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NUMERICAL AND EXPERIMENTAL ANALYSIS OF BIOMECHANICS OF THREE LUMBAR VERTEBRAE

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A three-dimensional numerical model of the human spine including three vertebrae of the lumbar spine (L1, L2, L3) has been built using the ANSYS 5.2 FEM program. Mechanical properties of different elements of the spine have been taken into account, i.e., cortical bone, cancellous bone, posterior elements, etc., in the model. The model allows one to analyse spine displacements under various static and dynamical loads acting on the vertebral structure, as well as it enables one to select proper implants.
For verification purposes, the numerical analysis results having the form of displacements under different loads have been compared with the in-vitro experiment results obtained by other authors.
In addition, a test stand allowing for experimental investigation of displacements of different elements of the spine has been constructed. In the investigation into stiffness, the artificial vertebrae L1, L2, L3 have been used. A good agreement between the results obtained from the numerical analysis and experiments has been achieved.

Key words: lumbar spine, implant, FEM, in-vitro experiments

1. Introduction

Over the last decade there has been observed an intensive development in the field of implants used for stabilisation (surgical fixation) of spinal segments (Kaneda, 1991; Puno, 1991; Shimandle, 1994; Zdeblick, 1993).

The investigations have been focused mainly on biomechanical tests made before introducing a stabiliser into clinical practice. The tests allow one to determine the implant efficiency in stabilisation of the spine (Abumi, 1989; Evanson, 1990).

Biomechanical tests are laborious and expensive. Numerical modelling of the human spine, which could partly replace rather troublesome biomechanical in-vitro experiments is promising. Different authors employ two-, three-dimensional and axisymmetrical models.

2. Experimental in-vitro investigations

Until recently, a new stabiliser had only to undergo some routine mechanical tests before it was put into clinical practice. However, usually the testing conditions did not represent the real behaviour of the human spine. As a result, all the defects of a stabiliser connected with the fixation of the spine and a bad choice of implant were in fact tested on the living human body, which was extremely disadvantegous.

Harrington rods have been the most popular devices in spinal surgery for the last 50 years. The sixties and seventies were their heyday. Only after many years of their application did they start to be tested biomechanically in-vitro. The tests allowed one to discover the sources of many complications arising due to the use of these rods. The lack of an implant for three-dimensional stabilisation was also pointed out. As a result, the rods were modified so that they could better stabilise the spine (Nasca, 1990; Shirado, 1991).

In recent years the approach to the evaluations of stabilisers has changed. Apart from mechanical investigations, biomechanical tests made on a spinal segment taken from a cadaver and then stiffened by an implant are also required before introducing new designs into clinical practice (Ashman, 1988, 1989, 1993, 1994; Glossop, 1997; Hedman, 1997; Hosfijima, 1997).

From the mechanical point of view, a human spine is the most complicated part of the human skeleton. It is not possible to represent the real biomechanical properties of the spine by means of an artificial model. Therefore, in biomechanical tests the biological material is examined rather than the artificial model. So far the best experimental model has been a spinal segment taken from a cadaver and then stiffened by an implant (Glazer, 1997; Kenneth, 1990; Panjabi, 1988). However, the problem of obtaining a healthy material, i.e. with no spine pathology, still exists. The spine should be free from any serious illnesses such as osteoarthritis, degeneration, destruction caused by cancer or any other kind of illness. The spinal segment is also subject to radiological examination to avoid any pathological changes that can be only revealed in this way. After the anatomical specimen has been taken, it is stored at a temperature from −20°C (Brodke, 1997; Yerby, 1997) to −30°C (Cunningham, 1997) for a few hours in order to avoid drying up.

Because two identical spines do not exist, the investigations of a stabiliser are of comparative nature, i.e., stability of the healthy spine taken from a cadaver is compared with stability of the same spinal segment after simulating the illness and joining the unstable part by an implant (Abumi, 1989; Panjabi, 1988).

Beside the material taken from dead bodies (Goel, 1991; Panjabi, 1988), animal specimens are also used, especially those taken from big animals like calves (Gurr, 1988), pigs (Panjabi, 1989), goats (Sanders, 1993), dogs (Shimandle, 1994), and sheep (Nagel, 1991). The size and quality of these mammal spinal tissue are quite similar to the human spine. But as far as their anatomical structures is concerned, they are different. The difference concerns the back column of the spine (it has the essential influence on its stability).

Different authors have conducted research using different approaches. Panjabi, 1988) and Ashaman, 1988, 1989, 1993, 1994) established a procedure for testing biomechanical implants stabilising the spine. Nowadays the procedure is used by many researchers who cope with these problems (Dick, 1997; Puno, 1991). This procedure consists of three types of tests (Panjabi, 1988), namely: strength, fatigue and stability tests.

In the case of strength and fatigue tests, the stabiliser can be tested as an individual unit or the so called "construct" which is a spinal segment immobilised by an implant (Ashaman, 1994; Panjabi, 1988).

Strength tests are made by increasing the load until the implant or spine destruction occurs. Because this is a destructive test, only one type of load can be examined on one specimen. The strength test provides only the information about the load level the implant (or "construct") can bear (Panjabi, 1988).

