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MICROMECHANICS APPLIED TO MACRO-MODEL OF A SPINAL SEGMENT

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Abstract: *Spinal segments, with the complexity of spinal activities, call for a better understanding of 3D-biomechanical behaviour to improve the design of spinal implants. The biomechanics of endplates is one of the many areas that are still not fully understood. There are number of factors that might play a role in the biomechanical response of the endplates when the load is transferred from the superior vertebra via endplate and adjacent intervertebral disc to the inferior verterbra. Studies using finite element (FE) models usually present a simplified idealistic isotropic continuum as a bone tissue and cartilage model. This simplification might hinder the real stress-strain distribution at the region of prime interest – the endplate. Multiscale FEM provides the tool to overcome difficulties in simulation of macro model behaviour while considering the micromechanics of bone tissue. The specific patient model, evaluated from CT scans and applied to the existing FE model, gave promising results with the highest stress of 3.1 MPa at the central part of endplate while the model with isotropic continuum presented the highest stress of 1.3 MPa at the lateral side of annulus fibrosus. Results obtained from the patient specific model correspond to known clinical observations of the endplate damage.*

Keywords: Spinal Segment, Finite Element Method, Micromechanics.

1. Introduction

Finite element analysis (FEA) became a common tool in biomedical engineering mainly for the analysis and design of medical devices. With the new imaging technology introduced into the modelling process, usually based on CT scans, the possibility and in a sense the necessity to characterize tissue properties on micro and nano scale level emerged. Bridging the two different hierarchical levels, geometry macro-model and micro-, nano- properties of tissue, was possible due to newly developed mathematical tools. There are few recent studies, which assign heterogeneous tissue properties derived from CT scan images to the voxel while directly creating an FE model. This approach has two major drawbacks; given that the FE model is built from a large number of voxels, running the computation requires powerful computers and considerable computational time. The second shortcoming arises from the method leading directly to the FE model without geometry. Any alteration to the model means a modification to the FE model itself, which is a tedious task. This paper will present a different approach and provides comparisons between classical isotropic material models and specific patient orthotropic material defined with a novel approach developed at the Vienna University of Technology, Austria.

1.1. Problem description

Understanding the mechanics of a load transfer between two adjacent vertebrae requires analysis of large amount of clinical data. Such an approach would require, in a small hospital, a lengthy process of gathering a sufficient amount of data for meaningful statistical analysis. Thus when the request, to bring more information about the behaviour of endplates representing a specialized tissue connecting two

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vertebrae and the adjacent intervertebral disc (IVD) came, it was agreed to run a test "in silico" by means of FEA simulation.

1.2. Spinal segment model

The geometrical model of a virtual segment consisting of an IVD and two adjacent vertebrae was manually segmented by means of NURBS drawing software and CT scans. The bone tissue densities were represented by two material models. These were assigned the properties of isotropic homogeneous continuum, which was defined by a single value of Poisson's ratio, and Young's modulus of 16 GPa and 120 MPa for cortical and cancellous bone respectively. The surface of both vertebrae was coated by shell elements and material properties associated with cortical bone tissue. An average thickness of 1 mm was assumed over the entire outer surface. The endplate areas were discretized using shell elements and associated with the corresponding material model defining Young's modulus of 500 MPa as stated by literature. All solid elements enclosed in the vertebrae volumes were assigned properties that corresponded to material models commonly used to simulate the behaviour of cancellous bone. The simulation of posture with different load conditions was adopted from (Arjmand, 2006). Due to a lack of specialized experimental devices, the validation of results was then in hands of medical specialists. It was concluded that the endplate behaviour corresponds to basic clinical observation but the results could not answer the major question about strains and stresses at the location of interest due to the simplistic model of tissue properties. The results, based on isotropic materials as the only available resource and knowledge at that time, were published (Sant, 2012). This model is used in the work with label M_{iso} to compare the influence of micromechanics on the biomechanical response of the endplate.

