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Numerical Analysis of the Impact of Vibration on the Lumbar Spine of the Driver

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Abstract: ***The human body, as a complex biomechanical system, is daily exposed to oscillatory movements. Vibrations are observed as small displacements of points compared to the dimensions of the system. The body's sensitivity to vibration depends on many factors, such as body position, muscle tension, frequency, amplitude, and direction of vibration. Comfort is one of the important factors in the study of the quality of the vehicle. Exposure to vibrations over a long time can seriously and permanently damage some organs of the body. In this paper, the influence of vibrations on the lumbar part of the human body was investigated. Vibrations were determined experimentally while the vehicle was moving on the highway for the case of two different speeds. A 3D computer model of a lumbar spine was developed using CT scans. The acceleration values obtained by the experiment were the input values for the numerical analysis of the lumbar spine using the Ansys software package.***

Index Terms: ***Vibration, measurements, lumbar spine, numerical analysis***

1. INTRODUCTION

VIBRATIONS are a form of mechanical wave motion. The energy of vibration is transmitted to the human body. The effect of vibrations results in side effects (physical and psychological disorders) which are especially pronounced in cases of prolonged exposure. Negative effects of vibration were observed in the twenties and thirties of the last century with the rapid development of industrial machines and motor vehicles. Whole-body vibrations (WBV) occur when the body is in contact with a vibrating surface. Vibrations are transmitted to the whole body through the passenger's legs, the seat part and contact with the steering wheel. The magnitude of this vibration depends on the road surface, vehicle speed, and is transmitted to the occupants through all points of contact between them and the vehicle. Much research in recent decades has been devoted to investigating the effects of vibration and the effects it causes [1], [2], [3]. Whole-body vibrations are especially significant in the frequency range from 1 Hz to 80 Hz. This frequency range also includes the main resonance points of individual organs and parts of the human body (eg head, eyes, abdomen, and spine) [4], [5]. Adverse effects of these vibrations are related to the appearance of several health problems, among which the most characteristic is back and neck pain. Whole-body vibrations in the region of extremely low frequencies (below 0.5 Hz) cause "seasickness" [6]. Body vibrations are one of the risk factors for spinal diseases. Prolonged exposure of the body to vertical vibrations can lead to harmful effects on the musculoskeletal system, while reiterated repetitions can lead to the development of pathological changes in the spinal column. The vibrations absorbed by the body lead to muscle contractions that can cause muscle fatigue, especially at resonant frequencies. Vertical vibrations in the range from 5Hz to 10Hz cause resonance in the thoracic abdominal system, from 4Hz to 8Hz in the spinal part, from 20Hz to 30Hz in the area of the head and neck and from 60Hz to 90Hz in the area of the eyeballs [7].

Low back pain (LBP) can be defined as unpleasant pain or stiffness of the lumbar spine [8]. Low back disorders are anatomical or neuromuscular changes that in some cases can include the sources of LBP. These include intervertebral disc herniations, spinal stenosis, osteoporosis, osteoarthritis, ankylosing spondylitis, and spondylolisthesis. Although a link between Whole-body vibrations (WBV) and LBP is generally accepted, there is no consensus as to the mechanism of injury [9]. One mechanism by which WBV may lead to LBP is through

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changes in the system of spinal stability control. Such changes in the spine dynamics could lead to increased dynamic loads of the spine and increasing out-of-range compressive loads. In order to study the effects of WBV exposure, there is the need to quantify the vibration characteristics of the human body. The two primary characteristics of vibration are frequency and amplitude, and both have been shown to affect the human body differently.

The spinal column is the longest part of the axial skeleton [10]. It gives the trunk strength and its elasticity allows it to move. The spinal column is built of vertebrae, between each of them there are discs that function as shock absorbers (Fig. 1). 33-34 vertebrae are interconnected by joints, ligaments, and muscles into to form a spine. Depending on the part of the spine they build, they are divided into: Cervical (neck) (C1 - C7); Thoracic (middle back) (T1 - T12); Lumbar (lower back) (L1 - L5); Sacrum (S1 - S5); and Coccyx (tailbone). The basic functional unit of the spinal column is the so-called vertebral dynamic segment consisting of two adjacent vertebrae, the intervertebral disc, two intervertebral joints, and ligaments that connect them tightly together to the disc.