In fatigue tests a cyclic load is applied at a given frequency. The load level is much lower than the failure load. A cyclic load is applied until the specified number of cycles is accomplished or the spine (implant) is destroyed. From these tests we obtain the information about the implant lifetime (Panjabi, 1988).

Both strength and fatigue tests are destructive. In stability investigations the same part of the spine may be subject to loads of different magnitudes acting along different directions repeatedly and causing no destruction of the implant or "construct". The load magnitude used in the test is consistent with physiological conditions. It corresponds to the loads occurring in the spine in-vivo during usual physical activities. Therefore, from the medical point of view, the information provided by stability tests is much more valuable and important than that provided by strength and fatigue tests (Panjabi, 1988).

It is recommended that stability tests of the implants stabilising the spine should fulfil the following criteria (Panjabi, 1988):

- One end of the specimen (a part of the human or animal spine taken from a cadaver or an artificial model) should be fixed, whereas the second end should be left free to allow natural spinal movement under applied loads.
- The loads applied to the free end of the spine should be realized using the following moments: bending (forward, backward, left, right), torsional (left, right),
- Each load should be applied in three cycles in order to allow the "construct" to adapt.
- The displacements measured are the bendings, i.e. rotations about the axes of the cartesian coordinates system and translations, i.e. linear displacements along these axes.

3. Numerical modelling of a human vertebral column

Since biomechanical research conducted with the use of the specimens prepared from fragments of a human spine are laborious and expensive, numerical modelling of a vertebral column is very promising. The main advantage of numerical modelling is that the tests can be repeated and parameters can be modified straightforward. The results are obtained in numerical or graphical form, therefore, there is usually no need for their further processing (Zagrajek, 1990).

Various authors have created three kinds of spine models: two-dimensional, axisymmetrical and three-dimensional. The Finite Element Method (FEM) is commonly used in modelling. The authors often use the available packets of programs, originally constructed for engineering design purposes. The FEM is used to analyse durability of the individual elements of the spine (Goel, 1991, 1995), to calculate the stress state in each vertebra of the system (Bazic, 1994; Natarajan, 1994; Shirado, 1992; Teo, 1994) and also to examine the displacements due to the applied forces (Spilker, 1984).

This method makes it possible to take into account various characteristics of the individual element of vertebra – the osseous tissue (cancellous, cortical, processes), the intervertebral disc (nucleus, annulus fibers). It also enables one to take into consideration a complex structure of the vertebra and the loads at different points (Liming, 1997; Maurel, 1992).

Until now, the best models to describe the human spine are the three-dimensional ones (3D). When employing them, it is possible to take the three-dimensional nature of the osseous system, a part of which is the vertebral column, into consideration as well as to use mechanical characteristics of many kinds connected with the individual elements of the spine (cancellous bone, cortical bone, processes, nucleus, annulus fibers, etc.). The 3D models make it possible to apply forces on different planes and to test also stability of the spine, which is one of the most important features of the model considered.

Until not long ago many authors would apply the 2D modelling (Saito, 1991; Shirado 1992). Those models did not take into account the three-dimensional nature of the system. The range of their applicability was relatively narrow, being limited to some statistical research. Deformation and stress occuring due to applied loads could only be analysed in one plane. The simplifications used in the models were significantly affecting some characteristics of the system (Zagrajek, 1990).

Some authors constructed axisymmetric models (Spilker, 1984; Simon, 1985). They assumed axial symmetry of the vertebral body or of the intervertebral disc. While analysing the vertebra geometry, one can notice that the above assumption is not valid because both the vertebral body and intervertebral disc reveal a much more complicated structures than a cylinder (even with a curved lateral surface). It was impossible to take into account the rear vertebral column, i.e. processes.

The most reliable models to describe the spine are 3D models. Some authors took up modelling of one element of the spine, e.g. a disc (Natali, 1990; Natarajan, 1994). They paid attention to each element of the disc structure (nucleus, annulus fibers). Other authors described only the structure of the disc including its elements (Bozic, 1994; Silva, 1997). However, this approach to modelling such a complex structure as the human spine is, seems to over simplified. Modelling just one element (only a vertebra or a disc) cannot be practically used in the research into spine stability. It can be only used in further modelling of the whole motorial fragments of the spine.

On the basis of 3D models describing individual elements of the spine separately, some authors have started to model individual motorial segments (Yoganandan, 1996; Smit, 1997) and individual fragments of the spine (Robin, 1992; Maurel, 1992). Many of those authors did not verify their models to check if they correspond to reality. Therefore one does not know to what extent they are correct. Moreover, it has not been confirmed that this kind of models has been used in research into stability of short fragments of the spine subjected to stabilisation (the use of implants).

Global models have taken into consideration not only a spine, ribs and a sternum, but also an influence of some organs and muscles (Zagrajek, 1990; Eppinger, 1994). The models deal with the whole system in a very general way and individual parts of the spine (vertebrae and intervertebral discs) are described using a small number of finite elements, and thus the geometry and structure of individual elements of the spine (cancellous bone, cortical bone, processes, nucleus, annulus fibers, etc.) are oversimplified.

The present research attempts at creation of such a 3D model that could describe the geometry of the spine elements using the FEM and that it would contain at least two motorial segments (three vertebrae and two intervertebral discs).

The FEM numerical model has been verified. The results obtained while testing the model have been compared with the results obtained by other authors during in-vitro tests.

