The method for numerical analysis of the damping properties of lumbar discs during high impact loads

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Abstract

This document presents numerical analysis of the damping properties of the lumbar vertebral disc under high impact load. The elaborated Finite Element Model (FEM) of L4-L5 spinal segment, based on CT scans includes the L4 and L5 vertebrae divided into cortical and cancellous bone, the spinal disc with nucleus pulposus and spine ligaments modelled as elastic springs. The load impulse was applied into the model based on the initial velocity for the segment of the body placed under the spine segment L4-L5. We have examined the extent to which the disc can absorb the energy and the influence of possible changes of fibrous ring properties on transmitted load during impact load. The authors explain the mechanism leading to the damping of this high energy by conversion to power friction in the intervertebral disc.

Keywords: damping properties, lumbar disc, high impact load, Finite Element Analysis

1. Introduction

Spinal discs play a crucial role in the vertebral column, serving as shock absorbers between the vertebrae, preventing the vertebrae from grinding against one another, and allowing a wide range of movement in all directions [1]. Most spinal fractures, also caused by high-energy accidents occur in the lumbar spine and are a widespread medical problem [2]. Microanalysis of damping properties of lumbar vertebral discs contributes to the development of new biomaterials, including mechanical characteristics of discs, providing better protection to the spine. The structure of lumbar vertebral disc consists of highly deformable nucleus pulposus, constituting the compensating element of high impact load and annulus fibrous, a hydrated material with a high proteoglycan content that generates a large osmotic pressure [1].

The hitherto elaborated FE models of L4-L5 spinal segment [3-5] consist of lumbar vertebra divided into cortical and cancellous bone and intervertebral disc including nucleus pulposus and annulus fibrosus. The nucleus pulposus consists of water and layers of sturdy elastic collagen fibres. The most accurate FE models [5] consider: the division of vertebra into 5 zones according to Bone Mineral Density (BMD) distribution, the multilayer structure of annulus fibrous and ligaments of lumbar vertebral column: Anterior longitudinal ligament (ALL), Posterior longitudinal ligament (PLL), Supraspinous ligaments (SSL), Interspinous ligaments (ISL), Ligamenta flava (LF), Intertransverse ligaments (TL).

The analysis of damping properties of lumbar nucleus pulposus indicates extreme deformation and strain amplitudes as large as 12.5% in physiological loading conditions. It also has been shown that the nucleus pulposus contributes to the damping properties of the intervertebral disc [6]. Other analysis indicates that stiffness, but not damping, significantly correlates with preload [7]. This study highlights the need to incorporate the observed non-linear increase in stiffness of the spine under high loading rates in dynamic models of the spine and those investigating the response of the spine to vibration.

The aim of this work is analysis of the possibility of the damping and dissipation of the energy generated during axial load of the spine segment. The segment L4-L5 was selected due to the maximal stresses occurring in this spine level. The energy dissipation inside the intervertebral disc structure can be mainly caused by the friction forces generated between the surfaces of the fibre rings.

2. Material and methods

A detailed L4-L5 spinal segment model (Fig. 1) was elaborated using a computed tomography (CT) scans of a 40-year-old patient performed using an 8-row spiral CT with an accuracy of 2.5 mm. Bone structures were meshed with 8-node tetrahedral finite elements (23971 elements), because tetrahedral element instead of cubic or hexahedral were adopted to represent a smooth surface which accurately depict stress in the concentration areas with the use of local grid densification.

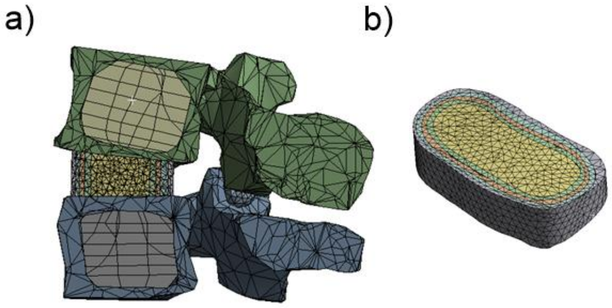

Figure 1: The model of spine segment L4-L5: a) view of vertebra L4 and L5 with the intervertebral disc, b) structure of intervertebral disc

Nonlinear Hyperelastic Properties (Mooney-Rivlin model) for nucleus pulposus was selected according to Schmidt experimental data [8]. The particular layers of Annulus Fibrosus were modelled as the isotropic elastic material with yield stress appointed from the Stress-Strain curve for annual fibres presented by Schmidt [8]. The Lumbar ligaments: ALL, PLL,

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SSL, ISL, LF, TL were modelled as one-dimensional cable elements.

2.1. Loading and boundary conditions

The elaborated model consists two masses representing the body part respectively above and below the L4-L5 segment. The loading was selected for a case in which the occupant of an armoured vehicle is sitting inside and an IED explodes underneath. As a result the vehicle is lifted up with a velocity proportional to charge mass [9]. Based on the empirical data the initial velocity was assumed at 700 mm/s, equivalent to 10 kg TNT [10]. Between 4 modelled rings of Annulus Fibrosus, the frictional boundary condition was assumed. The damping properties of the lumbar disc were investigated for 3 different values of the friction coefficient.