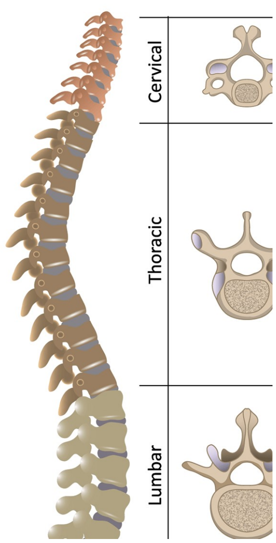

Fig. 1: Human spinal column

For many years, computer simulations have been present to study the loads on the spine and the stresses that occur during the movement of a person or certain body positions he occupies while performing daily tasks.

The aim of the study [11] was to estimate the load on the lumbar spine based on a model that accurately symulated this body part. The model was developed using the finite element method (FEM). FEM and Ansys 8.0 were used to develop a three-dimensional model of the musculoskeletal system of the human body. The lumbar spine was modeled in detail including the difference in structure between the lumbar vertebrae. Other elements of the trunk were shown schematically because the emphasis in this study was on the lumbar spine. The model consisted of six intervertebral discs (Th12 / L1 – L5 / S1), part of the sacral bone with the upper edge of the pelvis, part of the trunk above the intervertebral disc Th12 / L1, ligaments, and muscles. A simulation of two body positions has been developed; forward-leaning position and upright sitting position. After the simulation, the results showed forces that muscles develop and stresses in the intervertebral discs and lumbar vertebrae. Computer calculations showed that the stresses and compressive forces in the intervertebral discs increased with increasing load force. Also, these forces were significantly higher in the bent forward position than in the upright body position.

In this paper [12], a simulation of lumbar spine movement with serially connected parallel manipulators is proposed. The analysis of the structure of the human spine and its movements was calculated to simulate the movements and forces acting on the lumbar spine. A mechanical model with human spine parameters was designed using the characteristics of parallel manipulators and spring stiffness. The curvature (curvature) of the spine is an important aspect of the functionality of the human spine. The proposed model can include curvature inputs in the configuration of the entire spine model using proper relative positioning and movement of parallel manipulator units. The human spine model is modeled as a multi-module parallel manipulator with 3D-designed vertebrae. The 3D model was made in SolidWorks and then exported to the ADAMS software package to run the dynamic simulation. In ADAMS, the disc is modeled as a body attached to the vertebrae. The result of this work was a 3D model of the human spine used to simulate the behavior of intervertebral discs and muscle and tendon movements. The simulation results can provide an estimate of the forces supported by the intervertebral discs during the movement of the right spine. Another result of this work can be recognized in the provision of a virtual model that physicians can use to preliminarily study the functionality of the human spine or as an aid in the biomechanical study of torso functionality.

In this paper [13], a lumbar spine is presented as a hybrid model, which enables static and dynamic simulations of disc pressure and spine mobility. It consisted of five lumbar vertebrae (L1-L5) that meet the L5-based sacral spine C1. Each pair of vertebrae is separated by an intervertebral disc and connected by a pair of ground joints and a set of ligaments. The geometry was taken from the bodyparts3d database where all models are connected to calculate the FEM volumetric network of disks. All simulations were done using the SOFA library. Dynamic simulations were performed with the implicit Euler integration scheme. This work aimed to combine rigid bodies, finite elements as deformable bodies, joint constraints and springs into a spine model. Each vertebra is represented by a rigid body. The tetrahedral finite element was used for disks mesh. Brushed (faceted) joints are presented as elastic joints with six degrees of freedom, while the ligament is modeled using nonlinear one-dimensional elastic elements. The hybrid model presented in this paper greatly simplifies the modeling task and speeds up the simulation of the pressure inside the disks. This research represents the first step of a long process leading to solving biomedical problems. The model in this paper emphasizes the assumption of vertebral simplification because non-deformable body curls do not lead to loss of accuracy in movement quality, range of motion, and intradiscal pressure produced by the lumbar segment in three anatomical planes.

