the fields of the spinal cord mechanical strain generated by the injury. The purpose of our research was to correlate the results of Finite Element Analysis of SCI with the patient's neurological state and the injured spinal cord MR imaging.

The 3D Finite Element Model of the cervical spinal cord and vertebral canal of a 21-year-old male patient was created. The moment of the injury was reconstructed by a simulation of the displacement of nonelastic structure to the light of vertebral canal. A detailed spatial analysis of the stress, strain and dislocation distribution was performed.

The most injured region was the superficial zone of the white matter, the anterior part and central region of the grey matter, which was in good agreement with patient's neurological staus. An individualized Finite Element Model of traumatic SCI constructed by us enabled the evaluation of the influence of mechanical strain on a neurological condition of a patient. Further research will consist in validation of the results of endurance analyses based on a enlarged group of patients.

Key words: spinal cord injury, biomechanics, Finite Element Analysis, neurological recovery

1. Introduction

Traumatic spinal cord injuries (SCI) are a vital problem of a modern medicine. Despite a tendency between injured to become older [1], it is still mostly young persons who suffer from SCI, which is connected with severe social, mental and financial consequences. According to statistical data, each year 40 new cases of SCI per million USA nationals are reported [2]. As a result of the cervical spine injury, 54% of patients become tetraplegics and in almost 56% cases a complete spine injury is diagnosed [3]. The total cost of the treatment of the injured in the USA amounts to $ 9.7 billion per year [1].

In spite of a significant progress in the field of the basic science [4]–[14], the pahtophysiology of traumatic SCI still remains insufficiently surveyed. Our ability to assess properly the spinal cord injury is still limited to systematic neurological condition evaluation and an analysis of magnetic resonance images before and after the treatment [15], [16]. The most significant prognostic value of the latter method is ascribed to the presence (recently also the extensivity) of the hemorrhagic focus [15].

The influence of a scale and a layout of mechanical stress and strain in the spinal cord are considered by PANJABI and WHITE one of the main causes of neurological deficits observed in the patients with SCI [17], [18]. BILSTON and THIBAULT [19] surveying the mechanical properties of the spinal cord assumed the possibility of using the data gained for the research based on the Finite Element Analysis (FEA). According to up-to-date knowledge only mathematical modelling of the SCI phenomenon may provide real insight into a spatial location of the fields of the spinal cord mechanical strain generated by the injury. Such a knowledge may enable a more detailed pathophysiological

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examination of traumatic SCI and provide an opportunity to predict more reliably further condition of patients [17], [18]. Such attempts were made by WILCOX et al. [14] and ICHIHARA et al. [20], [21].

The former researched a process of a thoracic vertebra burst fracture based on the FEA model, which included also the spinal cord. However, the researchers did not provide any information about the mechanical strain of the very spinal cord. ICHIHARA et al. [21] modelled, e.g., a severe injury of the spinal cord using the FEA model. Both teams analysed the cases of hypothetical model injuries, which significantly limits the possibility of interpreting the data collected.

Taking account of the fact that the vast majority of the spine injuries are connected with the spinal cord injury and over 60% of the spine injury damages take place in cervical part [22], in our research we have focused on the analysis of this part of the spinal cord. The purpose of our research is to analyse the mechanical strain, imposed on the cervical part of the spinal cord of the patient, based on the three-dimensional, highly individualized FEA model, and to correlate the results obtained with the neurological state and the MRI image of the spinal cord directly after the injury and some time later. To our knowledge, similar attempts have not been made yet.

2. Materials and methods

For the purpose of the research, we have developed a three-dimension model of the cervical spinal cord and vertebral canal of a 21-year-old male patient with a complete spinal cord injury.

2.1. Patient

The 21-year-old male patient, G.A., on June 22, 2006 suffered from a cervical spinal cord injury as a result of a head-on diving. After the admission to the our centre the patient underwent the following diagnostic procedures:

- Systematic control of the neurological status completed with an examination with the use of an ASIA protocol.
- Neuroimaging: CT, MRI (in the day of admission and two months after the injury). A detailed metrological analysis of the CT and the MR images was performed using the procedure presented previously by BONO et al. [23]. The severity of the vertebral column injury was assessed based on the analog scale proposed by MOOR et al. [24].

2.2. Finite Element Model

Model construction. Model was built in the ANSYS 10.0 (ANSYS, Inc.) environment. The white matter and the grey matter were modelled as separate structures by eight-node brick elements. The mechanical properties of the white matter and the grey matter were considered on the grounds of ICHIHARA's et al. [21] experiments. The pia matter, which significantly influences the biomechanical properties of the spinal cord [25], was modelled by flexible four-node shell elements with Young's modulus and Poisson's ratio presented by OZAWA et al. [26]. The dura matter was similarly constructed with the use of flexible four-node shell elements and its mechanical properties were applied according to the procedure adopted by WILCOX et al. [12]. Following the results of the NICOLAS' and WELLER's experiment [27], the thicknesses of the pia matter and the dura matter were estab-

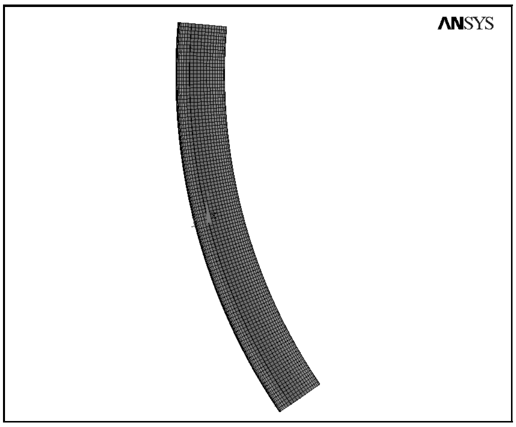


Fig. 1. Finite Element Model of the cervical spinal cord and vertebral canal. Lateral view

