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# Study on Lumbar Vertebrae Biomechanical Characteristics for Speed Skating Athlete Based on Finite Element Method

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**Abstract.** Objective: To establish the three-dimensional finite element model of lumbar motion segment (L4-L5) that considers material property and geometrical behave, to investigate mechanical characteristics of lumbar spinal motion segment for application of prevention and reduction of lumbar trauma for the speed skating athletes. Methods: three-dimensional finite element model (FEM) of the human lumbar spinal segments was established by using CT scanning technology and based on 3D interpolation method, and boundary conditions and loads were imposed on the model and finite element analysis was carried out. Results: The three-dimensional FEM of lumbar motion segment (L4-L5) was established. The volume of the model: 82941.13mm3, the surface area of the model: 19064.55mm2. The model consisted of the two vertebrae, one intervertebral disc and five pieces of ligament, the entire model comprised 56351 elements and 21643 nodes. Conclusion: When the speed skaters were skating, the stress on disc mainly concentrated on middle-anterior location of exterior annulus fibrosus, especially anterior location; equivalent stress on anterior location of vertebral body was higher than that of the nucleus pulposus, stress on adjacent vertebral endplate was significantly higher than other parts of the body, equivalent stress concentrates on the location, stress focused on up and down articular processes of facet joints and pedicle of vertebral arch.

**Key words:** biomechanics; model; finite element method; spine; speed skating

## 1. Introduction

Speed skaters keep a long-term bending waist posture and repeatedly engage in mechanical movements due to requirements of the skills. Therefore, the athletes are prone to suffer from the strain of neck and lumbar or fatigue and trauma of lumbar muscles[1]. Structure, material properties, loading and other aspects of the spine are complex, so we can’t obtain global information through using the traditional test methods such as electrical testing, photo-elastic method, holography etc; however, finite element method holds far more advantages than other methods in the spinal surgery research. The mathematical mechanical model is used to make numerical mechanical analysis, to restore the mathematical behavior of engineering system. Part of structure, parameters and loads can be changed by applying the mathematical model to simulate mathematical characteristic of spine that includes elements, nodes, material property, loads and boundary conditions and so on from the physical property, thus the arbitrary displacement and stress on the arbitrary point can be simulated and stress change occurred in the pathological process can be explained[2]. The author established the three-dimensional FEM of lumbar segment and discussed the method of establishing the finite element model of complex three-dimensional structure and the biomechanical characteristic of lumbar spine for the speed skating athletes using the reverse engineering software with the CT data.

## 2. Object and methods of the research

One healthy volunteer, without pain experience and former injury in waist, received X-ray examination in lumbar vertebrae and no degeneration and deformity was found. Continuous scanning to the volunteer’s the upper edge of fourth lumbar vertebrae to the lower edge of the fifth lumbar vertebrae was fulfilled through spiral CT (Siemens Somatom Sensation 10) with fine definition and function of post photograph processing and out-putting. The volunteer had to keep one position to lie on his back and scanning data were

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directly stored according to standard of Dicom3.0, bone structure window with 1mm layer gap, 1mm layer thickness, 136 layers in tatol.

# 3. Biomechanical analysis of lumbar spine to speed skating athlete

Lumbar spine was the main load-bearing parts among spine. The size and the way of the loads acted on various parts of lumbar spine were inconsistent. In upright position, the disc pressure came from the disc inner pressure, body weight above the location measured and muscle strength acted on this motion segment. In flexion and rotation, the compressive stress and tensile stress acted on the disc increased. The loads on lumbar spine were directly related with the position.