With the progress and development of new technologies, new possibilities for monitoring the movement of certain parts of the body have been introduced, and thus, a better understanding of their behavior. Modern smartphones contain powerful sensors for measuring physical phenomena in the environment where they are placed. Acceleration sensors placed into smartphones are increasingly being used in laboratories. In this study, using a mobile phone we measured the vibrations that occur in the body of the driver driving on an asphalt road. After that, we modeled the 3D model of the human lumbar spine, according to the real dimensions. Finally, we applied to the model a measured acceleration in order to study the Von Misses stresses of the human lumbar spine..

2. Materials and Methods

A. Numerical Part

A 3D computer model of a lumbar spine was developed using CT scans. The CT scans were read into Mimics 17.0 (Materialize Inc., Leuven, Belgium) visualization software, where the images were segmented by the threshold to obtain a 3D model (Fig. 2).

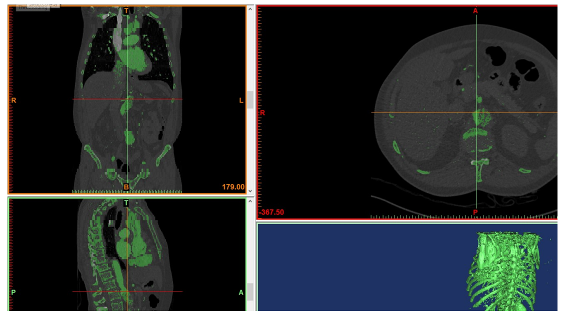

Fig. 2: The process for the 3D FE model - CT scan and 3D reconstruction

Several stages make up this whole process: acquisition of CT images, segmentation of CT images and contours detection, generating 3D models, processing the 3D models, creating a mesh of finite elements, and setting boundary conditions. Ansys R14.5 was used to produce 3D mesh (Fig. 3). Linear tetrahedron was used as the final element, where the field of displacement over the tetrahedral element is determined by the three components u_x, u_y and u_z. These displacements are linearly interpolated over the element from the node values:

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} u_{11} & u_{12} & u_{13} & u_{14} \\ u_{21} & u_{22} & u_{23} & u_{24} \\ u_{31} & u_{32} & u_{33} & u_{34} \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{bmatrix} \quad (1)$$

where N_1, N_2, N_3, N_4 are interpolation functions that are simply the coordinates of the tetrahedron; and u_{11},…., u_{34} are nodal displacements.

Finite element mesh consists of three groups of elements: finite elements that represent cortical bone, finite elements that represent nucleus and finite elements that represent annulus. Mechanical properties assigned to the each material are summarized in Table 1 [14], [15].

Name of the component	*Young's Modulus [MPa]*	*Poisson's ratio*
Cortical bone	*12000*	*0.3*
Nucleus	*1*	*0.49*
Annulus	*4.2*	*0.45*

Table 1: Material properties

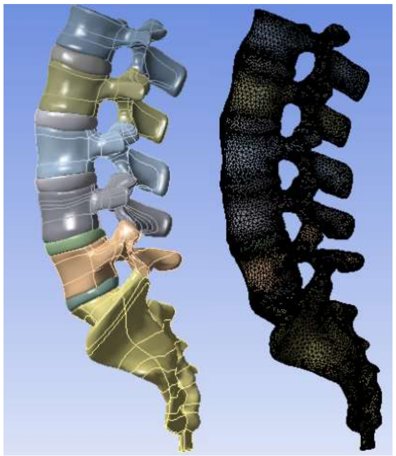

Fig. 3: 3D model of the human lumbar spine

One of the basic principles of continuum mechanics is the principle of virtual work. Starting from the equilibrium equations [16] by applying the boundary conditions, virtual work of internal and external forces can be equal

$$\delta W_{\text{int}} = \delta W_{ext} \tag{2}$$

Virtual work of the previous equation in matrix form can be written as:

$$\begin{aligned} \delta W_{\text{int}} &= \int_V \delta \mathbf{e}^T \boldsymbol{\sigma} dV \\ \delta W_{ext} &= \int_V \delta \mathbf{u}^T \mathbf{F}^V dV + \int_{S^\sigma} \delta \mathbf{u}^T \mathbf{F}^S dV + \sum_i \delta \mathbf{u}^T \mathbf{F}^{(i)} \end{aligned} \tag{3}$$

