EXPERIMENTALLY BASED NUMERICAL MODELS AND NUMERICAL SIMULATION WITH PARAMETER IDENTIFICATION OF HUMAN LUMBAR FSUs IN TRACTION

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1. ABSTRACT

Numerical simulation of the behaviour of human lumbar spine segments, moreover, parameter-identification of the component organs of human lumbar FSUs are presented in traction therapies, by using FEM analysis. First, a simple 2D model, than a refined 2D model, and finally a refined 3D model were applied for modeling lumbar FSUs. For *global* numerical simulation of traction therapies the material constants of component organs have been obtained from the international literature. For *local* parameter identification of the component organs, an interval of the *possible* material moduli has been considered for each organ, and the possible combinations of *real* moduli were obtained, controlling the process by the measured global deformations. In this way, the efficiency of conservative traction therapies can be improved by offering new experimental tensile material parameters for the international spine research.

2. INTRODUCTION

Numerical tensile models of human lumbar spine segments are obtained from a large scale in vivo experimental analysis of the usual traction bath treatment of patients, reported by *Kurutz et al*. [1, 2]. Time-related elongations of segments L3-L4, L4-L5 and L5-S1 were measured, by using a special subaqual ultrasound measuring method, developed by the authors. Segment elongations were measured as the change of the distance between two processus spinous of adjacent vertebrae. More than 3000 ultrasound pictures of 400 segments of 155 adult patients were evaluated. Based on the measured elongations in terms of time, aging, sex, body weight, body height and segment level, parameter-dependent global numerical viscoelastic models of human lumbar FSUs were created for numerical simulation. *Global* tensile viscoelastic parameters of lumbar segment complex were obtained by using three-parameter mathematical models. For numerical simulation, the material constants of component organs were obtained from the literature. For parameter identification, an interval of the possible material moduli has been considered for each organ, and the possible combinations of real moduli were obtained by controlling the process by the measured global deformations.

Keywords: human lumbar spine, FSU, traction, numerical model, simulation

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3. NUMERICAL TRACTION MODELS OF SPINE SEGMENTS

The suspension hydrotherapy is a Hungarian invention, introduced and described by *Moll* [3,4,5], and later by *Bene* [6], while the biomechanics, indications and contraindications of the therapy have been detailed by *Bene* and *Kurutz* [7]. The therapy needs a specially deepened basin with elastic suspension equipment. During the traction bath treatment, the patients were suspended cervically in lukewarm water for 20 minutes, loaded by extra lead weights applied on the ankles. Cervical mode of suspension provides the most effective stretching load to the lumbar part of spine, moreover, in this case the effect of muscles can be practically neglected. The cervical suspension has been applied for the regular 20 minute long treatment time. The 20-20 N extra lead loads have been applied on ankles.

In the case of cervical suspension, three load effects cause traction deformations along the spinal column: the *decompressive force* as the removal of the compressive load of the body weight before the treatment, the *active tensile force* due to the buoyancy, and the *extra loads* applied for the therapy. By comparing the three component forces detailed in [7] and [2], if applying cervical suspension, the dominant stretching load is the decompressive force. In the case of free cervical suspension in water, the effect of muscles can be neglected.

Tensile deformations of spine segments of patients suspended in water were considered as the decrease of compressive deformations existing before the treatment. Namely, zero deformation belongs to the common compressed state of segments of normal upright standing position of body. Tensile deformation of segments has been considered as change of the distance between two spinous processes of neighboring vertebrae.

In the beginning of the treatment, just being suspended, due to the removal of compression and the buoyancy, unloading of discs and segments occur, thus, even without any extra weights, significant immediate extension was registered. These elongations correspond to the elastic behaviour of segments with a mean value of 0,4-0,8 mm for males, 0,3-0,4 mm for females. At the end of the 20 minute long treatment, the total mean elongations were 0,9-1,4, and 0,8-1,3 mm with extra loads, and 0,7-1,0 mm and 0,7-0,8 mm without extra weights for men and women, respectively. During the treatment, both the ratio and the value of deformability increased with a decreasing tendency in distal direction.

