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CHOSEN SOLUTIONS OF COMPUTER LUMBAR SPINE SEGMENT MODELING

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Abstract

For many reasons Finite Element Method is very useful especially in biomechanical researches .One of them is difficulty of gaining real specimens for in vitro tests. The second one is that FEM provides relatively easy way to check how changing some parameters of spine geometry or materials, influences on spine segment behavior. Consider it, many research centers in whole world in last years started to prepare FEM models of spine. Some of them are quite simple, some are very advanced. This paper is a review of three chosen FEM lumbar spine models, made in different scientific centers in last years. Authors present their opinions about possibilities of using material coefficients of particular structures of spine in own model. It could be useful for anybody who wants to build proprietary spine model. Authors met many problems trying to obtain material coefficients from literature which may be adopted to own spine model. Models reviewed in this paper could be important assistance for creating own spine models.

Keywords: *Finite Element Model, spine, lumbar, material coefficients, discs*

1. Introduction

Finite Element Method is a wide spread method in situations where problems in testing of physical specimens exists. This problem appears very often in biomechanics, especially in human body investigations. The second advantage of FEM is that it makes possible easily conducts of qualitative research. The main disadvantage is that sometimes obtained results are not exact, and need physical, experimental verification [1,2,3].

There exist many of computer models publications. The more advanced the computer software and hardware is, the more sophisticated the models become. In this paper a few actual and modern computer models were reviewed, made in known world research centers.

2. Description of FEM model from universities in Ulm, Hamburg and Coventry (I)

This model was publicized in 2007 by the scientists from universities in Ulm, Hamburg and university in Coventry [1]. It is presented on Fig. 1. Ligaments which were included in the model: Anterior Longitudinal Ligament – ALL, Posterior Longitudinal Ligament - PLL, Ligamentum Flavum - FL, Interspinous - ISL, Supraspinous - SSL. VA means Vertebral Arch. Calculations were made in Ansys 10 program.

Values of material coefficients of particular model structures as intervertebral discs, vertebrae and ligaments, were assumed to achieve model behavior agreed with behavior of the real spine with at least 99% probability. Material coefficients of this model are presented on Tab.1.

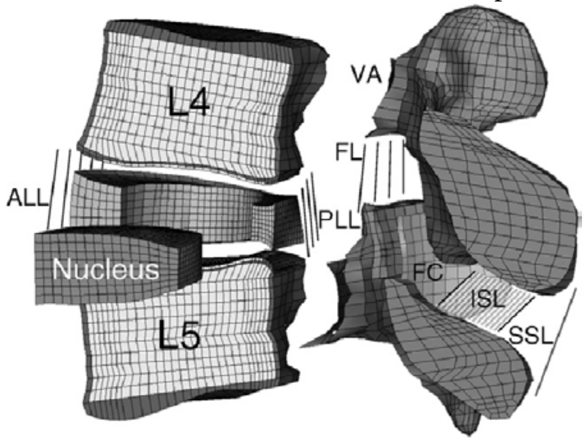

Fig. 1. Spine model from Ulm, Hamburg an Coventry, marked included ligaments [1]

Model imitates the following structures of spine:

1. **Vertebrae** were performed as built from cortical and cancellous bone included anisotropy of mechanical factors, with setting values of Young modulus and Poissons coefficient, including different values in different stress directions. Differences between anterior and posterior material of vertebrae were included.
2. The main **ligaments** were modeled: Anterior Longitudinal, Posterior Longitudinal, Capsular, Ligamentum Flavum, Interspinous and Supraspinous. Mechanical properties were taken from force-deflection curves placed in paper [4].
3. **Annulus fibrosus** were built from layers of fibers embedded in homogeneous substance. Fibers were composed in angle of 24º - 46º. Stiffness of fiber layers was higher at the outer side of disc, and decreased in center direction. Material of embedding substance was made using Mooney-Rivlin model, as almost uncompressible and with very low stiffness.
4. **Nucleus pulposus** was performed as incompressible solid, using linear material model. Material properties were Young modulus and Poisons coefficient.

Tab. 1. Material properties of spine structures [1]

Structure	Young and Kirchoff's modulus [MPa]	Poissons coef.
Cancellous bone	E_{xx}=11300, E_{yy}=11300 E_{zz}=22000 G_{xy}=3800, G_{yz}=5400 G_{xz}=5400	υ_{xy}=0,484 υ_{yz}=0,203 υ_{xz}=0,203
Cortical bone	E_{yy} = 140 , E_{yy}=140 E_{zz} = 200 G_{xy} = 48,3, G_{yz} = 48,3 G_{xz} = 48,3	υ_{xy}=0,450 υ_{yz}=0,315 υ_{xz}=0,325
Posterior elements	E=3500	υ=0,25
Bony endplates	E=4000-12000	υ=0,3
Cartilaginous Endplates	E=23,8	υ=0,4
Calibrated FEM model		
Annulus ground substance	Mooney-Rivlin c_1=0,18, c_2=0,045	
Nucleus pulposus	Mooney-Rivlin c_1=0,12, c_2=0,03	
Ligaments	Calibrated force–deflection-curves	

Non-calibrated model		
Annulus-substancja	Neo-Hookean c=0,348, d=0,3	υ=0,4999
Nucleus pulposus	E=0,2	
Ligaments	Force–deflection-curves	

This model was calibrated using data from experimental investigations. Authors present results of verification of calibrated and non-calibrated model. Calibration indicates changing material coefficients of disc and ligaments structures. For non-calibrated model the accuracy was 82.8% for flexion and 77.1% for extension, which was found to be in good and satisfactory agreement. Calibrated model showed an accuracy of 96.8% and 93.8% for flexion and extension compared to the median value of the intact specimens.