The angle between the trunk and the ground was determined according to skating posture [3], sketch of stress on lumbar spine as following:

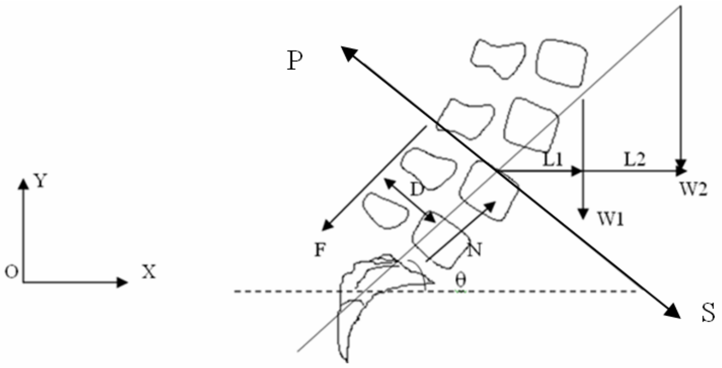


Fig. 1 Sketch of stress on lumbar spine

W1, body weight; W2, the total weight of head, neck and arm; F, the strength of Erector spinae to maintain spine flexion; θ, the angle between the trunk and the ground in flexion; N, the compression acted on L4; S, the component of the shear force; P and S, the counterweight, p= S

The lean angle of trunk was 20° while skating. The subject, height 170cm, weight 60kg, the weight of trunk accounted for 43 percent of the total body weight, W1=25.8kg; the weight of head and neck and arms accounted for 17 percent of the total body weight, W2=10.2kg; L1= 32cm, L2=55cm, D=5cm [4,5], according to the parameters of part of Chinese human body from literature[6], and anatomical structures of lumbar spine as well as the CT images.

The equilibrium equation was shown as following when skating, according to the principle of leverage.

$$\Sigma M = 0 \tag{1}$$

$$F \times D = W_1 \times L_1 + W_2 \times L_2 \tag{2}$$

Solution of equation was:

$F = (W_1 \times L_1 + W_2 \times L_2) / D = 2773.2N$ ;

$N = F + (W_1 + W_2)\sin 20^\circ = 2896.3N$ ; $N_x = N\cos 20^\circ = 2721.6N$ ; $N_y = N\sin 20^\circ = 990.6N$ ;

$S = (W_1 + W_2)\cos 20^\circ = 338.3N$

At this time, the strength of erector spinae to maintain spine flexion 2773.2N, the compression stress acted on L4 2896.3N, the component of shear force 338.3N, vertical compression stress 990.6N. This is just a simple calculation, but its results have a certain reference value.

## 3.1. Establishment and improvement of FEM

- Processing to CT images

The CT fault images were directly input in format of Dicom using medicinal picture processing software, Saving from the transferring procedure and information loss, speed and precision of modeling were greatly improved, the workload were reduced.In order to retrieve more exact contour of target vertebras, the threshold value is defined, which enables the soft-ware to form contour to the different layers of bony tissues and maximize the identifying capacity from other body tissues. Retrieving information from partly grey area with similar intensity to the target photograph through artificial distinguish to distinguishing those bony tissues, the different areas were segmented through region growing corresponding to different colors, the bony tissues were distinguished from CT images through region growing.

- Establishment of FEM of lumbar spine

The three-dimensional geometrical model of L4-L5 was established by 3D calculation, through region growing to segment the different regions, using medical software directly to input Dicom data. The intervertebral disc was defined as the soft tissue of annulus fibrosus and nucleus pulposus. The three-dimensional images segmentation was fulfilled with the disc as center, and redundant data were removed, finally the three-dimensional geometrical model of intervertebral disc L4-5was established by 3D calculation. The surface mesh was converted to the volumetric mesh, the anterior and posterior longitudinal ligament, interspinal ligament, supraspinal ligament and the intertransverse ligament were established referencing the physical form of human body specimen[7], and then, the three-dimensional FEM of L4-L5 was fulfilled. The volume of whole model, 82941.13mm3, the surface area of the model, 19064.55mm2. The vertebral body and intervertebral disc were adopted the element of SOLID185, the ligaments were adopted element of BEAM188 with nonlinear material property, the model consisted of elements of 56351 and nodes of 21643(Fig2).