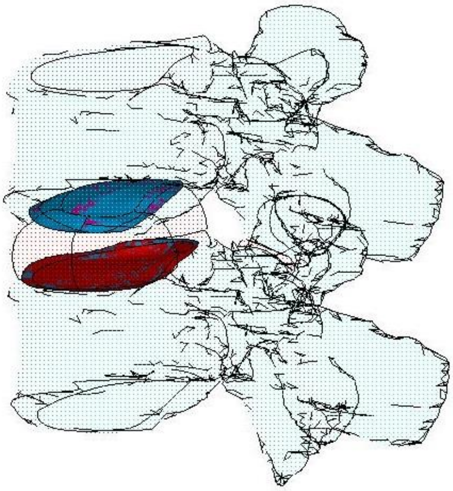

Fig. 1: Spinal segment L3-L4 with IVD endplates marked by colour.

2. Implementation of Micromechanics

In the presented work, a different strategy was used to assign the specific material properties from the subject's CT scan to the existing FE model. This novel method, developed at the Vienna University of Technology, Austria, by the team lead by Prof. Hellmich and described in (Blanchard, 2013), is based on the application of micromechanics. Each pixel/voxel recorded from the CT scan, represented by its voxel-specific grey value (GV), is associated with the density of the material documented in the respective voxel, which is composed of fluid filled vascular pores and extravascular bone tissue, the latter consisting of bone's elementary constituents: hydroxyapatite, collagen, and water. Corresponding voxel-specific vascular porosities constitute the key input data to multiscale micromechanics of bone tissue, delivering the voxel-specific elastic properties. The newly developed material model was then mapped onto representative volumes elements of the existing FE model. Fig. 2 depicts the distribution of patient's specific orthotropic elastic model of bone tissue that corresponds to the bone tissue density distribution. The map of

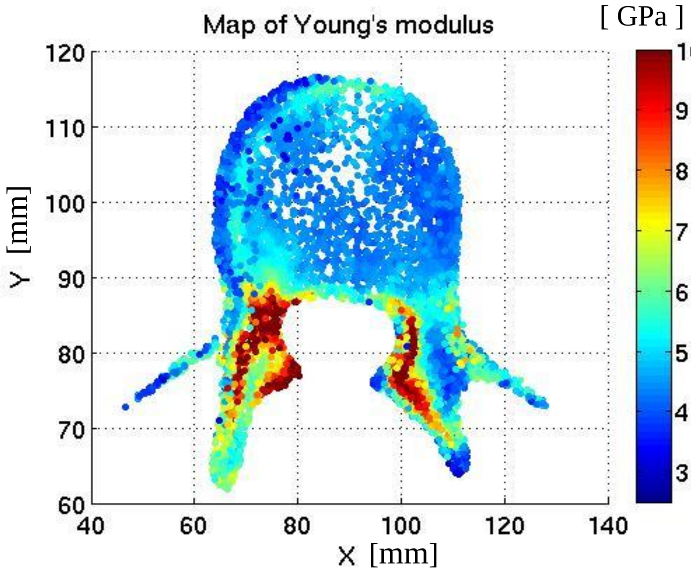

Fig. 2: Map of Young's modulus on the transverse cross-section at z-level of GCS.

Young's modulus on a transverse cross-section through the vertebral body and pedicle region reveals the variation of material properties.

Adjusting the material properties in the corresponding database provides the possibility to change the isotropic material properties in the existing FE model. Assigning orthotropic material properties in this case would require using GV as a variable controlling the selection of the corresponding mechanical properties according to the element representative volume position in the general coordinate system (GCS). The coordinates of the centroid and nodes for each existing element of the FE vertebra model were exported into a program, which selected voxels within the corresponding element volume for further processing. Then the selected number of voxels each with explicit density of tissue material were processed to obtain a homogenized property enclosed within the element volume and defined by a single GV. In this manner the material properties assigned to the GV were associated with the existing elements and for each GV, starting at 70 up to 225, a specific material model defined by Young's modulus E_x, E_y, E_z, shear modulus G_{xy}, G_{yz}, G_{xz}, and Poisson's ratio ν_{xy}, ν_{xz}, ν_{yz} was created. The coordinate system of elements was tilted to the directions that correspond to an orientation of the trabeculae alignment within bone tissue.

