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Finite element modelling of the cervical spinal cord injury – clinical assessment

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The aim of the study was to evaluate the efficiency of Finite Element Method (FEM) modelling of the clinical cases of traumatic cervical spinal cord injury (SCI). The study population consisted of 28 patients suffering from traumatic cervical spine injury with (study group) and without (control) neurological deficits. A numerical simulation of the trauma event was performed, based on validated 3D FEM model. All the results obtained underwent statistical analysis. Statistically significant differences between both groups were found in severity of bony and neural structure damage as well as in stress and strain ratios. The highest values of tensile stress and deformation were noted in the sagittal (Y) axis. The maximum stress and strain were found in anterior spinothalamic, lateral spinothalamic and dorsal columns. It was also found that stress and strain in each segment and axis of the spinal cord model were positively correlated with the severity of the cervical spine injury (R-Spearman 0.39 to 0.64) and neurological symptoms of SCI (R-Spearman: 0.43 to 0.82). It is possible to create a clinical numerical model of the SCI with the use of FEM. The correlations between the mechanical force and neurological deficits show tendencies which require further studies based on an improved model and a greater number of patients.

Key words: *Finite Element Method (FEM), cervical spinal cord injury, blood–spinal cord barrier, neurological recovery*

1. Introduction

Mechanical stress applied to the spinal cord at the very moment of injury is responsible not only for primary spinal cord injury (SCI) and immediate loss of neurological function, but it also leads – by the immediate damage of the blood–spinal cord barrier – to secondary SCI causing progressive degeneration of the previously undamaged nerve tissue and an increase of neurological deficits [1].

In 2007, MAIKOS and SHREIBER [2] showed that the extent of the damage of the blood–spinal cord barrier (BSB) is strongly correlated with the values of mechanical stress and strain generated at the time of injury. As stated by PANJABI and WHITE [3], knowing the value of mechanical strain on the site of injury may allow the potential extent of the secondary SCI in specific clinical cases to be determined.

Finite Element Method (FEM) appears to be the tool which gives the theoretical possibility of determining the value of mechanical spinal cord strain at the moment of injury. In the past years, a few attempts have been made to apply FEM to the analysis of traumatic SCI [4]–[7]. The authors of these studies used more or less complicated FEM models and worked with hypothesized, idealized SCI cases, which makes unequivocal interpretation of their results difficult.

Based on current literature, it can be stated that no complex studies have been carried out yet on the use of FEM in clinical cases of traumatic injury to the spinal cord in humans. The aim of our study was to perform a clinical analysis and validation of the Finite

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Element Method simulation of spinal cord injury based on certain clinical cases.

2. Materials and methods

2.1. Clinical material

The clinical material comprised patients treated for traumatic injury in the cervical spinal cord. The study was approved by the local ethics committee. Patients meeting the requirements of the following criteria were included in the study:

1. Aged from 16 to 65 years.
2. The level of consciousness that would allow a detailed neurological examination and signing a written consent.
3. The time of admittance to the clinic not later than 12 hours after injury.
4. Administration of methylprednisolone using a standard neuro-protective protocol when neurological deficits were diagnosed.
5. No history of previous trauma to the central and peripheral nervous system that could affect the evaluation of the neurological state of the patient.

The severity of the spinal injury was classified using the AOSpine guidelines [8]. The extent of damage to the bone and ligament structures was evaluated using the Moore 20-point scale [9]. An MRI of the cervical segment of the spinal cord was carried out in patients with neurological deficits. The imaging was performed using the GE 1,5T SignaHDx apparatus. In the course of the screening, T1 SE, T2 frFSE, T2 + FASAT 3.5 mm thickness scans were obtained. The images underwent comprehensive metrological analysis with the use of digital tools available in K-PACS v. 1-5-0 software.

A detailed neurologic examination was carried out and the severity of injury was determined using the ASIA (American Spinal Injury Association) form [10].

