THE MECHANICAL SIGNIFICANCE OF THE LUMBAR SPINE COMPONENTS – A FINITE ELEMENT STRESS ANALYSIS

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INTRODUCTION

Lumbar spine surgery is a technically difficult operation that requires thorough knowledge on the reasons of low back pain, as well as on the consequences of any caused change in the lumbar structure.

Mechanical loading has a large influence on tissue adaptation. Thus, determining the tensional state in a modified biological structure could lead to a prediction of tissue evolution that would be related to an updated biomechanical state. It would then be possible to evaluate at long or short term, the risks of developing a pathological state.

With this in mind, the objective of this study was the identification of the mechanical influence of each lumbar spine component in the biomechanics of an anatomical L3-L5 finite element model.

METHODS

A three-dimensional non linear finite element model of a lumbar spine segment L3-L5 previously validated was used. The global geometry was obtained from a CT scan based reconstitution of the L4 vertebra [1]. Mean dimensions and shape of each component were defined from literature's anatomical data and from histological observations (Figure 1). Annulus fibrosus was defined by three radial layers of three-dimensional nearly incompressible volume elements. Between each of these element layers, a bi-oriented fibre layer is modelled by tension-only hypoelastic [2] truss elements that cross each other in a radial plane, making an angle $\pm\alpha$ with the transversal plane. This angle increases from 25º at the periphery of the intervertebral disc, to 45º for the most inner layer [3]. Nucleus was assumed incompressible. Facet cartilages were defined by volume elements as hypoelastic [2], nearly incompressible and frictionless contact body. The non linearity was implemented in compression for the contact directions. The seven lumbar spine ligaments are represented as tension-only and hypoelastic [2] truss elements. Material properties and mechanical laws for all the other tissues are given in Table 1.

The model was subjected to axial compression, flexion, extension and axial rotation. The maximum load applied for flexion, extension and rotation was 15Nm [4]. For axial compression, the model was loaded at 1000N. Forces were applied on the upper bony endplate of L3 and were aligned with the normal directions of the endplate. The lower endplate of L5 was fixed in all directions.

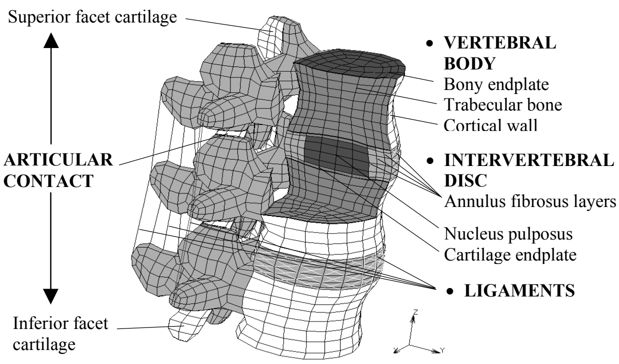

Figure 1. Finite element model of the L3-L5 lumbspine, with a sagittal cut at the L3/L4 level.

RESULTS

It is predicted that the cortical wall and of the annulus fibrosus are highly stressed, while the rest of the structure shows a low tensional state (Figure 2). Bony endplate and trabecular bone are more stressed in axial compression.

Principal stresses in the intervertebral disc indicate that, except for rotation, the nucleus pulposus is always in compression, while the annulus fibrosus keeps working in tension (Figure 3). Tensions were higher at the periphery of the annulus, surrounding its horizontal mid plane. In axial rotation, it appears that the maximum principal stresses follow the maximum shear stress direction.

Finally, Figure 4 indicates that the presence of cartilage endplate contributes to lower the tensions at the disc/vertebral body limits. At the same time, we found that the drop of stresses was accompanied by a rise of shear strain.