3. Results and discussion

Fig.2 presents the deformation of the intervertebral disc. Little stiffness of the Nucleus Pulposus causes that in the rings the stresses are much higher than in the nucleus.

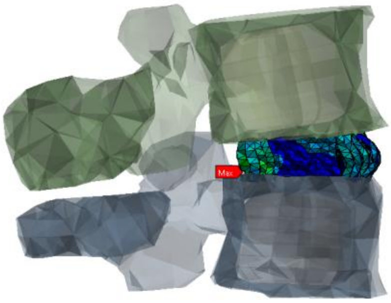

Figure 2: Deformation of the intervertebral disc

Fig. 3. presents the acceleration of the human torso for 2 friction coefficients between the Annulus Fibrosus rings. If the friction increasing the acceleration of the body is less, this suggests that the structure and mechanical characteristics of the intervertebral disc have an influence on the damping properties.

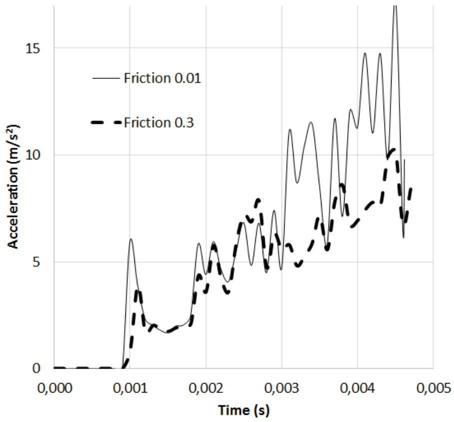

Figure 3: Acceleration of the torso for different values of the friction in the Annulus Fibrosus contact

Increasing the friction coefficient between rings also reduced the principal stresses (Fig. 4). The friction assumed equalled 0.49 with the result that the maximal stress in the rings was only 0.6 MPa, however, if the friction coefficient equalled 0.01, the maximal stress was 1.5 MPa or more.

Only the four fibre layers were modelled in the annulus but in practice, the annulus consists of 15–25 distinct fibre layers. The movements between fibres occur consequently in all disc layer. The dissipated energy is converted to power friction in the disc.

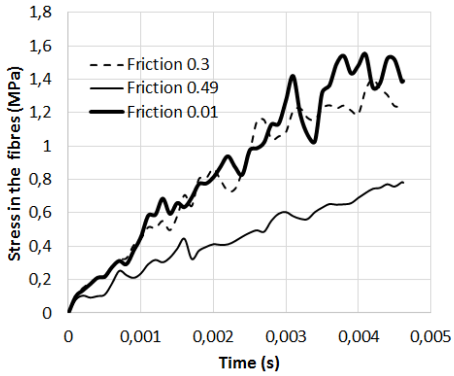

Figure 4: The maximal principal stresses in the intervertebral disc

References

[1] Newell, N., Little N.W., Christou, A., Adams, M.A., Adam, C.J. and Masouros, S.D., Biomechanics of the human intervertebral disc: A review of testing techniques and results, *J. Mech. Behav. Biomed. Mater.*, 69, pp. 420–434, 2017.

[2] Bickenbach, J., International perspectives on spinal cord injury, WHO, 2013.

[3] Zheng, Q., Liao, S.H., Wei, W., Liu, Y.S. and Shi, S.Y., FEM analysis of complex lumbar spinal stenosis decompression and intervertebral fusion. *Chin. J. Biomed. Eng.*, 31, pp. 566–571, 2012.

[4] Park, W.M., Kim, K. and Kim, Y.H., Effects of degenerated intervertebral discs on intersegmental rotations, intradiscal pressures, and facet joint forces of the whole lumbar spine. *Comput. Biol. Med.*, 43, pp. 1234–1240, 2013.

[5] López E., Ibarz E., Herrera A., Puértolas S., Gabarre S., Más Y., Mateo J., Gil-Albarova J. and Gracia L., A predictive mechanical model for evaluatingvertebral fracture probability in lumbar spine under different osteoporotic drug therapies, *Comput. Methods Programs Biomed.*, 131, pp. 37–50, 2016.

[6] Vogel, A. and Pioletti, D.P., Damping properties of the nucleus pulposus, *Clin. Biomech.*, 27, pp. 861–865, 2012.

[7] Wilson, S.E., Alkalay, R.N. and Myers E., Effect of the Degenerative State of the Intervertebral Disc on the Impact Characteristics of Human Spine Segments, *Front Bioeng Biotechnol.*, 1, 16, pp. 1-9, 2013.

[8] Schmidt, H., Heuer, F., Simon, U., Kettler, A., Rohlmann, A., Claes, L. and Wilke, H.J., Application of a new calibration method for a three-dimensional finite element model of a human lumbar annulus fibrosus, *Clin. Biomech.*, 21, pp. 337–344, 2006.

[9] Klekiel T., Biomechanical analysis of lower limb of soldiers in vehicle under high dynamic load from blast event, *Series on Biomechanics*, 29, 2-3, pp. 14-30, 2015.

[10] Sławiński G., Niezgoda T., Barnat W., Numerical analysis of the influence of blast wave on human body, *Journal of KONES*, 20, 3, pp. 381-386, 2013.