where we used the relation for the deformation components

$$\mathbf{e} = \begin{Bmatrix} e_{xx} \\ e_{yy} \\ e_{zz} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{Bmatrix} u_{1,1} \\ u_{2,2} \\ u_{3,3} \\ u_{1,2}+u_{2,1} \\ u_{2,3}+u_{3,2} \\ u_{1,3}+u_{3,1} \end{Bmatrix} = \begin{bmatrix} N_{1,1} & 0 & 0 & \dots & N_{N,1} & 0 & 0 \\ 0 & N_{1,2} & 0 & \dots & 0 & N_{N,2} & 0 \\ 0 & 0 & N_{1,3} & \dots & 0 & 0 & N_{N,3} \\ N_{1,2} & N_{1,1} & 0 & \dots & N_{N,2} & N_{N,1} & 0 \\ 0 & N_{1,3} & N_{1,2} & \dots & 0 & N_{N,3} & N_{N,2} \\ N_{1,3} & 0 & N_{1,1} & \dots & N_{N,3} & 0 & N_{N,1} \end{bmatrix} \begin{Bmatrix} U_1^1 \\ U_2^1 \\ U_3^1 \\ \vdots \\ U_1^N \\ U_2^N \\ U_3^N \end{Bmatrix} = \mathbf{BU} \tag{4}$$

Applying the principle of virtual work and the constitutive relations for linear elastic material in matrix form

$$\boldsymbol{\sigma} = \mathbf{Ce} \tag{5}$$

and by applying the concept of isoparametric interpolation [16] in the finite element, we can write the equation of equilibrium finite elements as

$$\mathbf{KU} = \mathbf{F}_{ext} \tag{6}$$

where K is element stiffness matrix, C - elastic constitutive matrix, e = BU - matrix deformation, U - displacements at the nodes, F_{ext} - external forces in the element nodes.

The equations of motion of a material system can be written by applying the principle of virtual work, taking into account the action of inertial forces. The elementary volume inertial force is:

$$d\mathbf{F}^{in} = -\ddot{\mathbf{u}} dm = -\ddot{\mathbf{u}} \rho dV \tag{7}$$

When the influence of inertial forces is taken into account, the virtual work of external forces is:

$$\delta W_{ext} = \int_V \delta \mathbf{u}^T \left(\mathbf{F}^V - \rho \ddot{\mathbf{u}} \right) dV + \int_{S^\sigma} \delta \mathbf{u}^T \mathbf{F}^S dV + \sum_i \delta \mathbf{u}^T \mathbf{F}^{(i)} \tag{8}$$

By time differentiation of equation (1) we obtain interpolations for velocities and accelerations of points:

$$\dot{\mathbf{u}} = \mathbf{N} \dot{\mathbf{U}} \tag{9}$$

$$\ddot{\mathbf{u}} = \mathbf{N} \ddot{\mathbf{U}} \tag{10}$$

where are:

$\dot{\mathbf{u}}$ - velocity of the material point in the element,

$\ddot{\mathbf{u}}$ - acceleration of the material point in the element,

$\dot{\mathbf{U}}$ - speed in nodes,

$\ddot{\mathbf{U}}$ - acceleration in nodes

By applying equation (1) for $\delta \mathbf{u}$, the equality of virtual works of external and internal forces will have the following form:

$$\delta W_{ext} = \int_V \delta \mathbf{u}^T \left(\mathbf{F}^V - \rho \ddot{\mathbf{u}} \right) dV + \int_{S^\sigma} \delta \mathbf{u}^T \mathbf{F}^S dV + \sum_i \delta \mathbf{u}^T \mathbf{F}^{(i)} \tag{11}$$

that is:

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{KU} = \mathbf{F} \tag{12}$$

where **M** is the finite element mass matrix.

The previous equation can also be written in the following form:

$$\mathbf{M}\ddot{\mathbf{U}} + {}^{t+\Delta t}\mathbf{K}^{(i-1)} \Delta \mathbf{U}^{(i)} = {}^{t+\Delta t}\mathbf{F}_{ext} - {}^{t+\Delta t}\mathbf{F}_{int} \tag{13}$$

In the linear analysis of solids, a basic assumption is that the moving solids are infinitesimally small and that the material is linearly elastic. Also, the assumption is that the nature of the boundary conditions remains unchanged under the action of external loads. Under these assumptions, the equation of equilibrium is derived for finite element structural analysis.

