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A non-linear finite element model of human L4-L5 lumbar spinal segment with three-dimensional solid element ligaments

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Abstract This paper establishes a non-linear finite element model (NFEM) of L4-L5 lumbar spinal segment with accurate three-dimensional solid ligaments and intervertebral disc. For the purpose, the intervertebral disc and surrounding ligaments are modeled with four-nodal three-dimensional tetrahedral elements with hyper-elastic material properties. Pure moment of 10 $\mathrm{N\cdot m}$ without preload is applied to the upper vertebral body under the loading conditions of lateral bending, backward extension, torsion, and forward flexion, respectively. The simulate relationship curves between generalized forces and generalized displacement of the NFEM are compared with the in vitro experimental result curves to verify NFEM. The verified results show that: (1) The range of simulated motion is a good agreement with the in vitro experimental data; (2) The NFEM can more effectively reflect the actual mechanical properties than the FE model using cable and spring elements ligaments; (3) The NFEM can be used as the basis for further research on lumbar degenerative diseases. © *2011 The Chinese Society of Theoretical and Applied Mechanics.* [doi:10.1063/2.1106401]

Keywords lumbar spine, non-linear, ligaments, finite element analysis

Approximately 70% of the population in industrialized countries experiences low back pain once in their lives.[1] The pain always limits the patients' quality of life. Epidemiologic and biomechanical studies have shown the role of the mechanical loads in the onset of low back pain.

In the past, many in vitro studies were performed to describe the mechanical environment of the lumbar spine.[2–5] However, in experimental investigations, only certain parameters can be measured, e.g., the relative movement between two adjacent vertebrae, disc bulges, or the stress in individual areas of the body.

The finite element (FE) method, as an effective alternative in vitro biomechanical study, is helpful to quantify the parameters such as strains or stresses in different regions, which cannot be characterized easily in experiments. Recently, with the development of optimization and computer technology, the FE model has been used extensively for the analysis of normal and abnormal mechanics of lumbar spine.[6–11] However, there are some problems in the FE models of the lumbar spine, i.e., the oversimplification of the material properties and the inaccurate geometry of the ligaments and intervertebral disc. Davidson et al.[12] developed an FE model of the lumbar spinal column of an eight-year-old human spine and compared flexibilities under pure moments, adults, and pediatric loading with different material models. But the ligaments were assumed as tension-only link elements. Hendrik et al.[13] established an FE model of L4-L5 lumbar segment, which assigned non-linear mechanical properties to the vertebrae and intervertebral disc. But the ligaments were simplified as spring elements. In the model proposed by Renner et al.,[14] the annulus matrix was assumed as a composite material consisting of fibers embedded in a homogenous matrix material. The major ligaments were also modeled by two-node non-linear cable elements. The ligaments were built on the solid model by Tsuang et al.[15] But all the ligaments and intervertebral disc in their study were assigned to elastic material properties. Marwan et al.[16] investigated the effect of loading rate on the lumbar spine using an FE model. The ligaments were modeled with four-nodal or three-nodal shell elements with visco-elastic material property. However, the stress of shell elements ligaments was concentrated easily in some regions of each ligament. There is little research on the spinal segment model with both the highly geometric similarity and the non-linear material property.

The degeneration of ligaments would increase the range of motion and accelerate degenerative disease in the spine, but the two-dimensional models for ligaments could not reflect the biomechanical changes in ligaments directly. So it is necessary to model the ligaments with three-dimensional solid elements.

The present study focuses on establishing a non-linear FE model (NFEM) which can effectively reflect the mechanical property of L4-L5 lumbar segment. For this purpose, the surrounding ligaments were modeled with three-dimensional solid elements. The NFEM of L4-L5 segment was established with a variety of materials, then verification of the NFEM was performed by comparing the simulated results from the NFEM with the corresponding experimental results from in vitro specimens.

The NFEM of L4-L5 lumbar spinal segment was

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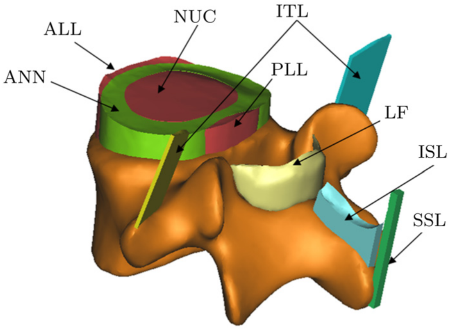

Fig. 1. The three-dimensional L5 lumbar segment model with ligaments and intervertebral disc.