Since the traction load was constant during the 20 minutes long treatment, thus, a typical creeping process developed and could be documented numerically. The creep process has been measured in the group of patients with less degenerated segments, loaded by 20-20 N extra weights on ankles. For viscoelastic numerical model, the Poynting-Thomson type three-parameter spring-dashpot model has been used, seen in Fig. 1, where spring constants represent the elastic properties, damping coefficients concern creep effects.

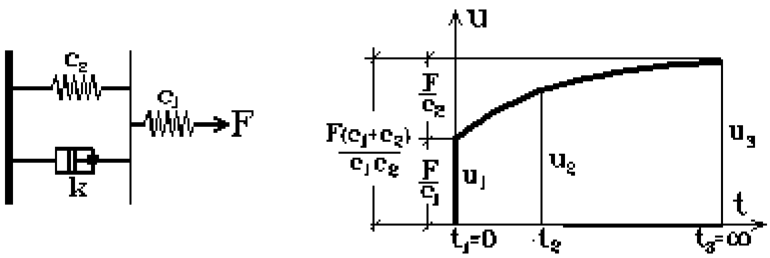


Figure 1: Three parameter viscoelastic spring-dashpot model

The parameters, namely, the spring constants c_1 and c_2 , and the damping coefficient k were determined by the time-related in vivo measurements. We supposed that the last state at the 20th minute of the treatment concerns the steady state of the creep process. Creep functions and moduli of the lumbar segments have been obtained in terms of sexes, aging and other parameters. From the results of the measured lumbar segments L3-4, L4-5 and L5-S1, a general lumbar FSU model L3-S1 have been created for numerical simulations, seen in Table 1.

Creep Moduli of General Lumbar FSU Model L3-S1				
extra weight 20-20N	units	**male**	**female**	**total**
segments	*number*	108	128	236
mean age	*years*	47,9	51,7	50,0
mean body weight	*N*	758	671	711
mean body height	*cm*	175	164	169
mean BMI	*kg/m^2*	24,9	25,1	25,0
u_1 elong. at t=0 min	*mm*	0,66	0,43	0,52
u_2 elong. at t=3 min	*mm*	0,83	0,74	0,78
$u_3$elong.at t=20min	*mm*	1,15	1,11	1,13
Creep parameters				
spring coeff. c_1	*N/mm*	742	1018	887
spring coeff. c_2	*N/mm*	999	643	756
damping coeff. k	*Ns/mm*	422	190	245
time constant T	*min*	7,04	4,93	5,40

Table 1: Parameters of the creep model of general lumbar FSU model L3-S1

4. FEM-MODELS OF SPINE SEGMENTS

To check the measured elongations of FSUs, first a simple 2D model was used for SKANSKA FEM-design software. Since the healthy spine segment is a symmetrical structure, a simple 2D model was related to the sagittal plane of the FSU, seen in Fig. 2.