B. Experimental Part

In this research we used vehicle RENAULT Megane 3. The car was driven on asphalt, on the straight highway Kragujevac - Batocina. All vibration measurements were written down using a Samsung Duos 3 phone at the position shown in Fig. 4.

Fig. 4: The position of the smartphone and 3 accelerometer axes

Accelerometers used in this smartphone is highly miniaturised and measure the acceleration around three axes. It is a digital, triaxial ±2g to ±16g sensor BMA 250, (dimensions 2mm x 2mm, height 0.95 mm), with intelligent on-chip motion-triggered interrupt controller, 10bit resolution and a sample frequency from 7.81 Hz to 1 kHz [7]. The typical temperature measurement range is -40°C up to 87.5°C. VibSensor application was used to measure vibrations. This application makes collecting, analyzing, and exporting high-quality accelerometer data easy. The experiment included two driving speeds: 70 and 110 km/h. The following section will show the results of the two driving modes.

The boundary conditions are defined so that the weight of the upper body (2/3 of the total weight) is set on the upper part of the L1 vertebrae, while the acceleration measured on the three-axis accelerators is set on the sacrum. Fig. 5 presents the input boundary conditions given to the mobile device.

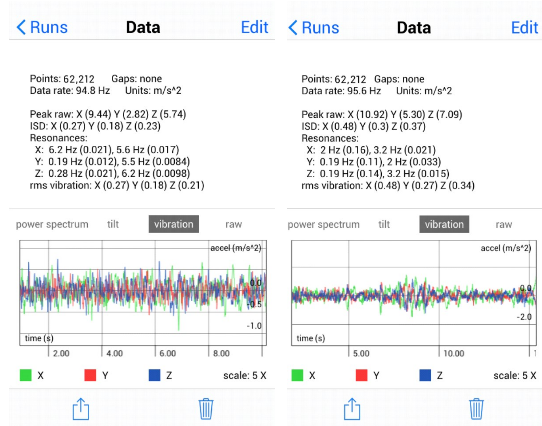

Fig. 5: The input boundary conditions obtained to the mobile device; measured vibrations for the velocities of 70 km/h (left) and 110 km/h (right).

3. RESULTS

In this section, we present the results of numerical simulation. A numerical analysis of the impact of vibration on the human lumbar spine was carried out using the software package Ansys R14.5. Fig. 6 show von Misses stress distribution on the L4 and L5 vertebral body while driving speed was 70 km/h. The emphasis is on that part of the spine because most of the problems occur in that lower back when the driver is exposed to prolonged driving combined with continuous vibration action. Based on this analysis, it is clear that the highest load is on the vertebral body L5, so the highest recorded von Misses stress is 0.45 Mpa, mean 0.19 Mpa. Observing the vertebral body L4, slightly lower values were observed, so the mean von Misses stress value in that part was 0.14 MPa.

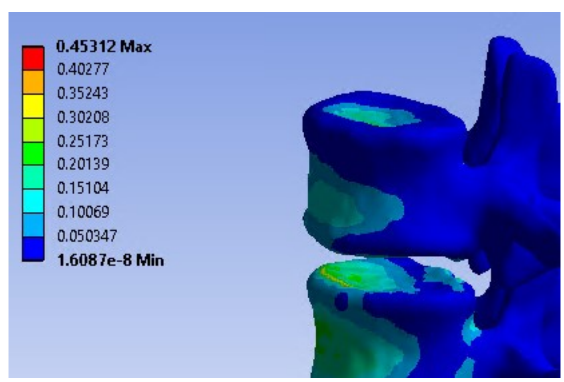

Fig. 6: Von Misses stress distribution along the vertebral body L4 and L5 during driving speed of 70 km/h

Fig. 7 show von Misses stress distribution on the L4 and L5 vertebral sections during driving at speed of 110 km/h. From the figure it can be concluded that a drastic increase in speed leads to a lower load on the spine. This is a consequence of the fact that at high speeds there is a vibration reduction, so significantly less vibration (caused by bumpy roads) is transmitted to the body of the driver. The bigest load, in this case, is also on the vertebral body L5. The highest recorded von Misses stress is 0.36 Mpa, mean 0.12 Mpa. Observing the vertebral body L4, slightly lower values were observed, so the mean von Misses stress value in that part was 0.08 MPa.