2.2. Numerical analysis

2.2.1. FEM model design

A three-dimensional numerical model of the human cervical segment of the spinal cord was created using the ANSYS Multiphysics version 11.0 and 12.1 software (ANSYS, Inc., USA). The model design and experimental validation as well as the procedure for

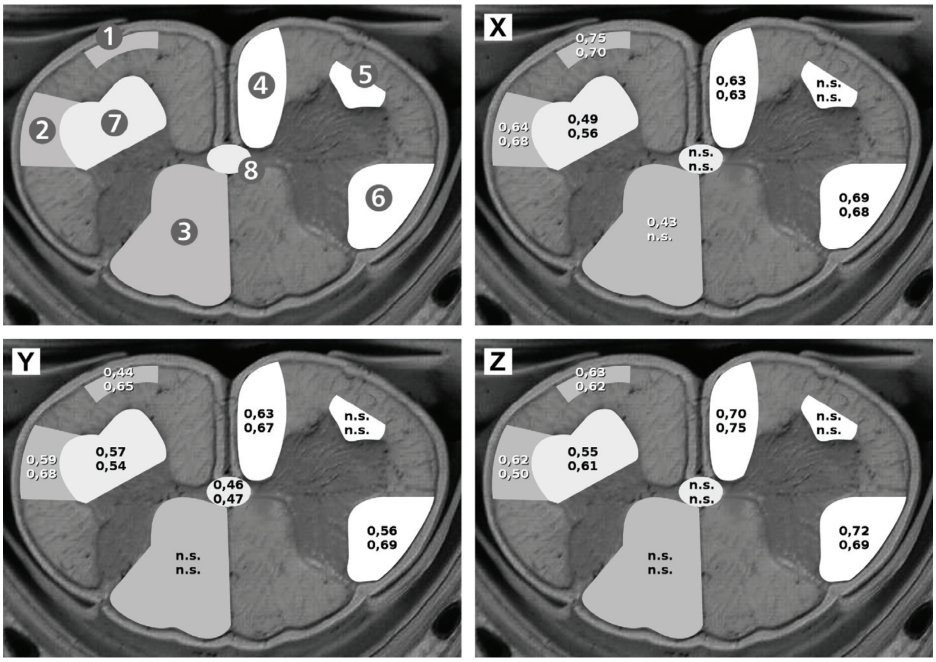

Fig. 1. A scheme of ascending and descending cervical spinal cord tracts (left upper graph): 1 – anterior spinothalamic (light touch), 2 – lateral spinothalamic (pain), 3 – dorsal columns (deep sensation), 4 – anterior corticospinal (skilled movements), 5 – medullary reticulospinal (automatic respirations), 6 – lateral corticospinal (skilled movements), 7 – anterior horn (segment muscles), 8 – central area. An illustration of R-Spearman correlation coefficients between mechanical stress (upper line) and strain (lower line) and neurological symptoms for particular functional areas in transvers (X), sagittal (Y) and cephalo-caudal (Z) axes of the cervical spinal cord

model individualization were described in detail in [11]. Briefly, the average axial and transverse dimensions of the spinal cord measured above and below the place of injury in a given individual were used to adjust the geometry of the model to the patient's anatomy. The model of the spinal cord consisted of two components: a model of white matter and a model of grey matter, complete with a model of the dural sac and seven pairs of denticulate ligament, whose geometry was designed based on available anatomical data. The white and the grey matter were modelled as two different structures using 8-node HEXA-HEDRA type elements of three degrees of freedom in each node. The pia and dura mater were modelled using shell elements. The denticulate ligament anatomically built as a composite structure was modelled using shell elements of the pia mater resistance parameters, covering the 8-node elements of HEXA-HEDRA core of the strength parameters of collagen. Experimental validation was carried out based on a porcine spinal cord model. Each of the seven segments underwent dorso-ventral compression with the use of Material Testing System Synergie 100 (MTS Systems, Inc., USA). The compression process was documented photographically. For every model each stage of compression was simulated using the FEM. The contact and sliding between the surfaces – virtual solid beams (E = 200 GPa, v = 0.3) and ventral and dorsal surfaces of the spinal cord, respectively, were modelled. Measurements of the location of reference points before and during the compression were carried out. The results were analyzed statistically.

Calculations were carried out on Hewlett-Packard XW 8600 workstations using the 12.1 versions of ANSYS Multiphisics software (ANSYS, Inc., USA). Each station was equipped with two four-core Intel Xeon X5470 3.33 64 bit processors, 16 GB RAM, and 300 GB RAID 0 HDD matrix. Clinically important anatomical and functional zones of the cross-sections of the spinal cord were determined for post-processing purposes (figure 1).