The model has been used to test stabilisers in order to check if it could be used as a model to test implants of various kinds in the future.

Additionally, a test stand to carry out biomechanical research in-vitro has been built and the results obtained on the basis of the numerical model have been compared with those obtained during in-vitro tests performed with this equipment.

4. Numerical modelling of a segment of the lumbar part of the human vertebral column

The computational capability of the ANSYS 5.2 finite element program based on the finite element method has been employed in modelling of a fragment of the human spine. It is necessary to take into account the complex geometry of the human spine in order to analyse its mechanical properties and this software makes it possible to employ the non-linear geometry and the non-linear modelling of mechanical systems.

The division into finite elements has been made with the use of two kinds of elements taken from the ANSYS version 5.2 library: the "SOLID 92" tetrahedral element having 10 nodes (Fig.1) and the "CONTACT 49" contact element of (Fig.2).

The three lumbar vertebrae (L1, L2, L3) are taken into consideration. A plastic model of the average-size human spine and anatomical atlases (Bo-

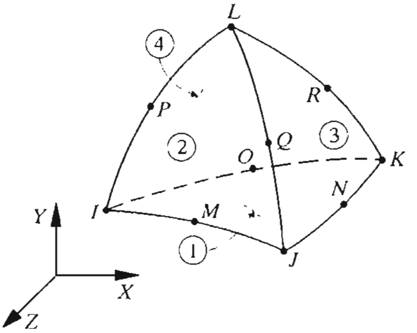

Fig. 1. SOLID 92 element

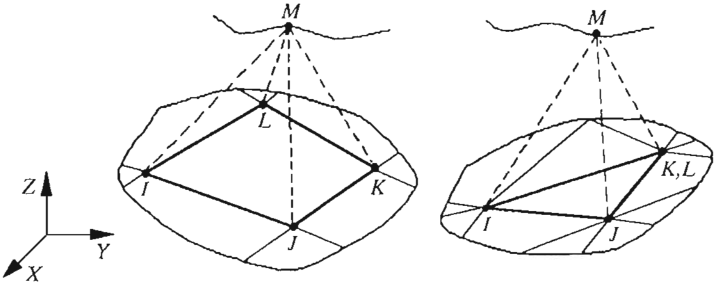

Fig. 2. CONTACT 49 element

chenek, 1990; McMinn, 1994) have been used to model lumbar vertebrae. A 3D model of three lumbar vertebrae has been constructed. The structure of a nucleus, annulus fibers, a vertebral body with cancellous and cortical parts and also processes (spinous process, transverse processes, superior and inferior articular processes, an arch base and an arch) have been analysed.

The geometry of the three lumbar vertebrae (L1, L2, L3) is modelled on the L2 vertebra which is copied on the adjoining two vertebrae. The intervertebral space has been filled with the intervertebral disc, the shape of which corresponds to the shape of the disc situated between the L1 and L2 vertebrae.

In the model, an emphasis has been especially put on the correct modelling of the front vertebral column, i.e. the vertebral body with its cancellous and cortical parts and the disc with its nucleus and annulus fibers. While constructing the model, we tried to pay special attention to a precise modelling of articular joints at the point of contact between the superior articular processes and the inferior articular processes. It was done in this way because some authors claim that it is the vertebral body together with the intervertebral disc which is the most vital as regards transmitting loads in the lumbar part of the spine (Ashman, 1989, 1994). As to other parts of the spine, their role is not clearly explained. According to some authors, the processes of the lumbar vertebrae carry about 20% of the load per each motorial segment. It is also stated that their contribution towards work of the spine begins only after exceeding a certain load. The others claim that the processes take part in transmitting loads only under special circumstances, e.g. in the case of damage of the intervertebral disc (Nachemson, 1976).

The structure of the vertebral body consisting of cancellous and cortical bones has been taken into consideration in the model. Concavities of the upper and the lower surfaces of the vertebral body and also the concavity around it have been modelled. The rear part of the vertebral body has been also rounded in the model in order to depict the anatomical structure of the gap in which the spinal cord is situated.

Then the solids created earlier have been divided into finite elements. First, the vertebral body has been divided: the cortical part into 927 elements and the cancellous part into 886 tetrahedral elements. The annulus fibers and the nucleus consist of 2054 elements (the nucleus itself – of 350 elements). The rear column of the spine has been divided into 744 tetrahedral elements. The articular joint situated at the point of contact between two surfaces placed opposite the articular processes has been modelled with the "CONTACT 49" element. Eventually, the total number of tetrahedral elements used in the model of the lumbar part of the spine (L1, L2, L3) has amounted to 11779 (Fig.3).

Six degrees of freedom have been taken from the basis (the lower surface of the vertebral body L3) in the numerical model of the three lumbar vertebrae (L1, L2, L3). The moments have been applied to the upper vertebra (L1).

The values of displacements due to static loads are compared with those obtained by different authors for in-vitro experiments. The comparison has made it possible to verify correctness of the numerical model.

The results obtained by Kenneth (1990) during in-vitro tests have been taken into account. The author applied the moments equal to 2, 6, 10 Nm, respectively, to the tested fragment of the spine and made it bend forward. The obtained displacements were shown in the Cartesian coordinate system used by Kenneth (Fig.3). Fig.4 presents an analysis of the displacements of the fragment of the lumbar part of the spine (3 vertebrae) having 6 degrees of freedom (3 revolutions about the XYZ axes and 3 displacements along those axes). The numerical model has been subject to the same forces (2, 6, 10 N).