Table 1. Material constants and mechanical formulations

Material	Formulation and references	E (MPa)	υ	G (MPa)
		140 *	0.1 *	38 *
Trabecular bone	Linear elastic [5]	140	0.3	77
		250	0.3	77
		8000 *	0.4 *	2000 *
Cortical bone	Linear elastic [6]	8000	0.3	2400
		12000	0.3	2400
Bony endplate	linear elastic [5]	1000	0.3	
Bony posterior elements	linear elastic [2]	3500	0.3	
Cartilage endplate	linear elastic [5]	24	0.4	
Annulus matrix	Linear elastic [2]	4.2	0.45	
Nucleus pulposus	Hyperelastic, Mooney-Rivlin [1]	C_{10}=0.192, C_{01}=0.048		

* The Young's moduli are presented respectively in the xx, yy and zz directions. The Poisson's coefficients and the Coulomb's moduli are given respectively in the xy, yz, and zx directions (see Figure 1).

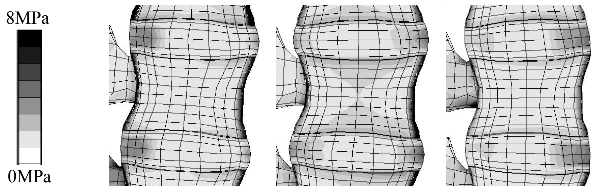

Figure 2. Von Mises stresses within the L4 vertebra and the adjacent intervertebral discs. a) Forward flexion b) 1000N axial compression c) Axial rotation

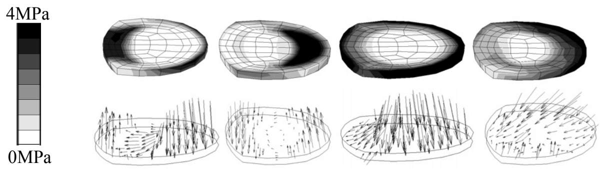

Figure 3. Maximum principal stresses within the intervertebral disc horizontal mid plane at L3-L4 level: magnitude and direction.
a) Flexion b) extension c) compression d) rotation.

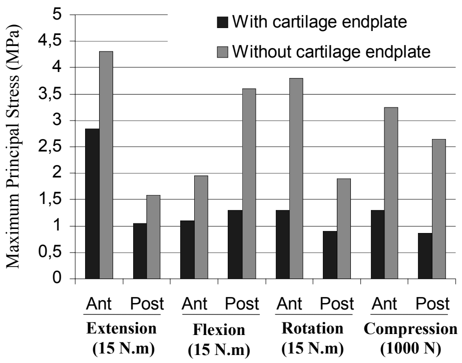

Figure 4. Maximum principal stresses at the annulus fibrosus/vertebral body limits for the L3-L4 level.

DISCUSSION

For all load cases cortical bone absorbs stresses and transmits it to the annulus fibrosus. Under axial compression, trabecular bone and bony endplates assume a transversal distribution of the axial pressure induced by the nucleus pulposus.

The high stresses found in the annulus fibrosus are due to the fibres whose stiffness rises rapidly with strains. Figure 3 shows that fibre tension can be induced either by a direct traction of the adjacent vertebral bodies or by disc protusion. In the case of disc protusion, the most outer layers are put in tension by both the nucleus pulposus and the vertebral bodies. In axial rotation, very high stresses are found in the annulus fibrosus at small magnitudes of rotation (about two degrees). This is due to the initial orientation of the fibres; the reorientation that occurs before working in traction is small and fibres acquire rapidly a high rigidity. By this way, they limit shear strains in the intervertebral disc and protect facet cartilage from excessive contact forces. Fibre gradient orientation can then be mechanically understood; in one hand, the most outer fibres, oriented at 25º, witch have to reorient themselves up to the shear stress direction at 45º, allow a little axial rotation motion before the structure gets locked. In another hand, the most inner fibres are naturally oriented at 45º and directly protect the nucleus pulposus from shear strains.

Finally, when simulations were performed without cartilage endplate, the high stressed attachment area of the annulus fibrosus to the vertebral body appeared to be related to a loss of shear strain deformation capability. Higher stresses appeared also in the nucleus pulposus and the bony endplate. Thus, the cartilage endplate seems to play an important protecting role as well

CONCLUSION

The present study showed the ability of our anatomical finite element model to describe the mechanical influence of the components of the lumbar spine. We could mechanically justify the presence and define the influence of some features such as endplates definition, annulus fibrosus and trabecular bone organisations, or cortical wall geometry. The mechanical role of each of these components during lumbar spine motion, can only be totally characterized by the stress analysis of an anatomical numerical model.

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