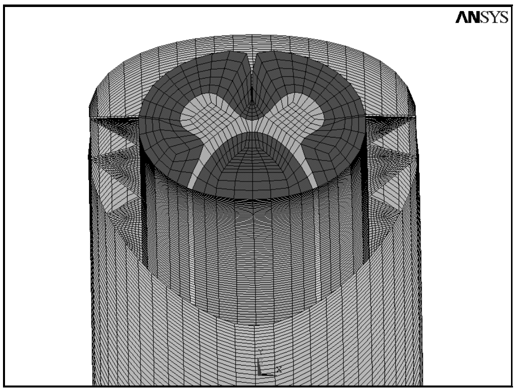


Fig. 2. Close-up view of the structure of the spinal cord FEA model. The model consists of grey matter, white matter, pia matter, denticulate ligament and dural sac

Table. Mechanical properties of the components of spinal cord model

Material	Element	Mechanical properties	References
Grey matter	8 node, brick	$E = 0.656$ MPa, $\upsilon = 0.499$	[21]
White matter	8 node, brick	$E = 0.277$ MPa, $\upsilon = 0.499$	[21]
Pia matter	4 node, shell	$E = 2.3$ MPa, $\upsilon = 0.3$	[26]
Dura matter	4 node, shell	$E = 142$ MPa, $\upsilon = 0.45$	[12]
Denticulate ligament a) Membranous component b) Solid component	4 node, shell 8 node, brick	a) $E = 2.3$ MPa, $\upsilon = 0.3$ b) $E = 100$ MPa, $\upsilon = 0.3$	a) [26] b) [29]

lished to be 0.1 mm and 0.4 mm, respectively. Denticulate ligament, playing a vital role fixing the spinal cord in vertebral canal [28], was created as a complex of shell–pia matter component and solid–collagenous component according to NICOLAS and WELLER [27] and TUNITURI [29]. The FEA model (figures 1 and 2) consists of 109046 elements and 110170 nodes.

Mechanical properties of the structures described are presented in the table.

The model individualisation. At the very beginning of the numerical procedure, the operator had the possibility of setting the following parameters: 1) the axial and transverse diameters of the spinal cord and anterior median fissure, 2) cephalocaudal extension of the spinal cord, 3) geometry of the dural sac. An adequate information was gained during a metrological analysis of the patient's neuroimaging documentation. In the metrological analysis, Scion Image for Windows 4.0.3 (Scion Corporation, 2000) was used. The measurements performed are presented in figure 3.

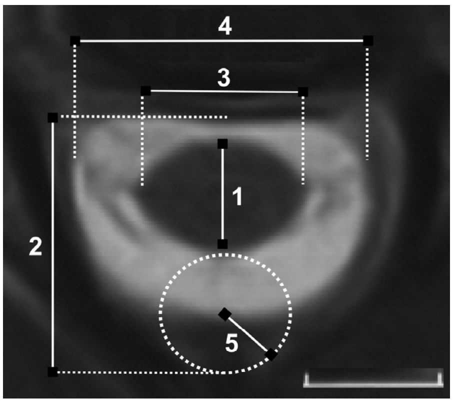


Fig. 3. The MRI transversal section of the patient's cervical spinal cord. The measurements performed: 1) anteroposterior diameter of the spinal cord; 2) anteroposterior diameter of the dural sac; 3) transverse diameter of the spinal cord; 4) transverse diameter of the dural sac; 5) the radius of a dorsal curvature of the dural sac. The bar indicates 10 mm

The injury simulation. The moment of the injury was reconstructed few days after the patient's admission by simulating the displacement of nonelastic structure to the light of vertebral canal (figure 4). The shape and trajectory of the artificial C3 vertebral body fragment were obtained due to a detailed analysis of the fusion of the patient's CT and the MRI images. Taking into account the irregularity of the bone fragment, the length the vector of the displacement ranged from 5.3 to 1.3 mm for the most central and most peripheral regions of the spinal cord's transversal section, respectively.

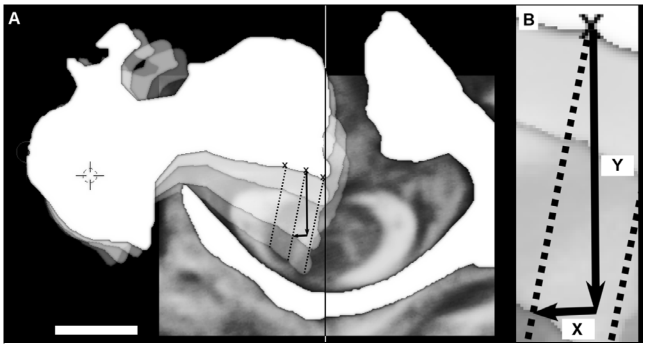


Fig. 4. Displacement of the bone fragment into the vertebral canal. The simulation of the rotation of free bone fragment around the axis perpendicular to the facet of the right superior articular process. Control points are indicated as *X*. The trajectory of the displacement is shown as a line interpolating control points in the subsequent steps of rotation (A). The real vectors of the displacement are represented by its *X* and *Y* components (B). The bar indicates 10 mm

The pia matter was immobilised in the anteroposterior direction (the *Y*-axis) on the level of C3 vertebra, which simulated the presence of C3 neural arch. The mobility of the remaining spinal cord segments was reduced and controlled by a denticulate ligament attached to the stiff and motionless dura mater.

3. Results

3.1. Patient

June 2006. Neurological status: tetraplegic patient with the symptoms of complete spinal cord injury. (ASIA A).