The mechanical characteristics of individual spine elements assumed in the

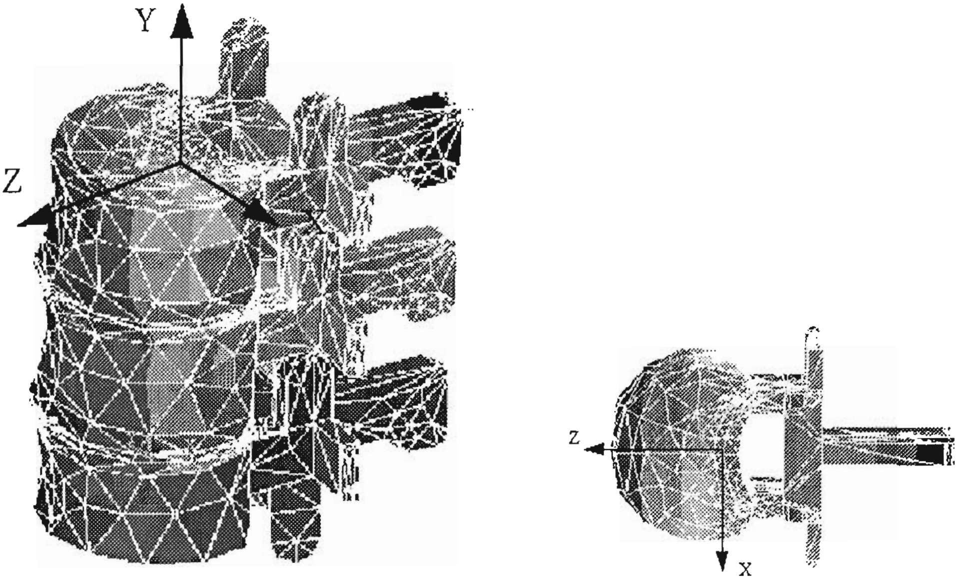

Fig. 3. Displacement of the numerical model of the lumbar part of the vertebral column

model are presented in Table 1. The values for the FEM model received as a result of the applied forces correspond to a large extent to the results emerging from Kenneth's biological model (Awrejcewicz, 1997, 1998).

Table 1. Mechanical properties of the lumbar part of the spine used in the FEM model

	E [MPa]	ν
Cortical bone (Yang, 1984)	11032	0.25
Cancellous bone (Yang, 1984)	345	0.2
Bony posterior elements (Goel, 1995)	3500	0.25
Annulus fiber (Lee, 1983)	20	0.45
Nucleus (Yang, 1984)	10	0.49

The numerical model has been compared to another spine model tested with the use of the biomechanical equipment for in vitro tests. In this case the mechanical properties of an osseous tissue and an intervertebral disc presented in Table 2 have been used. The numerical model is subject to the moments of 5, 10, 15 Nm, respectively, which make it bend forward and backward. The displacements of the numerical model caused by those loads are shown in Fig.5. The displacements have been compared to the results of the research