2.2.2. Boundary conditions

The proximal and distal ends of the model of the spinal cord were fixed in transverse (X), sagittal (Y) and longitudinal (Z) axes. The model of dura mater was fixed in X and Y axes, which was supposed to correspond to the places where dura mater was fixed to the immovable osseous wall of the spinal canal. The denticulate ligament model merged the model of the spinal cord with the model of the dura mater.

Each clinical case was described by the so called *variable boundary conditions*, which enabled the reconstruction of the moment of injury. The variable boundary conditions were designated as:

1) The displacement of a certain part of the model of the spinal cord – its direction, magnitude and the initial point, all of which were set individually for each clinical case based on a metrological analysis of CT and MRI scans and the results recorded using special SCI Cards (figure 2). Based on the results of the experiments carried out by HALL et al. [12], it was assumed that in a group of patients presenting neurological deficits, the maximal occlusion of the spinal canal was 80% of its primary sagittal dimension. In the group of patients without neurological deficits, the maximal spinal canal occlusion at the time of injury was assumed to be the same as that observed in the patients' CT scans at the time of admission.

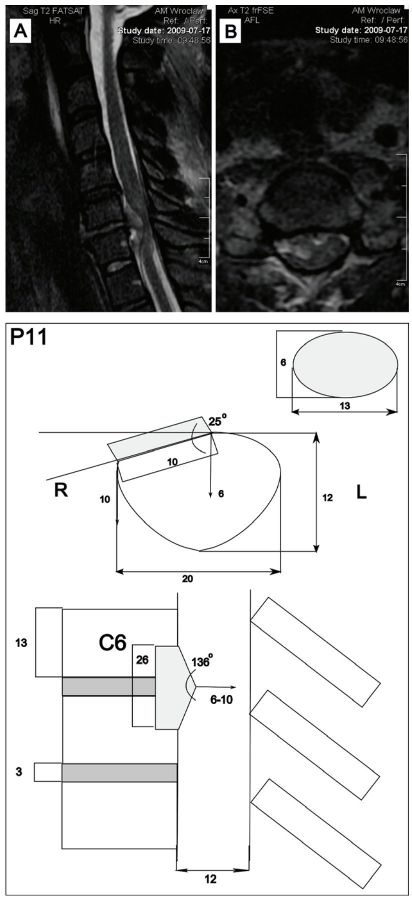

Fig. 2. An example of a patient's sagittal (A) and axial (B) T2 MR images. Note the spinal canal occlusion caused by traumatic C6/C7 intervertebral disc herniation. A standardized SCI card is presented below. Cross-section of the undamaged segment of the spinal cord is visible in the right upper corner. All measurements are expressed in millimetres. The depth of the occlusion was estimated according to literature data [12]

2) The support of the opposite area in the spinal cord model to the one being compressed simulating the contact of this area with the dural sac and the osseous framing of the spinal canal.

2.2.3. Post-processing

The analysis of results (post-processing) consisted of:

1. Development of a 3D model of the deformation of the injured segment of the spinal cord at the moment of maximal occlusion of the spinal canal.

2. Development of the axial and sagittal cross-sections of the centre of the injured segment of the spinal cord and visualization of the distribution of mechanical stress and strain in X, Y and Z axes.

Based on the images obtained (figure 3), the maximal and minimal values of mechanical stress and strain for the injured segment of the spinal cord were defined. The strain and distortion values in the above mentioned spinal cord zones were recorded.

2.2.4. Statistical analysis

The STATISTICA ver. 9.0 (StatSoft, Inc., 2009) was used to analyse the results of the study. Statistical significance was set at $p < 0.05$.

To analyse the normal distribution of certain features, the Shapiro–Wilk W test was used.

To test differences between the groups of patients with and without neurological deficits, the Mann–Whitney U test and ANOVA were used. To analyse relationships between the results of FEM analysis, results of neuroimaging and the neurological examination, a non-parametric analysis with Spearman's rank correlation (for ASIA protocol) or Fi correlation coefficient (for deep sensation, respiration, and presence of the central cord syndrome) were used.

3. Results

The inclusion criteria were met by 28 patients (3 women and 25 men). The FEM analysis was performed in 14 patients with neurological symptoms of SCI and in eight patients without neurological deficits, in whom radiological examinations revealed contact between osseous structures or ligaments and cervical spinal cord. A summary of the basic demographic, epidemiological, anatomical and FEM data together with the results of statistical comparison is presented in table 1. Statistically significant differences which were found between the severity of bony and neural structure damage were also expressed by significant differences between stress and strain ratios in both groups.