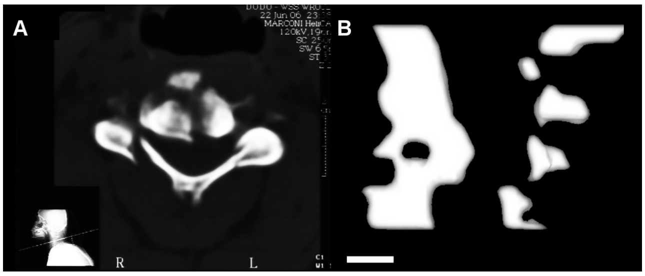


Fig. 5. Post-injury CT evaluation. Transverse scan reveals serious displacements of bone fragments (A). Sagittal reconstruction shows the narrowing of the vertebral canal (B)

CT of the cervical vertebral column: the burst fracture of the C3 and C4 vertebral bodies with the fracture of both laminas of C3 neural arch. The stenosis of a vertebral canal and the severity of injury were assessed to be 32% and 11/20 points, respectively (figure 5).

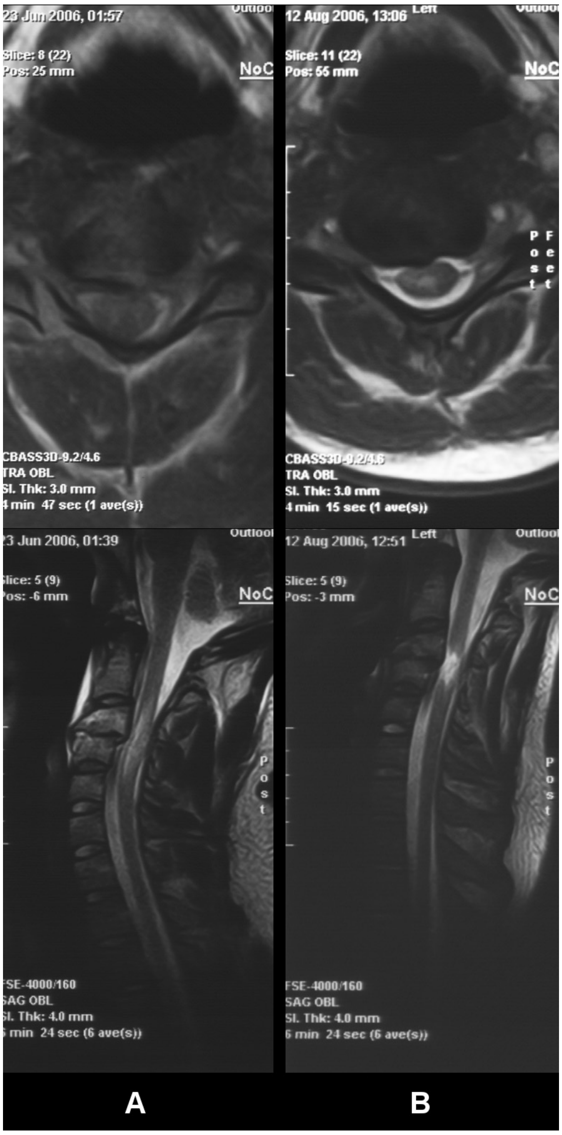


Fig. 6. Sagittal and transverse MRI images one day (A) and two months (B) after the injury. A detailed description in the text

MRI of cervical spinal cord: the area of a high signal on T2-weighted sequence in the C3 and C4 segments. The compression of the dural sac (particularly on the right side) and the right C4 ventral root.

August 2006. Neurological status: paraplegic patient (paralysis of lower extremities), ASIA D (236 points: lower extremities – 9, upper extremities – 7, sensory function – 120, the presence of a voluntary anal contraction).

MRI of the cervical spinal cord: the volume of 0.9 cm × 1.3 cm × 0.5 cm diameters of the high signal on T2-weighted and CBASS sequence and low signal on T1-weighted sequence in the C3 and C4 segments. The image indicates the presence of the spinal haemorrhage. The breakthrough of the MRI results is presented in figure 6.

3.2. FEA model

The simulation of the patient's spinal cord injury has revealed that the most injured region was the superficial zone of the white matter being in a direct contact with a free bony fragment. Taking into account the severity of the damage of the grey matter, its anterior part of the injured side and a central region of the grey matter were subjected to the greatest strains. The detailed analyses of the stress, strain and displacements of the spinal cord model have been presented in figures 7–9 and graphs 1–6.

4. Discussion

Finite Element Analysis (FEA) has been a tool used to analyse the vertebral column mechanics for many years [30], [31]. Owing to the above-mentioned tool, a biomechanical examination of various parts of the spine under proper [32], [33] and pathological [14], [34] conditions has been carried out. Despite a considerable advance in the biomechanics of osseous and ligamentous structures of vertebral column, the few of them tackling the issue of mathematical modelling of the spinal cord mechanics are available [14], [20], [21].

A mechanical strain of the spinal cord in the course of injury was investigated by PANJABI [17], [18]. His deliberations were based on simple geometrical models and the knowledge of the physiology of dura, pia matter and denticulate ligament of the spinal cord. Not being in possession of the detailed

Fig. 7. Finite Element Model of the cervical spinal cord. Deformation of spinal cord cross-section in the region of load application: a) original shape of model cross-section, b) deformation caused by 25% of maximal loading, c) deformation caused by 50% of maximal loading, d) deformation caused by 75% of maximal loading, e) deformation caused by maximal loading

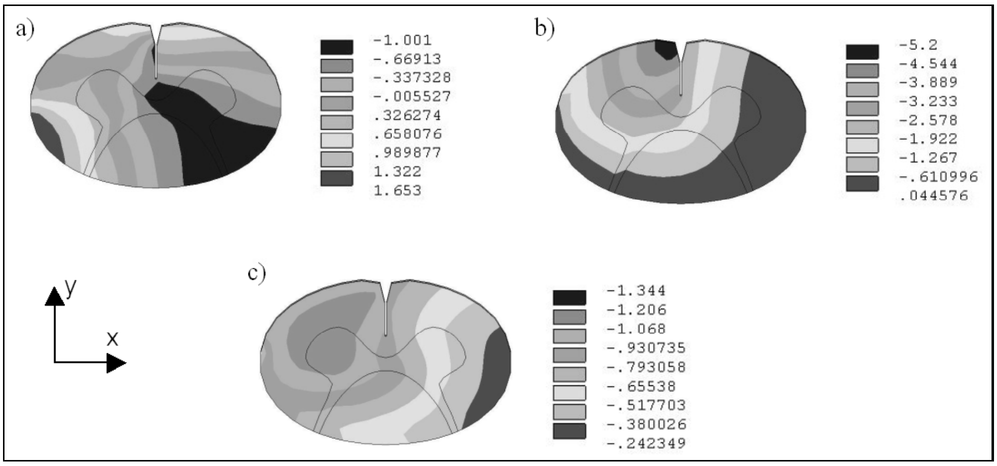


Fig. 8. Finite Element Model of the cervical spinal cord. Distribution of displacement components in the spinal cord cross-section: a) U_x displacement component, b) U_y displacement component, c) U_z displacement component