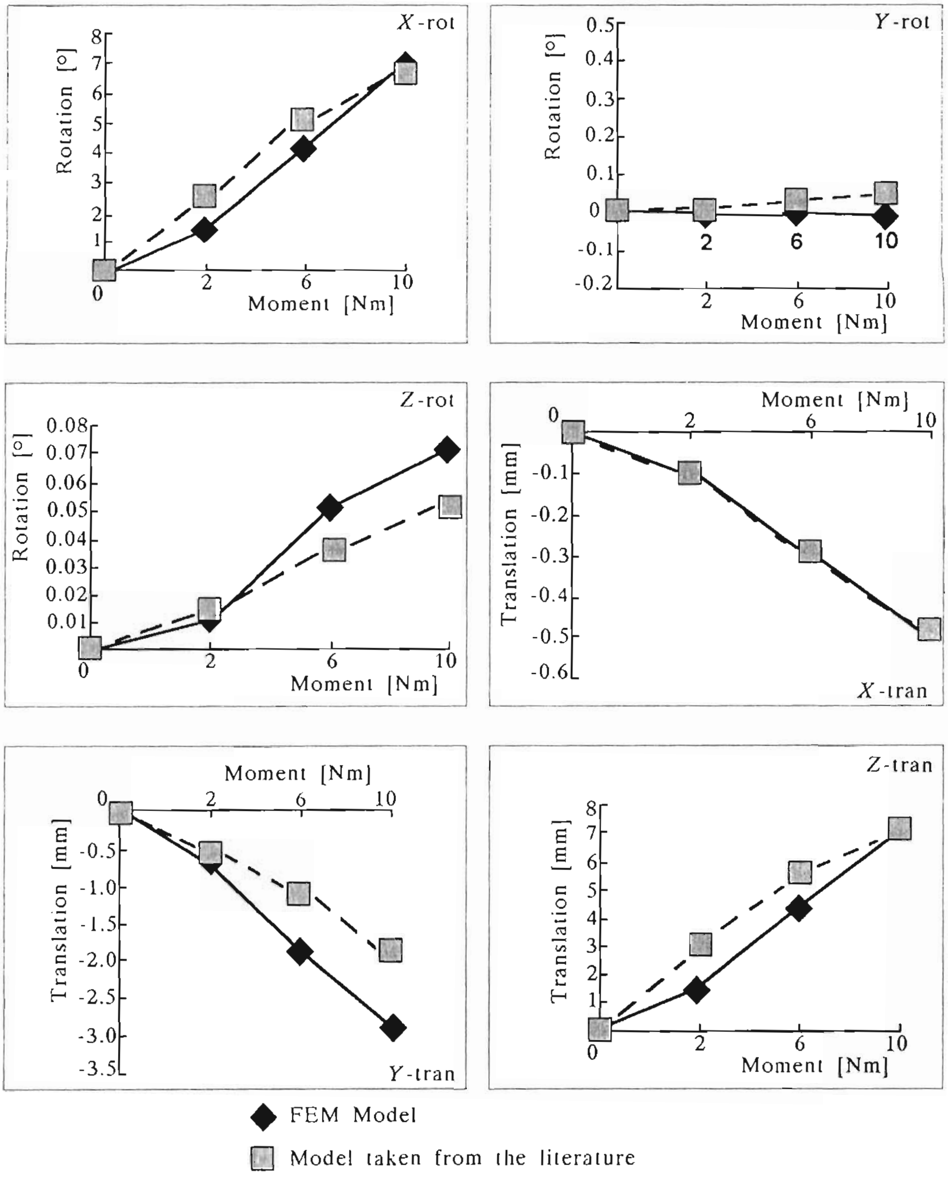

Fig. 4. Displacements of the lumbar part of the spine without an implant

conducted by Panjabi (1988). The author loaded the model using moments of the same magnitudes and causing the forward-backward bend. The results obtained in the case of the numerical model are consistent to a large degree with the results presented by Panjabi (1988) for the model tested in-vitro.

Table 2. Mechanical properties of the lumbar part of the spine used in the FEM model

	E [MPa]	ν
Cortical bone (Yang, 1984)	11032	0.25
Cancellous bone (Yang, 1984)	345	0.2
Bony posterior elements (Goel, 1995)	3500	0.25
Annulus fiber (Yang, 1984)	92	0.45
Nucleus (Yang, 1984)	10	0.49

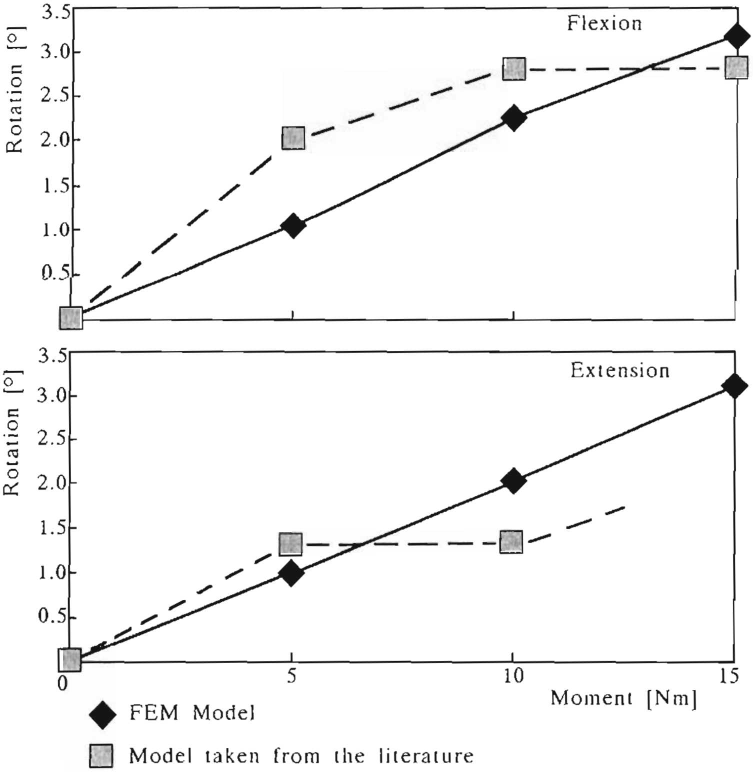

Fig. 5. Displacement of the lumbar part of the spine without an implant

5. Modelling of the vertebral column with an implant having a shape similar to the ZPLATE-ATL stabiliser

The middle lumbar vertebra (L2) has been removed from the three lumbar vertebrae (L1, L2, L3) and the spine has been stabilised with an implant having a shape similar to the ZPLATE-ATL. Then, all the solids have been divided into finite elements (Fig.6 and Fig.7). The cancellous part is divided into 3150 elements. The cortical part is divided into 1964 elements, the intervertebral disc into 995 elements, four bolts into 2071 elements and the implant into 491 elements. The total number of tetrahedral SOLID 92 elements amounts to 15882. It is assumed that the mechanical properties of the plate and of the screws are the same as the properties of steel (the Young modulus $E = 2.1 \cdot 10^5$ MPa and the Poisson ratio $\nu = 0.3$) and the mechanical properties of the other elements of the spine (cortical bone, cancellous bone, processes, disc) correspond to given in Table 2.