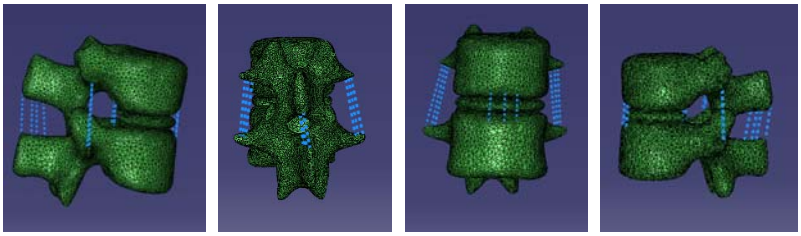

Fig. 2 The three-dimensional finite element model of L4-L5

- The definition of material property

The density, E-Modulus and Poisson Coefficient of different materials were calculated based on the gray value of CT images, which realised material assignment of the bone tissue with non-uniform material properties and anisotropic mechanical properties. The density of spongy bone $0.9*10^{-6}$ kg/mm$^3$, E-Modulus 2764MPa, Poisson Coefficient 0.29; the density of compact bone $1.9*10^{-6}$kg/mm$^3$, E-Modulus 16800MPa, Poisson Coefficient 0.22. The material properties of intervertebral disc and ligaments were from the previous studies[8], the density of disc $1.02*10^{-6}$ kg/mm$^3$, E-Modulus 3.4MPa, Poisson Coefficient 0.39; the material properties of ligaments was nonlinear

- Validation of the three-dimensional FEM

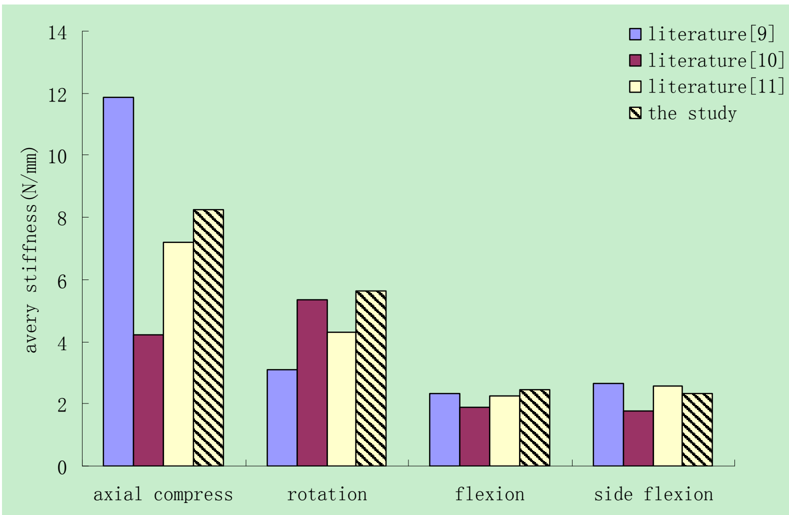


Fig.3 The average stiffness between this model and the literatures

The object of establishing the FEM was to provide the mechanical basic for clinical diagnosis, to verify the validation the FEM, the rationality of boundary conditions, constraint points, and the way of loading and simplification of the model. The average stiffness of this model was measured under the condition of vertical compression, torsion, flection, side flection. Compared with the previous studies, the results of this experiment and that of previous studies [9-11] were almost consistent, and precision of the model meet the needs of research. Consequently, it can be said that the three-dimensional FEM was valid and reliable, which can be used to clinical and experiment studies.

### 3.2. The boundary and loads

To simulate the mechanical characteristics of L4-L5 while skating. The lower endplate of L5 was fixed, the connection between the zygapophysical joints, vertebrae and intervertebral disc were considered sliding contact. Flexion torque of 138Nm and axial load of 990.6N were imposed on the model, the external loads were uniformly distributed on the surface of endplate, and equivalent stress and displacement of part of lumbar spine were calculated.