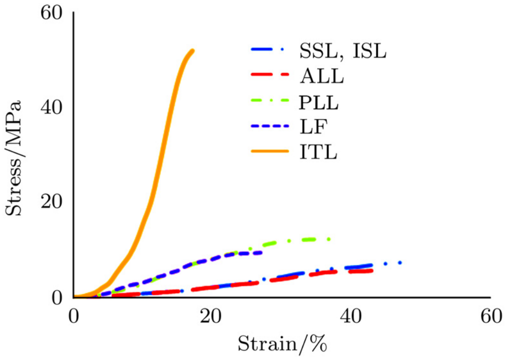

Fig. 2. The stress-strain curves for ligaments.

generated based on computer tomography (CT) scan of a 23 years old healthy male volunteer with a slice thickness of 0.75 mm. The CT data were transferred into MIMICS software to establish the L4-L5 lumbar model and subsequently meshed in MAGICS software. The intervertebral disc was created between the intervening endplates with both MIMICS and SOLIDWORKS softwares. The intervertebral disc was subdivided into nucleus pulposus (NUC) and annulus fibrosus (ANN) with a proportion.[17] The surrounding ligaments, anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), intertransverse ligament (ITL), ligamenta flava (LF), interspinal ligament (ISL), supraspinal ligament (SSL) were modeled with four-nodal three-dimensional tetrahedral elements. The facet joints and capsular ligament (CL) were simulated by eight spring elements. Figure 1 showed the three-dimensional model of lumbar spinal segment L5 with ligaments and intervertebral disc. Since ALL and PLL were attached to the endplates, in this study, we used the interception of these two ligaments, which connected to the upper and lower parts of the vertebral endplate, and the aim was to simulate the restriction of ALL and PLL on the vertebral activity.

The models of vertebral bodies, ANN, NUC and all the ligaments were imported into ABAQUS software and the surface mesh was converted to volumetric mesh. The minimum edge length of the tetrahedral elements was 0.7 mm and the maximum edge length of the tetrahedral elements was 0.9 mm. The numbers of nodes and elements of the FE model were listed in Table 1.

The bone materials were represented in MIMICS software. As the previous studies shown, the relationship between gray value and apparent bone density is approximately linear,[18] and there is a correlation of cancellous bone apparent density and elastic modulus.[19] In this paper, the empirical expression was chosen as[20]

$$\rho = 1.6 \times HU + 47 \ (\mathrm{g/mm^3}), \tag{1}$$

$$E = 0.098\,82\rho^{1.56} \ (\mathrm{MPa}). \tag{2}$$

As the visco-elastic property of the intervertebral disc and ligaments were not obvious in the quasi-static loading condition,[21] the material properties of different tissues were modeled as hyperelastic, which were obtained from the previous reports. The fluid-like behavior of NUC and ANN were both modeled with a hyper-elastic Mooney-Rivlin formulation.

The form of the Mooney-Rivlin strain energy potential is

$$U_{M-R} = c_{10}(\overline{I_1}-3)+c_{01}(\overline{I_2}-3)+(J^{\mathrm{el}}-1)^2/D_1, \tag{3}$$

where U_{M-R} is the strain energy per unit of reference volume; c_{10}, c_{01} and D_1 are temperature-dependent material parameters; $\overline{I_1}$ and $\overline{I_2}$ are the first and second deviatoric strain invariants defined as

$$\overline{I_1} = \overline{\lambda}_1^2 + \overline{\lambda}_2^2 + \overline{\lambda}_3^2, \quad \overline{I_2} = \overline{\lambda}_1^{(-2)} + \overline{\lambda}_2^{(-2)} + \overline{\lambda}_3^{(-2)}, \tag{4}$$

where the deviatoric stretches $\overline{\lambda_i} = J^{-1/3}\lambda_i$, J is the total volume ratio, and λ_i are the principal stretches. The initial shear modulus and bulk modulus are given by

$$\begin{aligned} &c_{10} + c_{01} = \mu/2, \\ &D_1 = (1-\nu)/(c_{10} - c_{01}), \\ &k = 2/D_1. \end{aligned} \tag{5}$$

The parameters in this study were chosen as[13]

$$\begin{aligned} &\mathrm{ANN:}\ \ c_{10} = 0.56, c_{01} = 0.14, D_1 = 1; \\ &\mathrm{NUC:}\ \ c_{10} = 0.12, c_{01} = 0.12, D_1 = 1. \end{aligned} \tag{5a}$$

The stress-strain relationships of the different ligaments are obtained by the experimental study,[22] as shown in Fig. 2. In the experimental study, the non-linear behavior of the stress-strain of ligaments was described by hyper-elastic Ogden-3 formulation in ABAQUS software.

The form of the Ogden strain potential energy is

$$U_{\mathrm{o}} = \sum_{i=1}^{3} \frac{2\mu_i}{\alpha_i^2}(\overline{\lambda_1}^{\alpha_i} + \overline{\lambda_2}^{\alpha_i} + \overline{\lambda_3}^{\alpha_i} - 3) + \sum_{i=1}^{3} \frac{1}{D_i}(J^{\mathrm{el}} - 1)^{2i}, \tag{6}$$

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