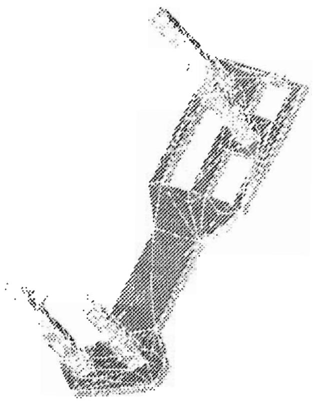

Fig. 6. An implant with the bolts divided into elements

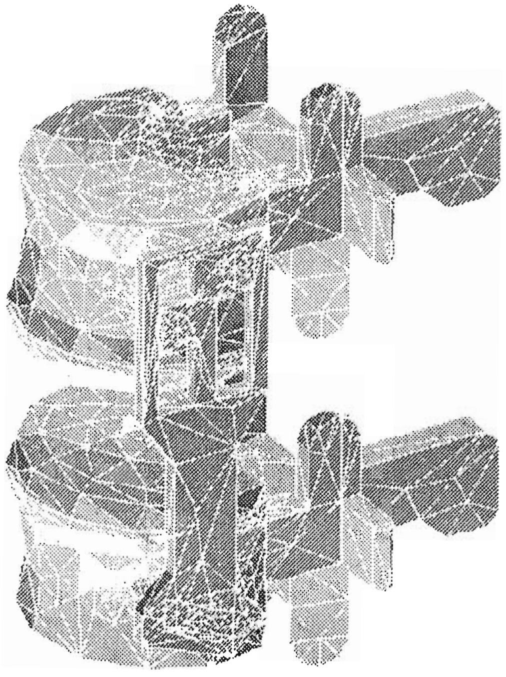

Fig. 7. A division of the model with an implant into FEM grid

The numerical model consisting of two lumbar vertebrae (L1, L3) is stabilised with an implant and the numerical model representing the three lumbar vertebrae (L1, L2, L3) without an implant are subject to the identical moments of 8 and 15 Nm. The displacements in the spine with the stabiliser, due to the forces, are compared with those in the healthy spine (Fig.8). In the case of rotation about the XYZ axes, the displacements of the spine with an implant and of the healthy spine are of the same magnitude. As regards the translation along the axes, the difference is of one order of magnitude.

The applied implant stabilises the damaged fragment of the spine sufficiently, which guarantees its recovery. However, it has caused overstiffness of the stabilised spine as compared to the healthy one.

6. Test stand for examination of stability of the spinal segment

To verify the numerical model, a special stand has been built for in-vitro research into the displacements of the lumbar vertebrae (L1, L2, L3) of the human spine. While examining the stability of the spine, an artificial model of the L1, L2 and L3 vertebrae has been used. The vertebrae and the spinal discs are made of an artificial material. The mechanical properties of these elements were tested experimentally (Table 3).

Table 3. Mechanical parameters of the artificial lumbar spine measured in-vitro

	E [MPa]	ν
Vertebrae	117	0.26
Spinal disc	3.5	0.49

The lower vertebra (L3) is immobilised and attached to the base by means of the especially designed handle which removes six degrees of freedom. The upper vertebra (L1) is free (not fixed). A permanent handle is attached to test different kinds of acting load (lateral, forward and backward bending, and rotation).

An extensometer has been especially designed and used for measuring the displacements caused by stresses. Another extensometer has been designed for the axial displacements due to compression, forward, backward and lateral bending. It measures the displacements between two points situated on the spine. Bending of the tested fragment along the vertical axis of the spine is measured by a special sensor.