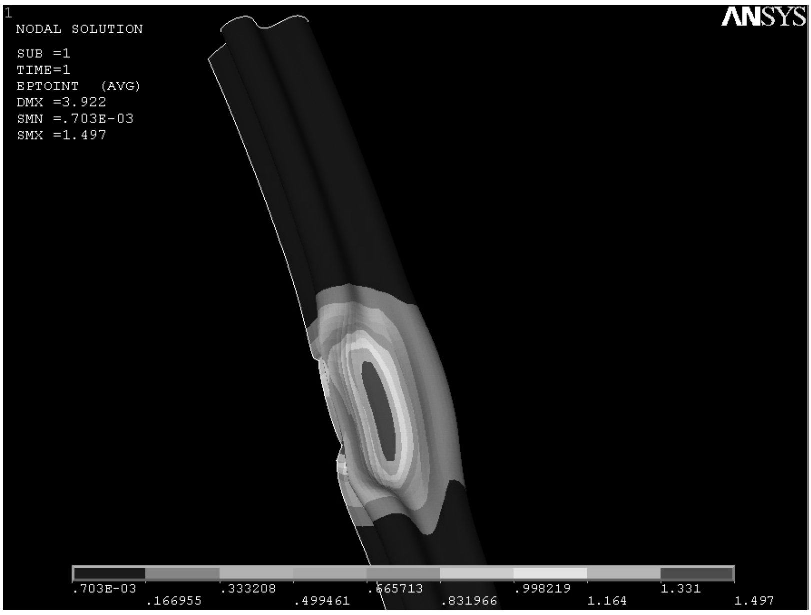
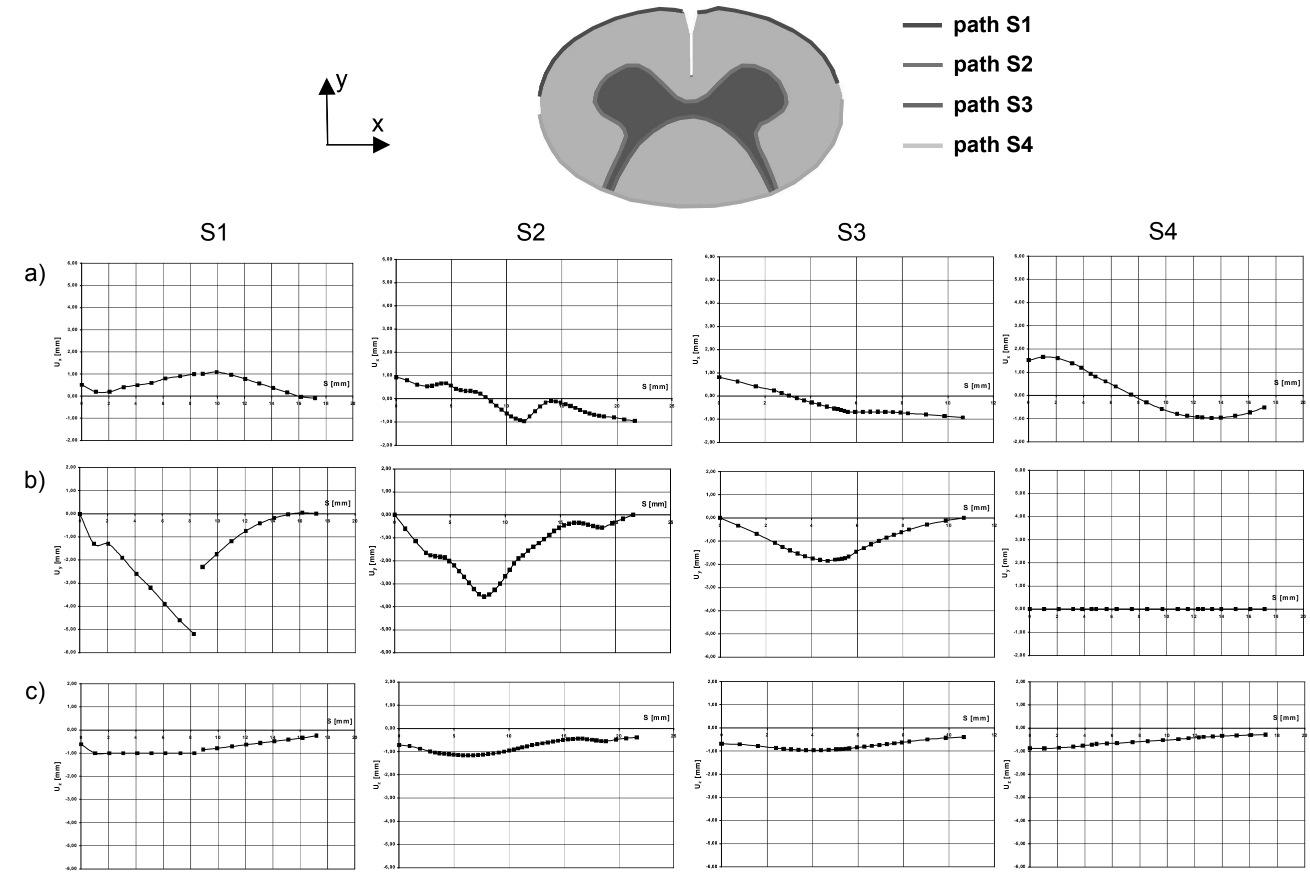


Fig. 9. Finite Element Model of the cervical spinal cord grey matter, the post-injury view.
The sum contour plot of grey matter displacement vector.
Bright colours indicate the fields of the highest rate of the deformation

endurance parameters of the structures analysed, the researcher was not able to build a mathematical model of the spinal cord. An advanced research concentrated on the biomechanics of a nervous tissue has been commenced relatively recently. For a long period of time, it was common knowledge that the grey matter and the white matter of the spinal cord do not differ in their biomechanical properties [19], [35]. The thesis by ICHIHARA was the watershed in the above-mentioned matter [21].