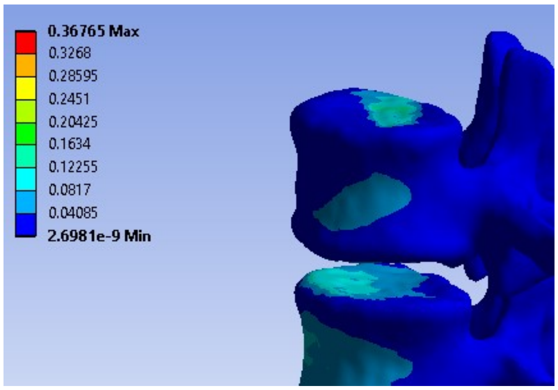

Fig. 7: Von Misses stress distribution along the vertebral body L4 and L5 during driving speed of 110 km/h

Fig. 8 shows the load of 5 intravertebral discs of the lumbar spine when speed was 70 km / h. The figure shows the S1-L5, L5-L4, L4-L3, L3-L2, and L2-L1 discs. It can be seen that the S1-L5 disk is the most loaded, as well as the L5-L4 disk. The highest von Misses stress value is 1.42 MPa.

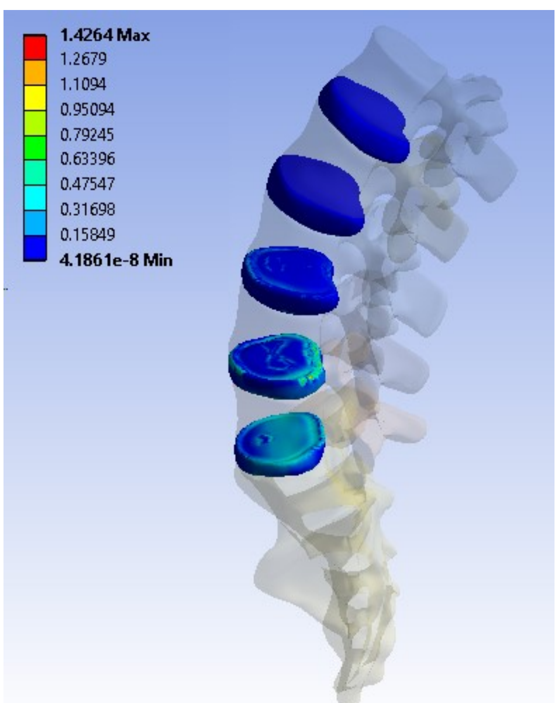

Fig. 8: Von Misses stress distibution along the intravertebral discs of lumbar spine during driving speed of 70 km/h

The mean von Misses stress of the intravertebral disc S1-L5 is 0.89 MPa, then of the disc L5-L4 0.46 MPa, and much less of disc L4-L3 0.11 MPa. This proves once again that the lower back, i.e., the lumbar spine with an emphasis on the L4-L5 region, suffers the greatest loads while driving a car.

4. CONCLUSION

The FEA performed in this study demonstrated pattern of von Misses stress distribution through the human lumbar spine during drives with different car speeds. Using a smartphone, we measured the vibrations and studied the impact on the modeled 3D model of the human spine. Results of this study, for the car speed of 70 km/h, showed that the mean von Misses stress of 0.19 MPa was on the vertebral body L5, while in the same case, the mean von Misses stress of 0.14 MPa was observed on the vertebral body L4. In the second case, a drastic increase in speed led to a lower load on the spine. The results showed that the mean values of the von Mises stress decreased, for the L5 disk the stress was 0.12 MPa, and for the L4 disk it was 0.08 MPa. We also showed the way of von Mises stress distribution in the case of intervertebral discs of the lumbar region. It has been observed that the highest loads during body vibrations when driving are on the S1-L5 disc as well as on the L5-L4 disc. The mean von Misses stress values of these discs were 0.89 MPa and 0.46 MPa, respectively.

The finite element method provides excellent opportunities to study the behavior of the spine during several daily activities. Conducted results give a clearer picture of the impact of vibrations on the human spine and its main parts. It would be interesting to see how the seating angle affects the amount of load while driving a car. Our future research will go in that direction.

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