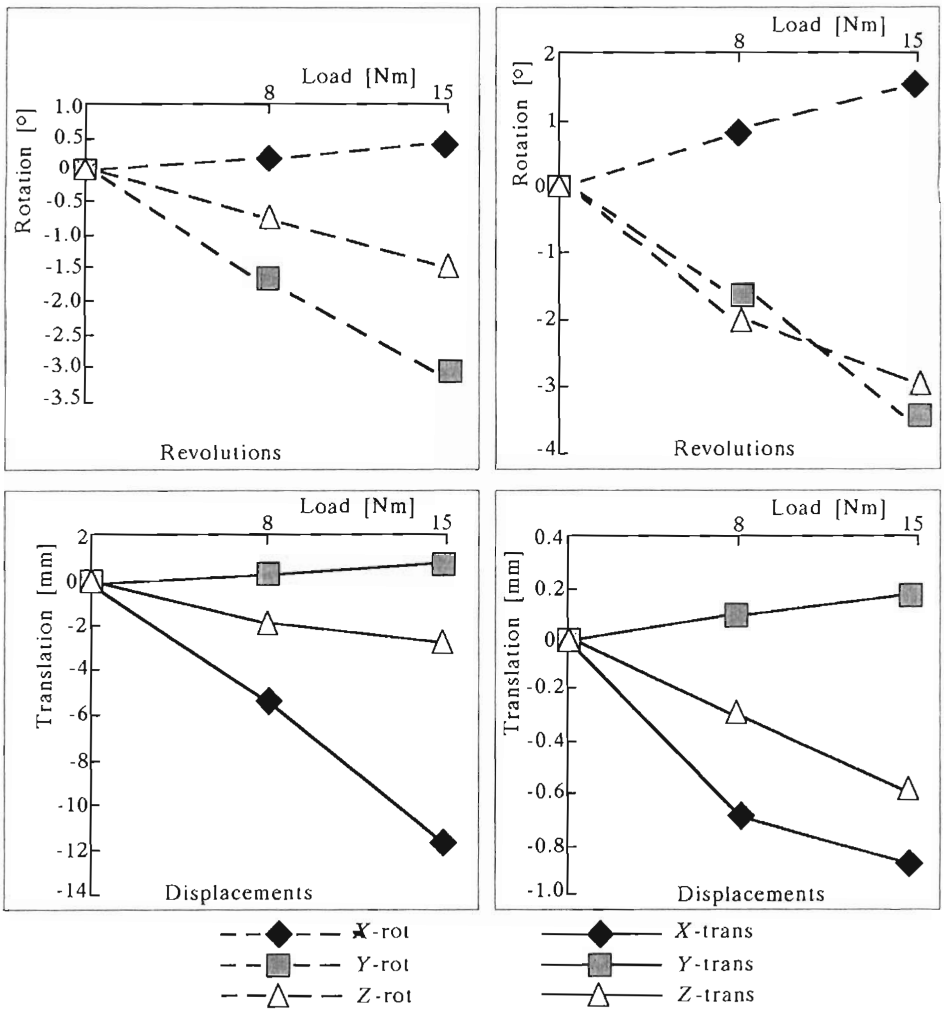

Fig. 8. Displacements of the numerical model with and without an implant (ZPLATE-ATL); (a) model without the implant, (b) model with the implant

In the FEM numerical model, the similar properties of the vertebrae and spinal discs are assumed as for the artificial model tested on this stand (Table 3). The numerical model is characterised by the same values and directions of a load as the artificial model of the spine. The values of displacements obtained in each case: compression (Fig.9), lateral, forward, backward bending, rotations (Fig.10), for both (numerical and artificial) models are presented in the corresponding diagrams.

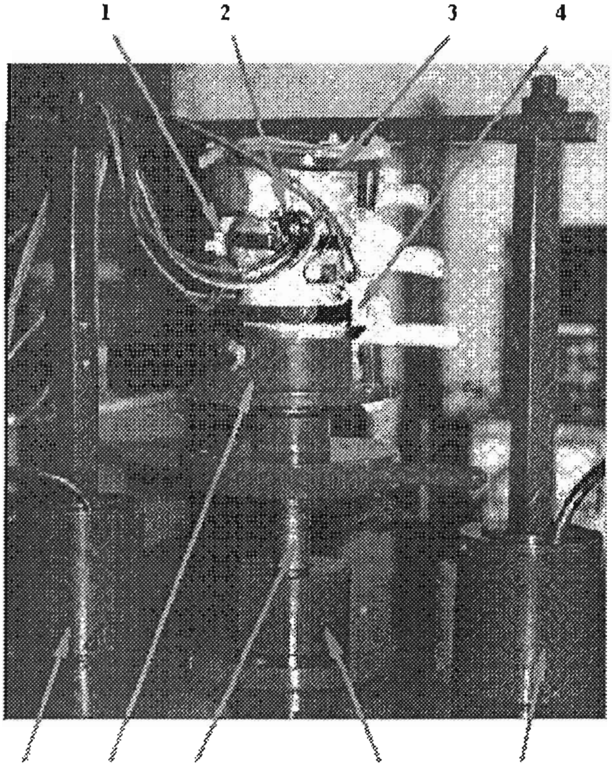

Fig. 9. Stand for examining spine (L1, L2, L3) by compressing; 1 – upper sensor of rotations, 2 – extensometer measuring the material constants E and ν, 3 – upper handle of the spine, 4 – lower sensor of rotations, 5 – first strength sensor, 6 – lower handle of the spine, 7 – screw lift, 8 – base, 9 – second strength sensor

The translational and axial rotations of the lumbar spine (L1, L2 and L3) as a function of the axial load are presented in Fig.11. The solid line presents the spine deformations of the numerical model of the spine (FEM).

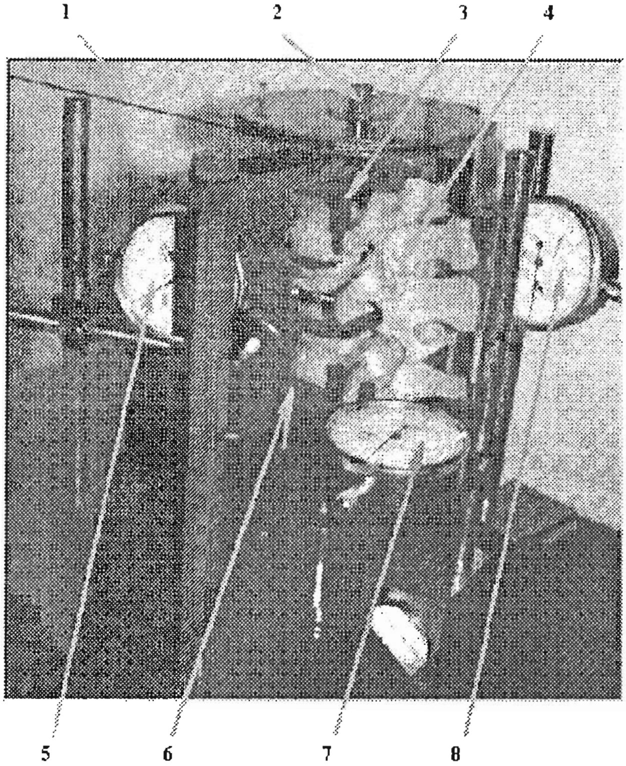

Fig. 10. Stand for examining spine by axis rotation; 1 – steel cable, 2 – shield with cable, 3 – upper handle of the spine, 4 – spine, 5 – sensor of the L2 vertebra rotations, 6 – lower handle of the spine, 7 – sensor of the L3 vertebra rotations, 8 – sensor of the L1 vertebra rotations

For the numerical and physical models, the measurement is made at the same measuring points under the influence of the load used for both the models. The conclusions are similar.