Graph 1. Displacement distribution along selected paths: a) U_x displacement component on paths S1–S4, b) U_y displacement component on paths S1–S4, c) U_z displacement component on paths S1–S4

Apart from introducing mechanical properties of the white matter and the grey matter, the author made an attempt to create a FEA model of a severe spinal cord injury [20], [21]. Although the results of his experiments have a significant empirical value, they cannot be implemented in a given clinical case in a straightforward manner, taking account of the idealized geometry of the model and hypothetic conditions of the osseous fragment relocation.

A three-dimensional model of the spinal cord used in a simulation of a burst fracture of the thoracic vertebra was created by WILCOX et al. [14]. In all probability the mechanical strain of the spinal cord was not the subject of their interest and no data regarding the above was presented.

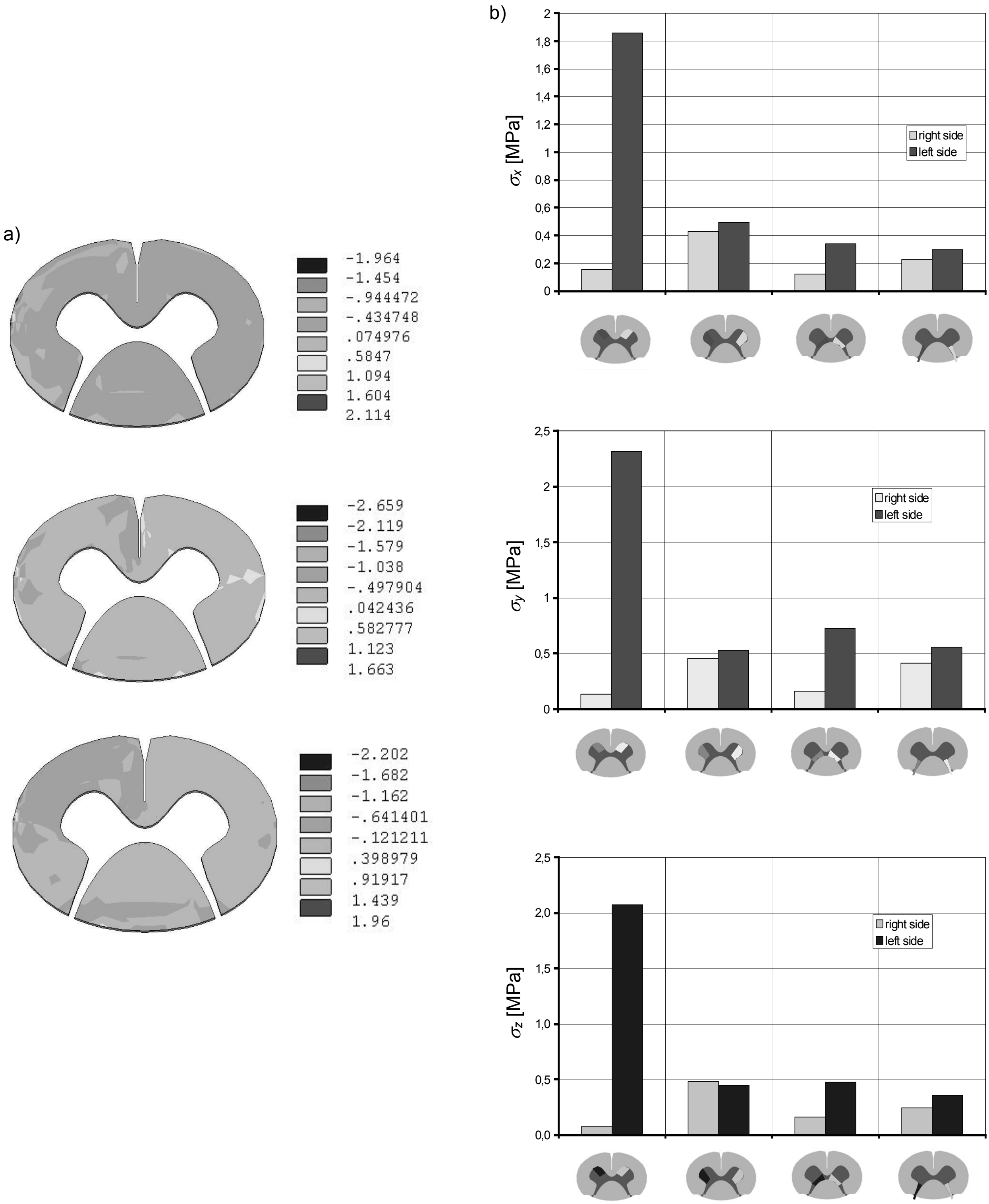
Our attempt to use an individualized FEA model of the spinal cord in order to analyse an actual SCI traumatic case is the very first undertaking of this type. Owing to an appropriate structure of the ANSYS input file it is possible to easily modify the geometry of our model. This enables an adaptation of the model to the individual properties of the patient's spinal cord and vertebral canal and therefore an immediate individualization of the research and its greater reliability.