### 3.3. The finite element analysis of mechanical characteristics of lumbar for speed skaters

The spinal biomechanics research methods currently were mainly animal experiments, physics experiments, in vitro (body) experimental and computer simulation experiments. Computer simulation experiments, such as the finite element model, the model can simulate repeatedly experiments or change some parameters to reflect the changed condition according to organisms mechanical mechanism, it was impossible to do using other experiments.

The basic principle of finite element method is to divide the object that is made up of unlimited number of particles into finite elements, which have simple structure and morphology, and the mechanical properties are known, the process is called the discretization of finite element model, the finite element model with discretization is used to instead of the original object, different types of elements are adopted according to the geometrical material properties of the original objects, as well as the stress conditions, such as the mass element, shell element, surface element, pipe element and so on, the between elements was connected through nodes, the stress was transferred by nodes. The unknown numerical values of the internal point of element were obtained by the element nodes numerical value interpolation through the elected function. Some structure can be accurately analyzed using finite element method, and the entire process of the internal stress and deformation were showed while stressed, which is an important direction to the development of orthopedic biomechanics.

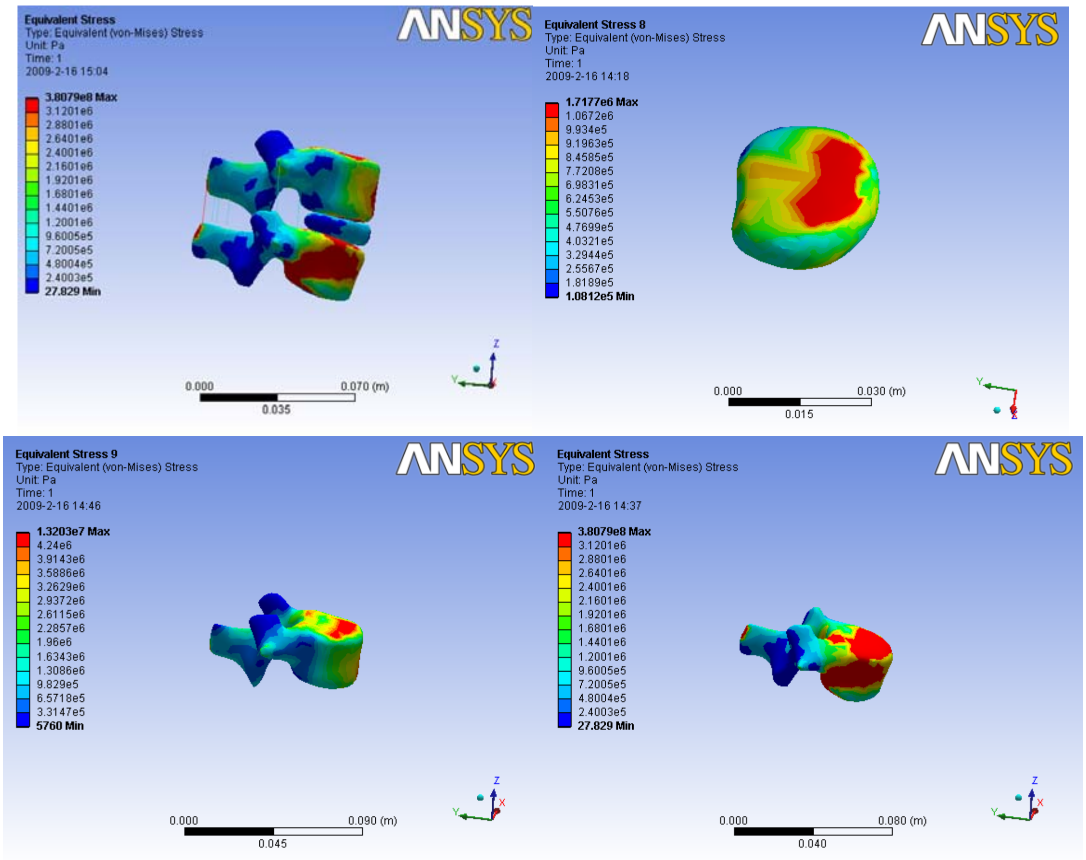


Fig.4 Equivalent stress of L4-L5 in flexion

The finite element analysis of mechanical characteristics of L4-L5 was fulfilled, equivalent stress of L4-L5 were shown in Fig 4, equivalent stress focused on anterior location of vertebral body in flexion, equivalent stress acted on vertebral body was higher than that of it's under nucleus pulposus, stress on adjacent vertebral endplate was significantly higher than other parts of the body, equivalent stress concentrated on the location. Equivalent stress gradually increased from top to bottom, the largest stress focused on anterior location of vertebral body was 3.8079*106Pa, the maximum equivalent stress on the vertebral body of L4 was 1.3203*107Pa; equivalent stress of posterior location concentrated on up and down articular processes of facet joints and pedicle of vertebral arch, but, the stress obviously declined, the stress acted on pedicle of vertebral arch gradually decreased from bottom to top. The stress acted on the intervertebral disc focused on middle and anterior location of exterior annulus fibrosus, the maximum stress was 1.7177*106Pa.