The stand for in-vitro tests allows examinations of stability of the lumbar vertebrae (L1, L2, L3). The conclusions drawn from the biomechanical in-vitro tests have been compared with the conclusions from numerical simulation in terms of the FEM model providing verification of the numerical model.

The stand has been designed and built in such a way that stability investigation can be concluded after a small modification (but only the lumbar spine can be examined). In addition, thoracic parts (with a geometry similar to the lumbar part) and even cervical parts (with a different geometry) can be investigated.

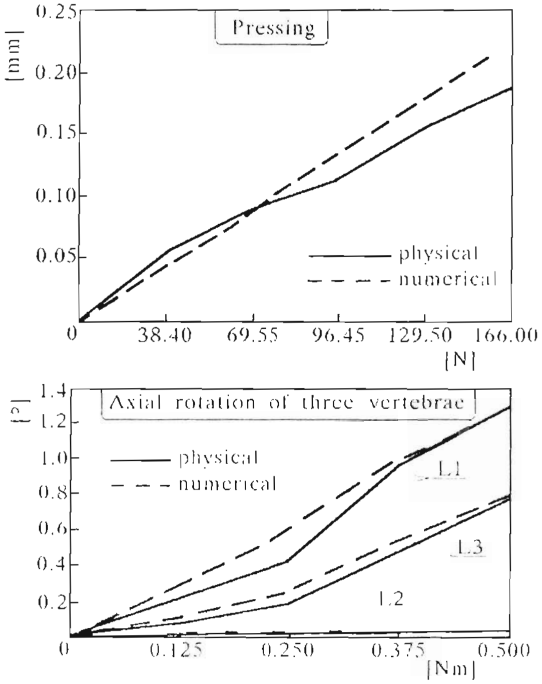

Fig. 11. Translational and rotational displacements of the lumbar spine (L1, L2 and L3) as a function of the axial load (compression)

The stand has been built especially for stability tests of healthy parts of the human spine taken from the cadaver and also for the parts where illness is simulated and an implant has been used.

7. Conclusions

The presented numerical model of parts of the lumbar spine allows for analysis of the static and dynamic properties of the lumbar spine.

This model is used in static investigations. The results (spine displacements) obtained where the loads were applied are compared with the values given in the literature and obtained for biological models tested in biomechanical tests. The conclusions are similar. To sum up, we can say that the numerical model of the part of the lumbar spine is correct.

After removing one of the vertebrae from the model, a stabiliser of a similar shape to the ZPLATE-ATL type implant was used. The aim of the work was not to examine the implant but only to show that the model can be used to examine and choose different kinds of stabilisers with properties and ways of attaching which are depended on the clinical needs.

A special stand was built for biomechanical in-vitro tests of parts of the human spine. It enabled us to carry out biomechanical tests on the physical model of the spine. Comparing the experimental results with the results obtained from the numerical model, a good agreement has been found. It proves the reliability of the FEM numerical model of the lumbar spinal segment.

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Analiza numeryczna i doświadczalna biomechaniki trzech kręgów lędźwiowych

Streszczenie

Wykorzystując komercyjny program ANSYS 5.2 oparty na MES, stworzono trójwymiarowy model numeryczny kręgosłupa ludzkiego składający się z trzech kręgów lędźwiowych (L1,L2,L3). W modelu uwzględniono własności mechaniczne poszczególnych elementów kręgosłupa (kość korowa, gąbczasta, wyrostki, pierścienie włókniste, jądro). Model ten pozwala na analizowanie przemieszczeń zachodzących w układzie kręgosłupa pod wpływem różnych obciążeń statycznych i dynamicznych oraz umożliwia badanie i dobieranie różnego rodzaju implantów.

W celu zweryfikowania modelu numerycznego porównano otrzymane wyniki w postaci przemieszczeń, uzyskane pod wpływem różnego rodzaju obciążeń, z wynikami uzyskanymi przez różnych autorów w testach biomechanicznych na preparatach biologicznych in-vitro. Okazało się, że wyniki te są w dużym stopniu zbieżne.

W celu dodatkowej weryfikacji stworzonego modelu numerycznego zostało zaprojektowane i wykonane stanowisko umożliwiające badanie in-vitro przemieszczeń fragmentu kręgosłupa ludzkiego. W badaniach stabilności wykorzystano sztuczny model kręgów L1,L2,L3. Wyniki, które uzyskano w modelowaniu numerycznym są bardzo zbliżone do wyników uzyskanych podczas testów na tym stanowisku.

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