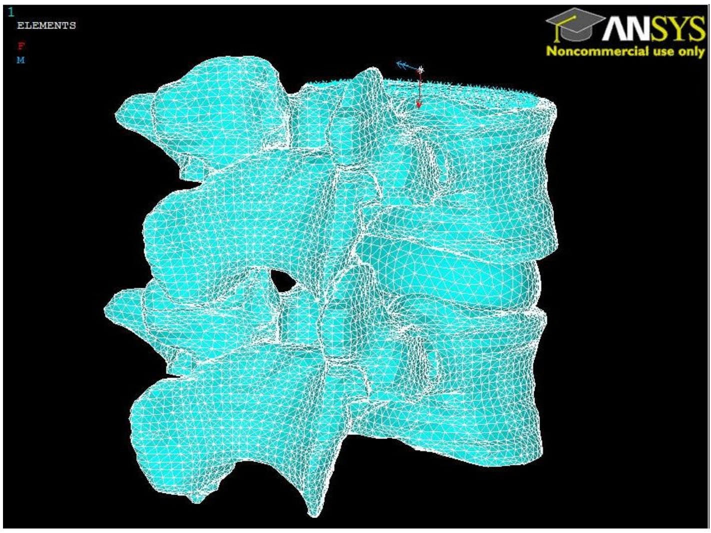

Fig. 3: FE model with applied load at the CP node from where is the normal and shear force, accompanied by sagittal moment transferred on the L3 superior endplate.

The boundary conditions (BC) were set to correspond to the same BC as implemented on the M_{iso} model. This assumed a stationary sacrum, thus the inferior endplate of the L4 vertebra was fully constrained. The load transfer between the vertebrae and the IVD was possible by means of two contact pairs between the vertebrae and adjacent IVD, set to a "bonded" condition. The applied load at the mid-point of IVD, as shown in Fig. 3, corresponds to the subject's upright position while carrying load of 180 N (Arjmand, 2006). The normal force orthogonal to the L3 superior endplate of 688 N, shear force in plane of the superior endplate of 90 N, and sagittal moment of 3.1 Nm were redistributed from the control node via an associated contact pair.

3. Results

All three models with identical geometry were assigned a different material properties. Model M_{iso} remained with initial isotropic continuum material model while the second model, M2, preserved the idealized continuum material of cortical and cancellous bone for the L4 vertebra only, and the GVs were mapped on the volume of elements of the superior vertebra L3 as described earlier. In the third model, M3, both vertebrae had bone tissue properties assigned based on the GV evaluated from the CT scan. In all three cases it was assumed that the IVD retains mechanical properties varying in radial and circumferential direction. These were extrapolated from (Acaroglu, 1995) assuming a linear variation in sagittal and transverse direction (Sant, 2012). The same loading

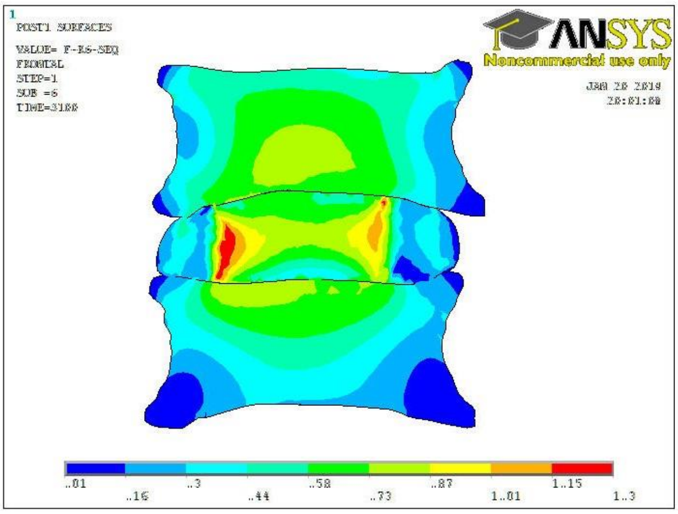

Fig. 4: von Mises stress distribution within the frontal cut through the segment - model M_{iso}.

condition and BC were applied to all models.