The results gained by us can be correlated with a neurological state of a patient. The improvement of sensory and motor functions of the left part of the body two months after the injury corresponds with the model simulating the strain and deformation level of grey and white matter.

Furthermore, it is possible to correlate the results of the FEA analysis with anatomical changes within the spinal cord. After two months a hemorrhagic focus has been observed in the patient's MRI. It is localized in the central part of the spinal cord, which corresponds to the area of an extremely strong concentration of mechanical strain and deformability.

Giving isotropic properties to the dura matter of our model should be subsequently commented. Testing the mechanical properties of the dura matter, TUNITURI [36] does not mention the differences between the longitudinal and circumferential samples in the values of the Young's modulus; however, the research carried out in the recent years indicates that it is an anisotropic material.

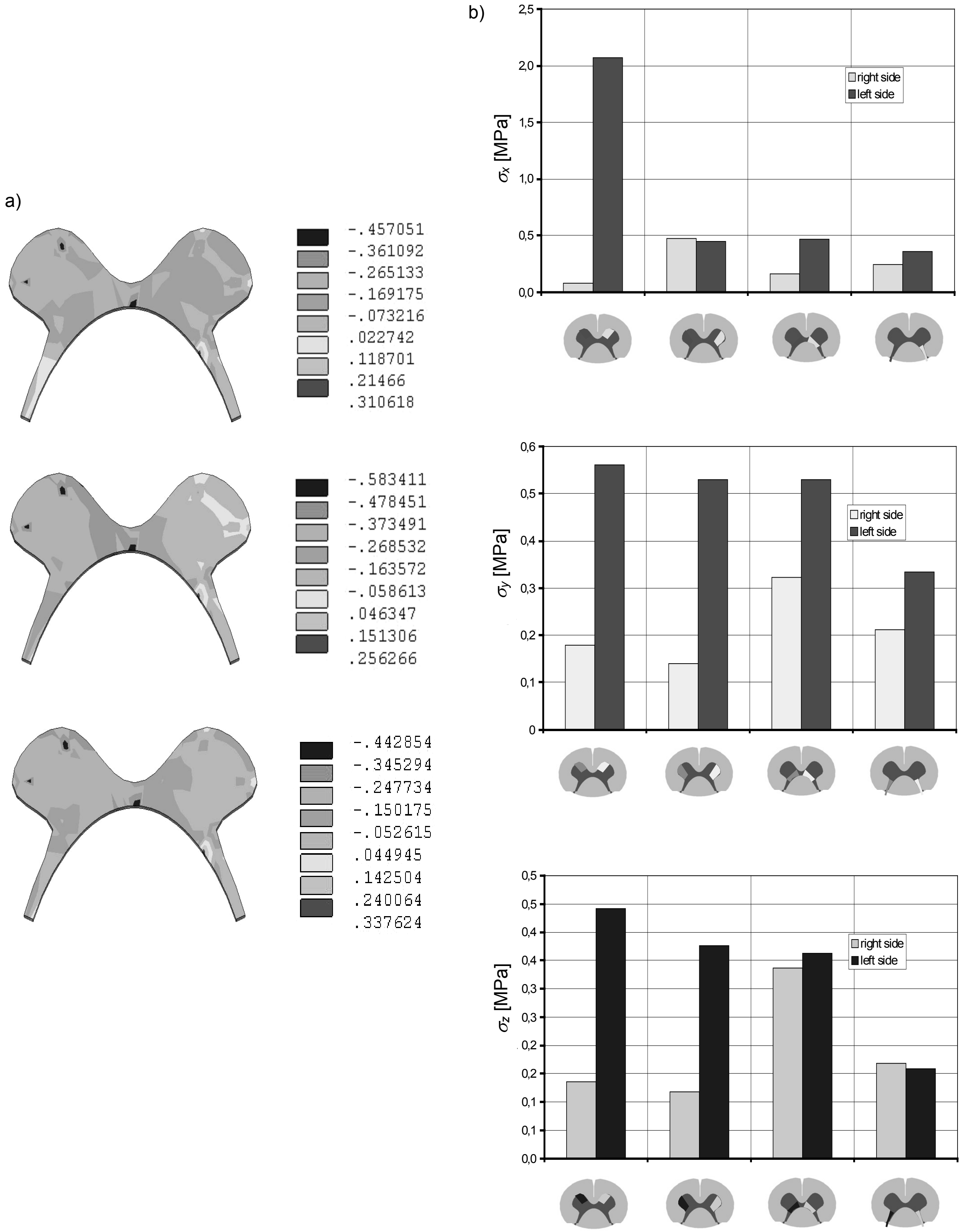
In none of the theses, a detailed data which would enable us to model the anisotropic properties of the



Graph 2. Distribution of stress components on white matter cross-section (a)
and the differences in stress absolute values in the left- and right-parts of spinal cord model (b)

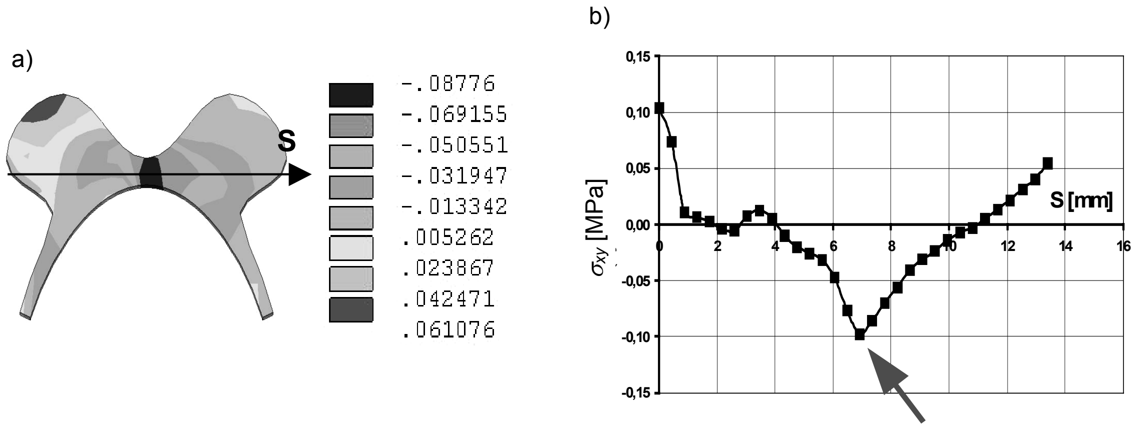
dura mater in a FEA environment was provided. Therefore we have adopted the Young's modulus provided by WILCOX [12] for the circumferential samples. We have resigned from using the dura matter as a material directly transferring the strain in the course of injury. Such a decision is justified considering the results of HALL's experiments [5].