3. Model from Laboratory of Orthopedic Hospital, in Berlin (II)

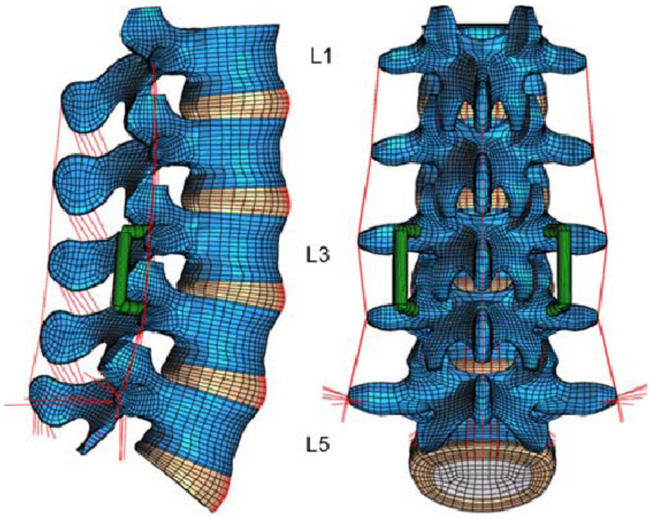

Fig. 2. Spine model from Berlin with implanted dynamic spine fixator [5]

Model publicized by scientist from Biomechanics Laboratory of Orthopedic Hospital in Berlin in paper from 2007 [5]. Models consist of 5 lumbar vertebras, discs and ligaments are depicted on Fig. 2. For particular parts of spine values of material coefficients are presented on Tab. 2. Calculations were made in Abaqus and as a postprocessor and preprocessor MSC/Patran program were used. Model was verified basing on comparison of calculations results with in vitro experiment.
Spine structures modeled were as following:

1. **Facet joints** had a gap of 0.5 mm and thin cartilaginous layer. Contact was simulated using “soft contact” with exponentially increasing of contact force.
2. **Nucleus pulposous** was crateated as incompressible fluid. Compressibility was increased from 0,0005 mm^2/N for healthy disc to 0,0503 mm^2/N for slightly degenerated.
3. **Annulus fibrosus** was modeled from few layers of fibers, placed in concentric rings. Fibers were embedded in angle of 30º-150º. Stiffness of fibers increased with distance from center of the disc.
4. **Ligaments** were created as nonlinear ‘spring’ elements. Material properties were set on basis of force-deflection curves available in literature.

The model was calibrated using experimental data of Heuer, Shmidt et al. from 2006 year, for different anatomical-reduction levels, loading directions and magnitudes. After calibration authors conduct comparison with four other publications, and assume good agreement between model and experimental data.

Tab. 2. Material properties of spine structures

Material	Young modulus [MPa]	Poissons coef.	Stiffness [N/mm]
Cortical bone	E=10000	υ=0,3	
Cancellous bone	E=200/140	υ=0,45/0,315	
Posterior bony elements	E=3500	υ=0,25	
Annulus fibrosus ground substance	Neo-Hookean C_{10} = 0.3448, D_1 = 0.3		
Annulus fibers	Nonlinear		
Nucleus pulposus (healthy)	Incompressible		
Nucleus pulposus (degen.)	Compressibe		
Ligaments	Nonlinear		
Pedicle screws (titanium)	E=110000	υ=0,3	
Dynamic fixation device			C=200
Rigid fixation device (titanium)	E=110000	υ=0,3	C=83000

4. Model from Uniwersity in Graz (III)

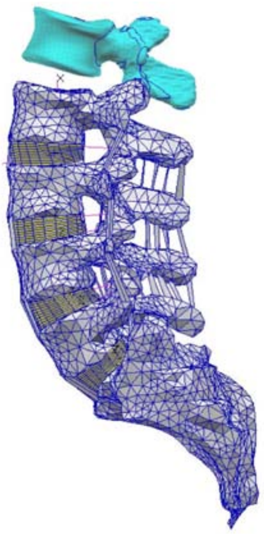

Fig.3.Geometry of the spine model from Graz [6]

This model was created in 2004 by scientists from University in Graz and from companies Sulzer and Zimmer. Was described in paper [6]. It consists of five lumar vertebras, discs and ligaments. Geometry of the model is depicted on Fig. 3. Authors included a sort of in vitro results which were used to achieve data to made force-deflection curves for particular ligaments. Finite element mesh was prepared in MSC Patran 2001 program, calculation were made in Abaqus. Model FEM results were verified and compared to in vitro experiment results.
Parts of spine were modeled as following :

1. Nucelus pulposous as well as annulus fibrosus were created using proprietary mathematical, material model, built on base of Cauchy-Green model.
2. Cartilaginous plates were 1mm thin, material coefficients were: E=23,8 MPa i υ=0,4.