The average number of elements and nodes in each particular model was 109046 and 110170, respectively. Detailed results of FEM simulations are presented in table 2. The stress and strain in each segment and axis were positively correlated with the severity of the cervical spine injury (table 3) and neurological symptoms of SCI (figure 1).

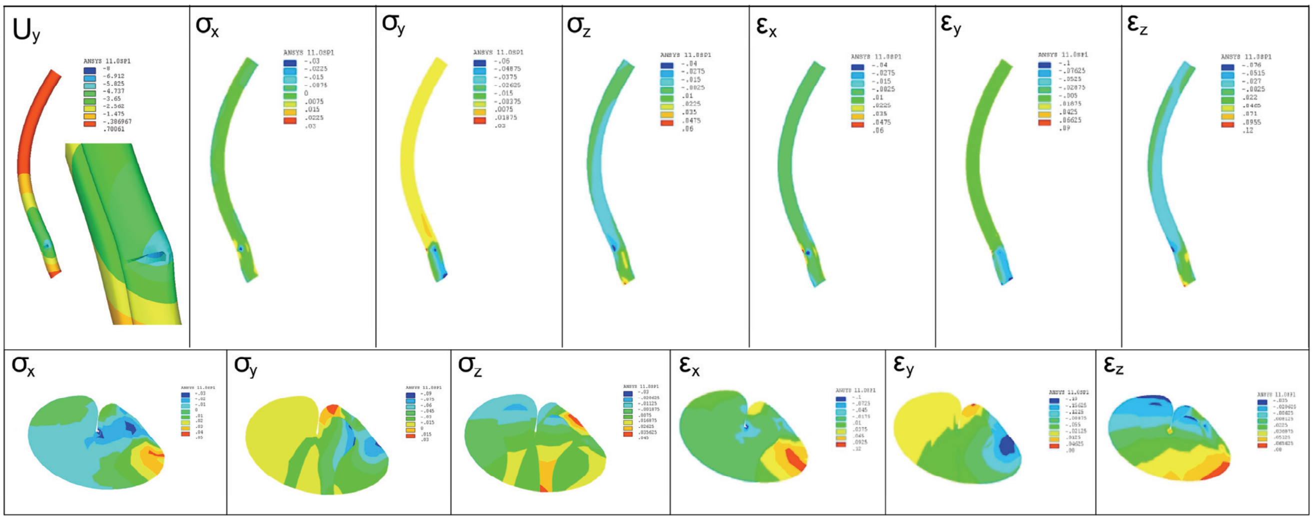

Fig. 3. An example of graphical card of FEM results for patient P11. Upper row – sagittal section of the entire cervical spinal cord. Lower row – cross-sections of the model of the spinal cord at the level of injury with different components of the state of stress (σ) and strain (ε)

Table 1. Summary of basic data describing the population of patient under study. Abbreviations: U – upper extremities, L – lower extremities, Deep – presence of deep sensation, Resp. – presence of respiratory disturbances, Lower case – *p* value for the statistical comparison between groups with (P 1-15) and without (K 1-14) neurological deficits

	Age	Sex (M/F)	Level	AO	Moore	ASIA					Deep	Resp.
						Motor		Light touch	Pin prick	Type		
						U	L					
Control (n = 14)	28 (15)	12/2	C5	B1	5 (5)	50 (0)	50 (0)	112 (0)	112 (0)	E	0	0
Study (n = 14)	31 (26)	13/1	C5	B2	10 (7)	31 (36)	10 (50)	59 (80)	61 (83)	B	0	0
p	0.27	0.58	0.48	0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.02	0.35

Note: Median (with interquartile range in parentheses) values reported for age, Moore's scores and results of ASIA assessment.

Table 2. Summary of results of the Finite Element Method simulations. Abbreviations: X – transverse axis, Y – sagittal axis, Z – longitudinal axis. Lower case – *p* value for the statistical comparison between control (without neurological deficits) and study (with neurological deficits) groups

	Stress [kPa]			Strain [%]		
	X	Y	Z	X	Y	Z
Control (n = 14)	0.25 (1.75)	0 (0.73)	0.065 (1.15)	0 (1)	0 (1)	0 (0)
Study (n = 14)	22.99 (23.25)	34.71 (89.25)	13.65 (6.63)	12 (9)	22.5 (28)	5 (3)
p	<0.0001			<0.0001		

Note: Median (with interquartile range in parentheses) values reported.