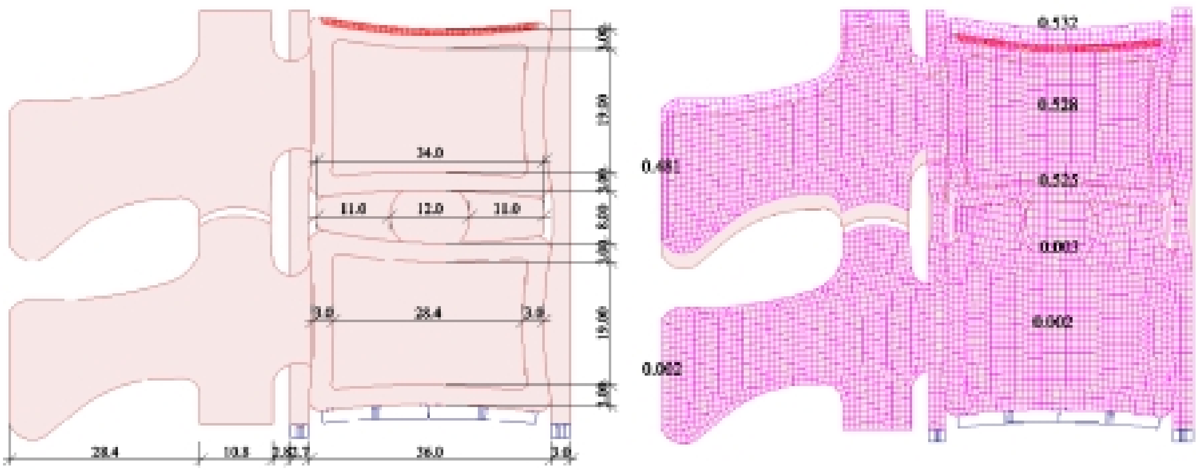


Figure 2: Geometry and FEM mesh with elongations of the 2D model

For the material constants we used the results of [8, 9, 10]. As Young's moduli E and Poisson ratio ν, for the vertebral cancellous bone E=1000 MPa and ν=0.4, for the vertebral cortical bone E=15000 MPa and ν=0.4, for the disc annulus E=5 MPa, ν=0.35, for the disc nucleus E=1 MPa, ν=0.49, for ligaments E=40 MPa and ν=0.35 were used.

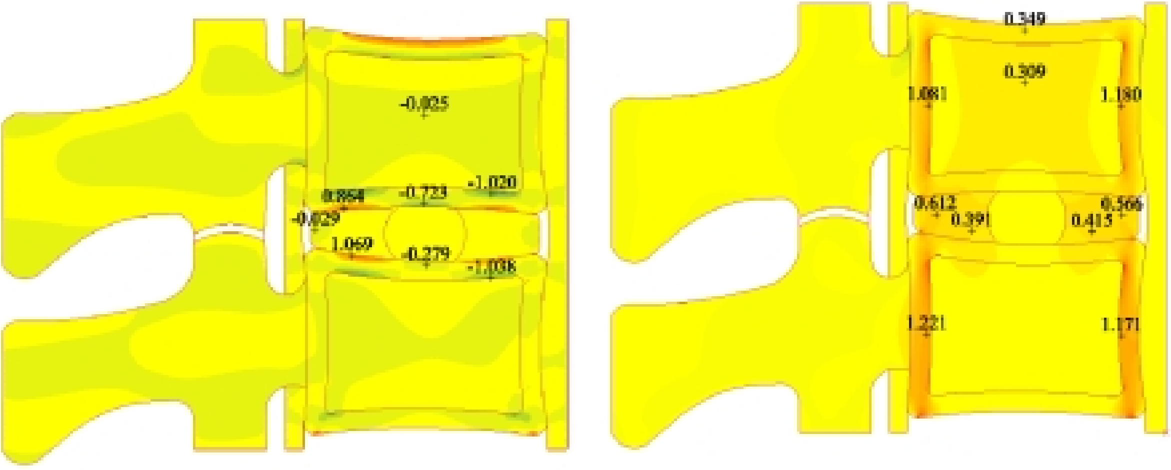


Figure 3: Vertical and horizontal stresses in the 2D model

The support of the structure was along the inferior surface of the lower vertebra. The load was distributed along the superior surface of the upper vertebra. For the global behaviour of the segment complex, we supposed bilinear material law. We assumed that the decompression takes place by the large stiffness that is valid for compression, and for the active tension of buoyancy and for the extra weights, we supposed a smaller stiffness. This behaviour was simulated by applying different disc moduli, namely, E=500 MPa for compression, and E=5 MPa for tension. In Fig.2 the geometry and the elongations, in Fig. 3 the vertical and horizontal stresses are illustrated, respectively.

As the second step of the numerical simulation, we refined the 2D FEM model to simulate the viscoelastic creep process, by applying NASTRAN software. Creep behaviour and creep curves of the general lumbar segment model L3-S1 are significantly different in terms of aging and sex. It was numerically verified that the initial stiffness increase and deformability decreases with aging. Similarly, damping coefficients also increase and creep deformability decreases with aging. As for the effect of sex, after the initially smaller deformability of females, due to the smaller damping of women, larger creep elongations occur. The final viscoelastic elongations were quasi equal.