3. Materiał of anterior and posterior bony elements was differentiated, for posterior elements coefficients were: E=3500 MPa, υ=0,25.

Mechanical properties applied to ligaments were set based on force-deflection curves gained from literature, including their different cross-sectional areas. Values of cross-sectional areas are presented in Tab. 3 with maximum and minimum. Differences between values point out that ligaments stiffness for spines may vary even few times.

Tab. 3. Values of cross-sectional areas of spine ligaments [6]

Ligament	Cross-sectional area minimum [mm^2]	Described study [mm^2]	Maximum [mm^2]
ALL	10,6	38	70
PLL	1,6	17	20
IT	1.8	6	10
FL	40	67	114
IS	12	35	60
SSL	6	30	59,8
CL	19	70	93,6

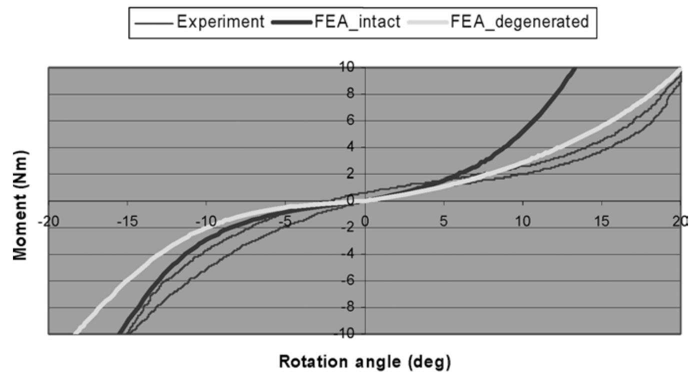

Fig.4. Force-deflection characteristic in flexion (+) - extension (-) movement

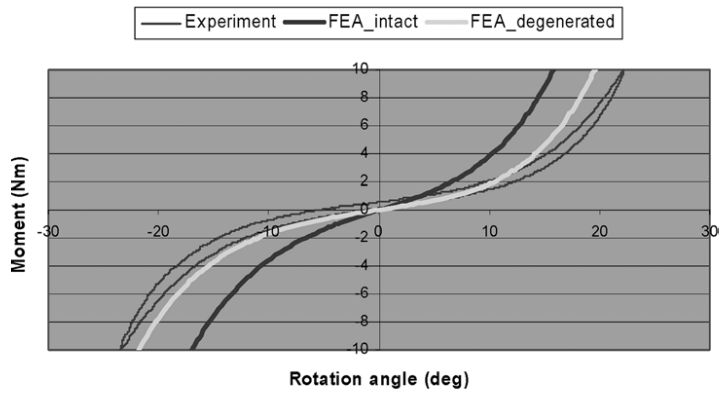

Fig.5. Force-deflection characteristic in lateral bending

Final computation results very good agreed with nonlinear stress-strain real spine curves. This model is the one of models for which whole curves were presented in paper, not only final values of deflection. Comparing curves gained in computation and in vitro experiment, it may be pointed out that model is slightly over stiffened for flexion-extension (Fig. 4) as well as for lateral bending (Fig. 5). Though, it seems that compatibility between computations and in vitro results is very good.

5. Conclusions

Models presented above are one of the most advanced and having good compatibility to real spines. For that reason they could be good example for building proprietary model. Many other spine models described in publications exists, some of them mathematically advanced, some relatively simple. Unfortunately information included in this publications are not enough to adopt to build own FEM model. That information often concerns the way geometrical data were gained, rarely describing in details applied material properties. In Tab.4 presented main disadvantages and advantages of models described above.

Tab.4 Features of described models

Model	Advantages	Disadvantages	Suggestions for own model
I	very high level of agreement with in vitro, advanced calibration procedure, bone anisotropy included	calibration only for flexion-extension	Useful calibration algorithms, material coefficients
II	validated and compared to many references, high quality of mesh in all segments	not included bone anisotropy	
III	very advanced material model of intervertebral disc, full characteristics included in paper,	not so good agreement to in vitro data as two other models	valuable force-deflection curves for ligaments, values of cross-sectional areas in paper

The most important for quality of model are proper material coefficients and characteristics for particular spine structures. For many reasons it is difficult to evaluate if the model is better or worse, but for sure, models in which only linear material models are used, are less accurate. Unfortunately many of old FEM spine models possess only linear material characteristics [7, 8]. Often models consists theoretically nonlinear material properties [9, 10], but their importance is not big enough to achieve nonlinearity of whole model.

For this reason such models can be used only in narrow range of load, in which nonlinearity could be ignored. Value of those models is small for applications in which real conditions have to be simulated, like flexion-extension together with lateral bending and axial rotations in wide range of load. Severe publications do not include full characteristics, only final values of deflection or force, even if model description gives impression that model is very advanced [11, 12].

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