Table 3. R-Spearman rank test correlations between the results of FEM simulations in X – transverse, Y – sagittal and Z – longitudinal axes and the severity of the cervical spine damage expressed as AOSpine and Moore'e scales

	AOSpine			Moore's		
	X	Y	Z	X	Y	Z
Stress	0.57	0.52	0.43	0.49	0.47	0.57
Strain	0.57	0.51	0.51	0.49	0.47	0.55

4. Discussion

In the period immediately after trauma, the actual extent of spinal cord injury and neurological dysfunction are difficult or impossible to determine accurately in many patients with SCI. Some data may be obtained from the neurological examination and analysis of MR images, particularly the DTI. This information may be useful in the decision making process concerning the type of surgical procedure applied and subsequent rehabilitation [13], [14].

According to SHARMA [1], the actual area of traumatic spinal cord injury is determined by the extent of damage to the blood–spinal cord barrier. This, in turn, closely corresponds with the amount of mechanical strain to which the spinal cord is subjected at the time of trauma [2], [15]. Therefore, the actual extent of the secondary lesions to the spinal cord can be hypothetically estimated based on data regarding the value of the mechanical strain on the patient's spinal cord. FEM is a method which allows the analysis of the spatial distribution of stress and strain fields generated by an applied force on an object. The development of an advanced and universal FEM model of the SCI can be a starting point for modern studies concerning diagnostic and therapeutic algorithms for the successful treatment of patients suffering from SCI.

In our study, we attempted to use an individualized FEM model of the human cervical spinal cord in clinical practice. We used two – comparable in terms of basic demographic, epidemiological and anatomical features – groups of patients after cervical spine injury. A study group – with neurological symptoms of acute spinal cord injury was compared with a control group – without neurological deficits. Our model differs from the existing ones because of the unique solutions applied during its creation [4], [5], [11], [16], [17]. The geometry of the spinal cord model was adapted to the geometry of the patient's spinal cord each time. Based on current literature, a numerical model of the dentate ligament was applied as the structure preserving the spinal cord in the three-dimensional spinal canal space [18], [19].

This study is an attempt to apply the FEM analysis of traumatic spinal cord injury in clinical practice. At the same time, it is the first publication in which the FEM model of the spinal cord is used for the analysis of actual clinical cases of traumatic spinal cord injury. Given the statistically significant correlations of the mechanical effort in FEM models with the results of a detailed assessment of the neurological status of patients, the application of the FEM analysis in clinical SCI seems viable.

The highest noted values of the mechanical strain on the anterior-posterior axis are not unexpected since the vector of force acting on the spinal cord during the SCI is thus directed. It is, however, difficult to clearly interpret the highest noted values of mechanical effort in the sensory ways: anterior spinothalamic, lateral spinothalamic, dorsal columns tracts. Although the ability to feel touch and pain is the first neurologic function to return to patients after SCI, this is difficult to correlate with the results of our observations [20].

At the same time, our results of numerical simulations should be treated with due caution because of the limitations of our FEM model. An obvious drawback of the model was the use of linear stress-strain characteristics. However, this problem has already been discussed [11]. Not considering the impact of CSF on the biomechanics of SCI and the modeling of the spinal cord without bone and ligamentous structures are two other disadvantages of the model. Both simplifications have occurred due to the technological constraints. Three-dimensional modeling of complex issues using the theory of large displacements, and taking into account the possible presence of CSF and vertebrae, exceeds the capability of currently available software and hardware resources [21], [22]. The current complexity of the model appears to be optimal for the instant acquirement of clinically useful information. In the future, we plan to introduce new elements into the model, taking into account the presence of CSF, the geometry of the cervical intumescence and the use of non-linear characteristics of strength of the modeled structures. The most promising way of validating the model seems to be a late clinical evaluation of a larger number of patients 6–12 months after the injury and the assessment of the prognostic value of the FEM model.

5. Conclusion

The results of the first clinical validation of the finite element method (FEM) model of traumatic cervical spinal cord injury confirm the usefulness of FEM for such analyses. Further technological development of the computational model, research based on a larger study group, and an assessment of application of the FEM for prognosis of the late outcomes of cervical SCI is planned for future studies.

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