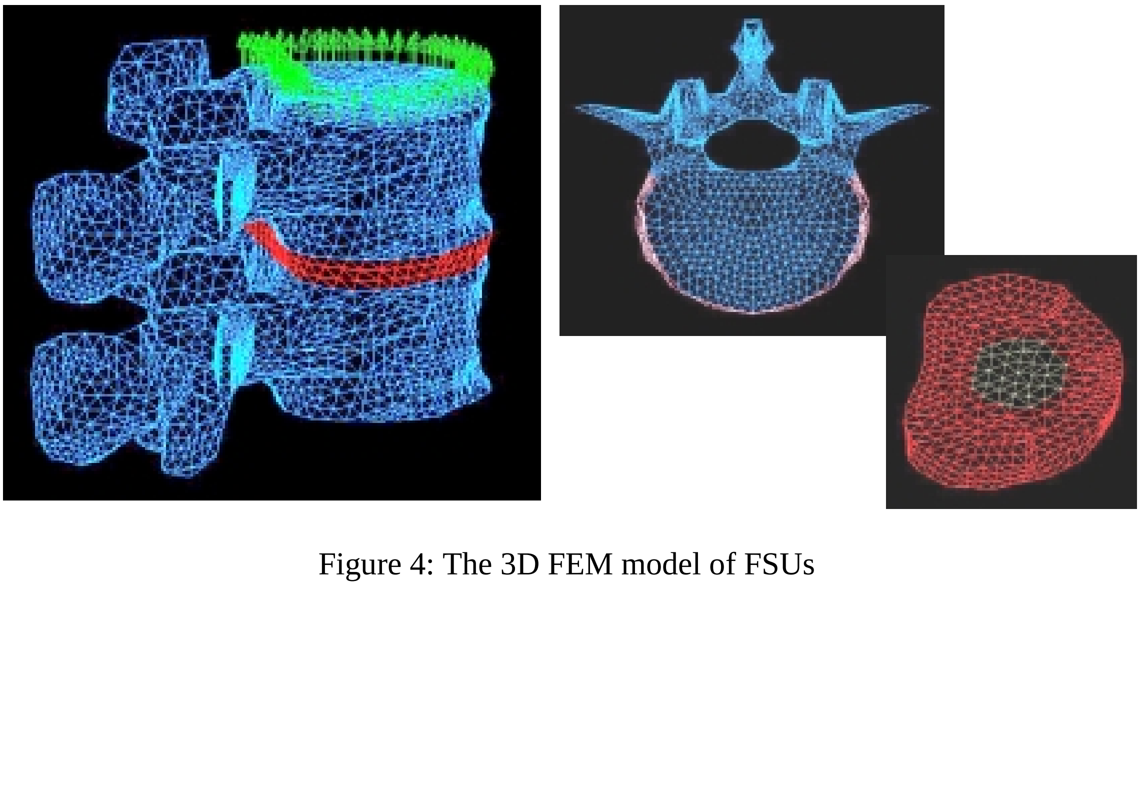


Figure 4: The 3D FEM model of FSUs

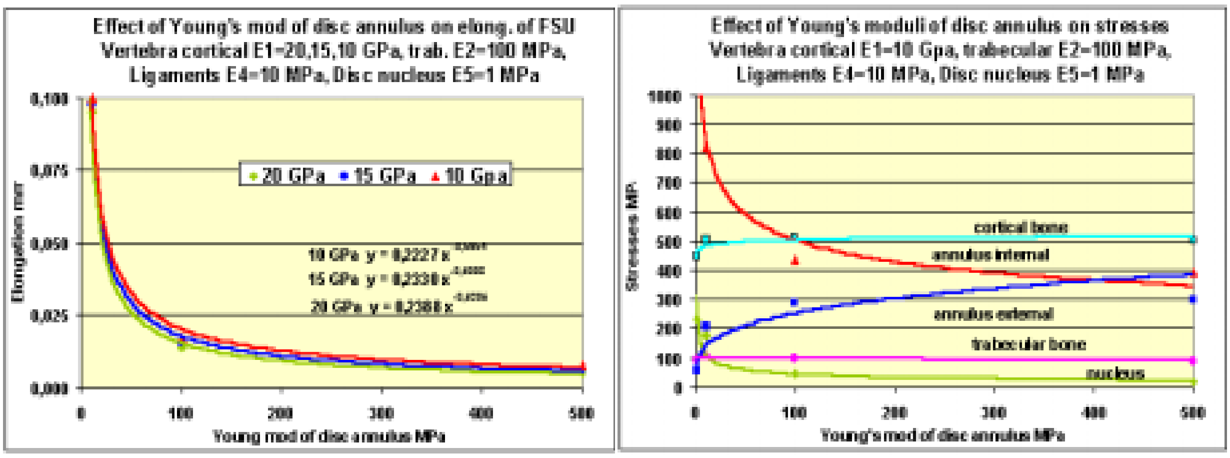
For parameter identification, the NASTRAN model was extended to the 3D configuration of the FSU. The segment model has 35 000 nodal points with the relating 110 000 equations. Fig. 4 illustrates the mesh of the vertebrae-disc complex and its components. In the numerical simulation and parameter identification the following material moduli are used for the component organs seen in Fig. 3. As Young moduli for the cortical bone: 1-20 GPa, for the trabecular bone 50-100 MPa, for the disc annulus 50-500 MPa, for the disc nucleus 1 MPa, for the ligaments 10-100 MPa were considered.

4. NUMERICAL SIMULATION AND PARAMETER IDENTIFICATION

The parameter identification aimed to determine the in vivo controlled tensile material moduli of the component organs of lumbar segments that are completely missing in the international literature. Namely, except for the results of *Kurutz et al.* [1,2] there can hardly be found any experimental results for in vivo human lumbar spine in pure centric tension, when the effect of muscles are excluded. Thus, the in vivo measured global elongations of FSUs were used as control parameters in determining the material moduli of the component organs.

During the parameter identification process, the material moduli of certain organs were kept constant while the material parameters of other organs were considered to be the variable of the problem. Under these parameters, numerical simulation was investigated, and those results were accepted that leaded to the in vivo measured elongations.