The research of the pressure changes inside the gelatine model of the spinal cord, which underwent a simulated severe injury, did not show any significant

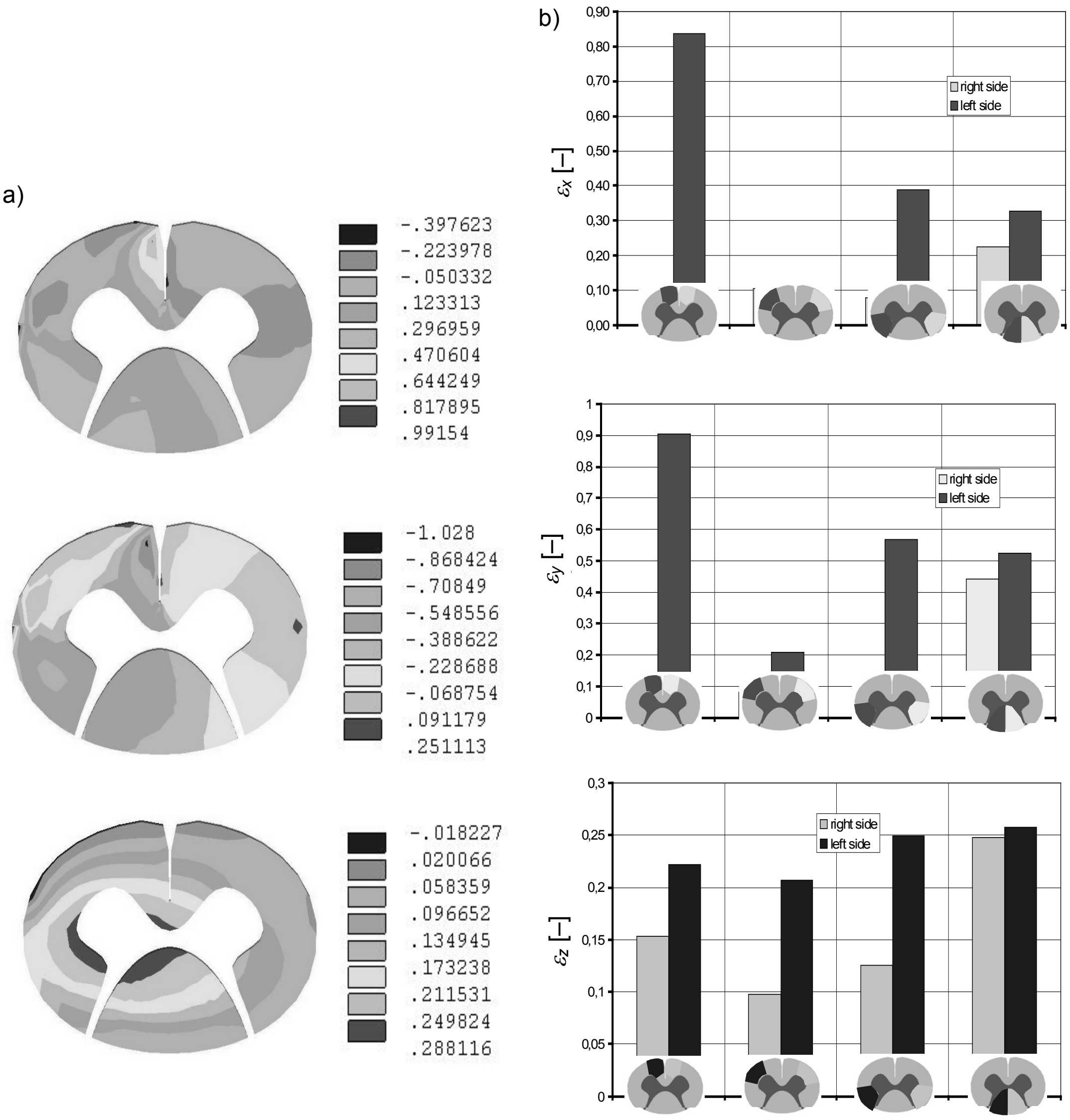


Graph 3. Distribution of stress components on grey matter cross-section (a)
and the differences in the stress absolute values in the left- and right-parts of spinal cord model (b)

influence of the dura matter on the changes in intraspinal pressure dynamics in the course of the injury. The maximal values of the pressure and the rate of its increase were not considerably different in the preparations without a dura and in the preparations equipped with its synthetic substitute. In a common form, the