Analysis of the results obtained for the M_{iso} model revealed the highest stress developed at the lateral side of the IVD with equivalent stress reaching 1.3 MPa as shown in Fig. 4. The highest stress occuring within the annulus fibrosus at the anterior part of the median plane reached 1.05 MPa. The stress in the region of the endplates did not exceed 1 MPa while the highest strain intensity occured at the left lateral side of the IVD. The results of the simulation run on the model M3 resulted in the highest equivalent stress at the central part of endplates as shown in Fig. 5. The maximum stress reached above 3 MPa somewhat posteriorly as shown in Fig.6 in the cut through the median plane.

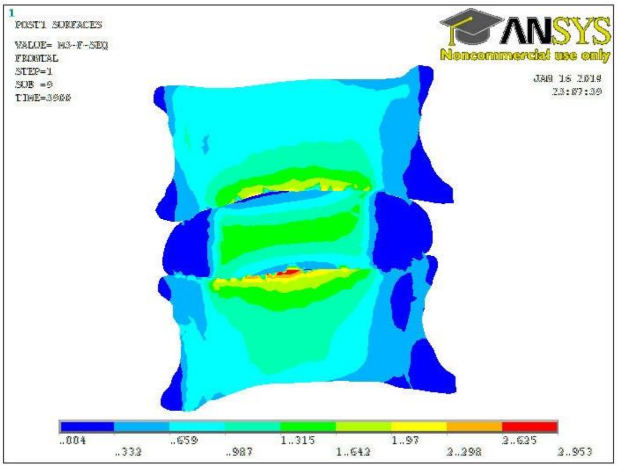

Fig. 5: von Mises stress distribution within the frontal cut through the segment - model M3.

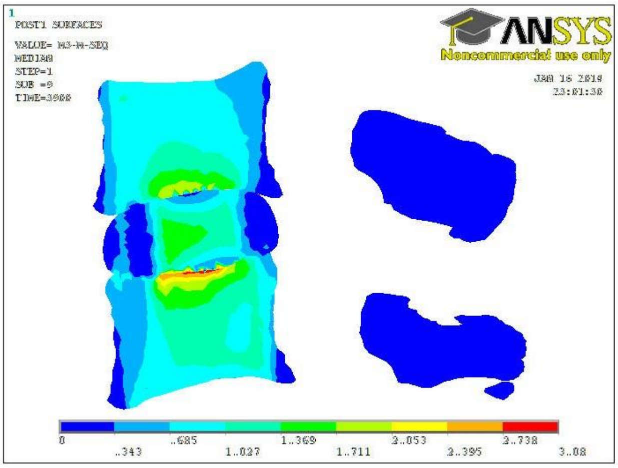

Fig. 6: von Mises stress distribution within the median cut through the segment - model M3.

4. Conclusion

The behaviour of the interface between the two vertebrae is highly dependent on the state of the IVD, the endplate condition, and the bone tissue quality. There is a difference in the stress and strain magnitude as well as in the distribution patterns within the models M_{iso} and M3. Whereas for the model M_{iso} the overall stress within the vertebra did not exceed 0.8 MPa, within model M3 the stress away from the endplates reached around 1 MPa with an increase in the caudal/cranial direction to its maximum slightly above 3 MPa at the endplates. The voxel-specific elastic properties, corresponding to the continually changing tissue density that respect the micromechanics of the composition, eliminated the unnatural stress concentration at the boundaries of two different materials as observed in M_{iso} model results. The stress of 1 MPa developed within the cancellous bone tissue corresponds to known measured values. The results obtained from M3 model are in agreement with clinical observation. These results should be verified experimentally, if possible.

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