Fig 5a. shows the effect of Young's moduli of disc annulus on the global elongation of FSU, by keeping constant the Young's moduli of trabecular bone as E_2=100 MPa, ligaments as E_4=10 MPa and disc nucleus as E_5=1 MPa. The Young's modulus of the annulus has a significant effect to the tensile deformability of segments, and we can hardly suppose that the tensile modulus of the annulus is far smaller than the compressive one. The stiffness of the cortical bone has no significant effect on the deformability of segments. In Fig 5b. the effect of Young's moduli of disc annulus is illustrated on the vertical stresses of the component organs: cortical and trabecular bone, internal and external annulus, by keeping constant the Young's moduli of trabecular bone as E_2=100 MPa, of ligaments E_4=10 MPa and of disc nucleus E_5=1 MPa. The Young's modulus of the annulus has practically no effect on the occurring stresses in the cortical or trabecular bone, but has a significant effect on the stresses of the nucleus and annulus itself.



a. b.

Figure 5: The effect of Young's moduli of disc annulus

5. CONCLUSION

By using the experimentally obtained numerical models of human lumbar functional spinal units, numerical simulation and parameter-identification of human lumbar spine segments was presented in centric tension. 2D and 3D FEM models were used, and the global elongations of FSUs were used for identification of the local material parameters of the component organs of lumbar spine segments. The model can be used for numerical simulation of conservative traction therapies.

Since there are no in vivo experimental results in the international literature for the human lumbar spine segments or discs in pure centric tension where the effect of muscles can be excluded, the presented results may arouse the interests of the biomechanical analysts of the human lumbar spine. By means of the special Hungarian invention "weightbath", new material parameters have been obtained and presented for the international spine research

6. REFERENCES

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