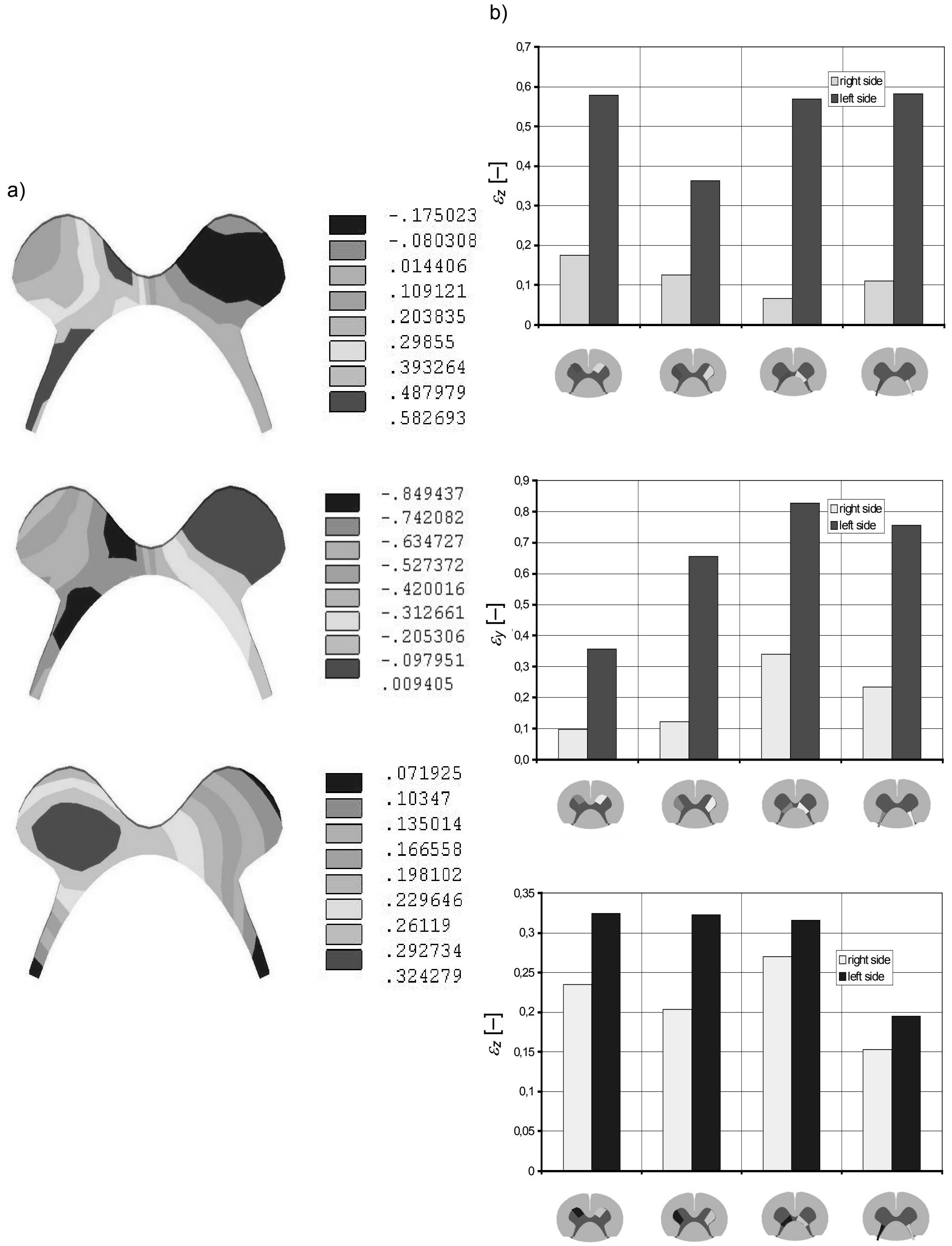


Graph 4. Distribution of shear stress component on grey matter cross-section (a) and along the line *S* (b)



Graph 5. Distribution of strain components on white matter cross-section (a)
and the differences in the stress absolute values in the left- and right-parts of spinal cord model (b)

dura matter along with denticulate ligament plays in our research a vital function, since if fixes the spinal cord in the three-dimensional space and it is not in a direct contact with the spinal cord model in the



Graph 6. Distribution of strain components on grey matter cross-section (a) and the differences in the stress absolute values in the left- and right-parts of spinal cord model (b)

course of the simulated injury. The displacement of the osseous fragment commences in the spinal cord area and does not take place in the dura matter and the cerebro-spinal fluid (CSF) layer. In pathomechanics of SCI, CSF still plays an unclear role [5], [37]. It should be expected that the experiments of other research groups specialized in the cerebro-spinal fluid biomechanics [38], [39] will prove to be useful for us during further stages of our experiment.

Endurance parameters of the white and the grey matter of the spinal cord have been derived from the paper by ICHIHARA [21]. We have intentionally resigned from the viscoelastic model, using the data on the isotropic properties of these structures. Surveying the mechanical strain of the spinal cord model, we have simulated only the very act of the osseous fragment displacement into the vertebral canal in the course of the injury, which lasts ca. 3–5 ms [5], [11]. In the planned dynamic analysis, the return of the osseous facet to the right position, observed in the examination with CT carried out after the patient's admission to our centre, will be simulated as well, since it is indispensable in restoring the viscoelastic properties of the spinal cord.

Taking account of the obvious limitations caused by the pioneering character of the present research as well as an insufficient amount of the data available in the professional literature, it is too early to establish the value of the strains that could be responsible for given traumatic changes in the spinal cord.

However, the results of our research allow a cautious prognosis on both a natural regeneration process and the degeneration of the spinal cord. Currently we are not able to estimate the boundary values of the strain at which a partial recovery of the neurological functions is still possible and above which irreversible damage occurs. In order to discover the correlation between the strain values and the character of the sequential changes within the spinal cord, it is indispensable to carry out a research based on an enlarged group of patients. This will enable us to validate the results received and to establish the standards.

Moreover, we will probably be able to predict the character and immensity of the degenerative changes of the spinal cord and a potential improvement of the neurological condition of a patient merely a few hours after the injury. Due to such a knowledge, a considerably rapid implementation of the proper therapeutic and remedial methods shall be feasible.

5. Conclusions

The individualized FEA model of traumatic SCI built by us have enables evaluation of the influence of mechanical strain on the neurological condition of a patient directly after and two months after the injury. Further research will consist in the validation of the results of endurance analyses based on an enlarged group of patients. It seems to be feasible to establish the standard for the dependences between the values of mechanical strain and the anatomical condition and function of the spinal cord many weeks after the injury.

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