Facet joints, intervertebral disc and ligaments have close relationship in term of load bearing among the lumbar motion segment. In flexion position, the loads acted on the facet joints declined, on the other hand, posterior ligament was stretched, resulting in pull-down, which leaded to obvious increase of interior pressure of intervertebral disc [12-14]. The lower articular process of upper vertebral body moved upward and forward, if single torque of flexion was acted on the vertebral body, the upper and lower articular processes will separate, the facets of joints didn't contact, the stress is zero. The paper simulated the mechanical characteristics of lumbar spine in flexion for the speed skaters. The loads acted on the lumbar spine consisted of not only the flexion torque, but also the axial compressive loads from the weight of upper limb and trunk. The horizontal shear stress from compressive loads made the articular surface contact, and than, the pressure from between the anticular surfaces. Therefore, in flexion, the facet joint also bear a certain loads.

This model can be applied to lumbar spine biomechanics of theoretical study and simulation research. The ultimate aim of FEM was to provide the mechanical basis and theoretical reference for the clinical, but, due to limitations of study conditions, this study didn't consider that the muscles affected the biomechanics of the spine, meanwhile, only one motion segment of lumbar spine is adopted as the model, the results of the analysis in this study and that for the several motion segments may be different, so the model needs continuous improvement.

## 4. Conclusion

The three-dimensional FEM of L4-L5 was established by inputting directly the data of Dicom format in the paper with no transform, avoiding the lose of information, and featured by fast speed of modeling and high precision of the FEM. Three-dimensional FEM of lumbar motion segment (L4-L5) was established, which was considered material property and geometrical behave, with the characteristics of geometrical material and contact nonlinear; the FEM can be used to simulate a realistic range of spinal movement, to research finite element analysis.

Equivalent stress focused on anterior location of vertebral body, when the speed skating athletes exercised in flexion, equivalent stress acted on vertebral body was higher than that of it's under nucleus pulposus, stress on adjacent vertebral endplate was significantly higher than other parts of the body, equivalent stress concentrated on the location. Equivalent stress gradually increased from top to bottom, the largest stress focused on anterior location of vertebral body was $3.8079*10^6$Pa, the maximum equivalent stress on the vertebral body of L4 was $1.3203*10^7$Pa; equivalent stress of posterior location concentrated on up and down articular processes of facet joints and pedicle of vertebral arch, but, the stress obviously declined, the stress acted on pedicle of vertebral arch gradually decreased from bottom to top. The stress acted on the intervertebral disc focused on middle and anterior location of exterior annulus fibrosus, the maximum stress was $1.7177*10^6$Pa.

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