# 척추 수술시 요추의 유한요소해석

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# Finite Element Analysis of Lumbar Spine under Surgical Condition

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**Key Words** : Lumbar Spine, Biomechanics, Finite Element Analysis, Fracture Behavior

## ABSTRACT

We study the fracture behavior of the lumbar No.4 and No.5 vertebra subjected to posteroanterior (PA) forces, a three dimensional finite element method (FEM). The lumbar spine was modeled 3-dimensionally using commercial software based on the principle of convert stacked two dimensional CT scan images into three dimensional shapes. Determination of the boundary conditions corresponding to actual surgical conditions was not easy, so that the simplified spine beam analyses were performed. The results were used in three dimensional finite element (FE) analysis. This FE analysis, indicates that the fracture loads of the lumbar No.4 and No.5 vertebra are respectively 1550 N and 1500 N. These fracture loads are for static loading, but in actual conditions the load on the lumbar spine varies dynamically. We found that the fracture load of lumbar No.4 vertebra is larger than that of lumbar No.5 vertebra, as a result of the total stress difference by the moment.

## 1. INTRODUCTION

Lumbar spine surgery on Lumbar No.5 and No.4 has so far depended on the experiential skill of surgeon. To systematize the procedures, we need accurate surgical data for biomechanics of the lumbar spine. However, the lumbar vertebrae are complex shaped structures, whose mechanical behavior is difficult to analyze. The finite element method is well suited to study such a complex structure, and many finite element models have been developed since 1974. These have allowed the mechanical properties and behaviors of the lumbar spine to be determined [1-4]. A three dimensional parametric modeling method was developed by Lavaste et al.(1992) [1]. In this model the geometry is constructed using six parameters per lumbar vertebra. Keyak et al.(1998) [5] introduced the concept of the factor of safety (FOS) to predict the fracture load of the femur, and used a CT scan-based finite element (FE) model to estimate the femoral fracture load. Finite element modeling is now a common technique for the analysis of lumbar spine biomechanics. Keller et al. (2002) [6] developed a mathematical model for the static and dynamic motion response of the lumbar spine to posteroanterior (PA) forces, and used the concept of flexible joint structure including intervertebral discs and other soft connective tissues (ligaments, muscles, tendons, and cartilage).

The present work analyzes the fracture behavior of the lumbar vertebra under PA forces using a three

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dimensional finite element method (FEM).

## 2. METHODS

This section, describes our three dimensional lumbar vertebra model and the analysis procedure. The data of Keller et al. [6] were used to determine the appropriate surgical boundary condition. Analysis of lumbar vertebra proceeds as follows; the surgical boundary condition is first determined using a simplified spine beam analysis. Second, based on this beam analysis, lumbar No.5 and No.4 vertebrae are analyzed.

Table 1. Summary of Flexible Joints Structure Stiffness Coefficients

| Stiffness Coefficient | Thorax | T12-L1 | L1-L2 | L2-L3 | L3-L4 | L4-L5 | L5-S1 | Pelvis and Sacrum |
|---|---|---|---|---|---|---|---|---|
| Kx(kN/m) | 1250 | 640 | 620 | 600 | 525 | 450 | 510 | 300 |
| Ky(kN/m) | 30 | 50 | 40 | 35 | 30 | 30 | 45 | 200 |
| Kz(Nm/rad) | 400 | 160 | 140 | 120 | 100 | 80 | 75 | 700 |

Table 2. Material Constants of Flexible Joint Structure

| Stiffness Coefficient | Thorax | T12-L1 | L1-L2 | L2-L3 | L3-L4 | L4-L5 | L5-S1 | Pelvis and Sacrum |
|---|---|---|---|---|---|---|---|---|
| Ex(MPa) | 101 | 48 | 47 | 45 | 40 | 34 | 38 | 22 |
| Ey(MPa) | 371 | 658 | 526 | 460 | 395 | 395 | 592 | 2633 |
| Gxy(MPa) | 0.014 | 0.65 | 0.568 | 0.486 | 0.405 | 0.324 | 0.304 | 2.84 |

Table 3. Material Properties of L5 and L4 vertebra [1]

| Part | E(GPa) | Poisson Ratio | Ultimate Strength(MPa) |
|---|---|---|---|
| Cortical bone | 12 | 0.3 | 800 |
| Cancellous bone | 0.1 | 0.25 | |

### 2.1 Modeling of Lumbar Vertebra

Three dimensional lumbar No.5 and No.4 vertebrae were modeled using the Bionix (Canti Bio co.) commercial bio-engineering software. The modeling principle converts stacked two dimensional lumbar spine column CT scan images of interval 3 mm into three dimensional shapes. Regions of intervertebral discs and other lumbar vertebra are then removed. Finally, this model is exported to our finite element model.

### 2.2 Simplified Spine Beam Analysis

In surgical conditions, the lumbar vertebra is loaded by PA forces. To determine the boundary condition, we use the data of Keller et al. [6]. Keller's dynamic analysis of the lumbar spine represented the thorax, pelvis and five lumbar vertebras as seven rigid structures and eight flexible joint structures. The flexible joint structures include the intervertebral discs and other soft connective tissues (ligaments, muscles, tendons, and cartilage) and were modeled using spring elements. The respective spring constants are summarized in Table 1. We convert these spring constants to material constants suitable for FE analysis using equation (1),

$$k_z = \frac{GI_P}{L}, \qquad F = k\delta, \qquad \delta = \frac{FL}{AE} \qquad (1)$$

where F is force, L is length, A is area, kz is the torsional spring constant, k is a spring constant, E is Young's modulus, G is the shear modulus, and $\delta$ is the extension. The material constants calculated in Table 2 are applied in FE analysis. Figure 1 shows the simplified spine column beam model due to Keller [6], and shows the loading and boundary condition, which is the same as in Keller's static analysis. A static concentrated PA force of $F = 100N$ in the negative y-direction was applied on the lumbar No.3 vertebral segment. The displacement distribution of the FE analysis is shown in Figure 2. This result coincides with Keller's result, and is shown in Figure 3. The PA static deformation was greatest at lumbar No.3.

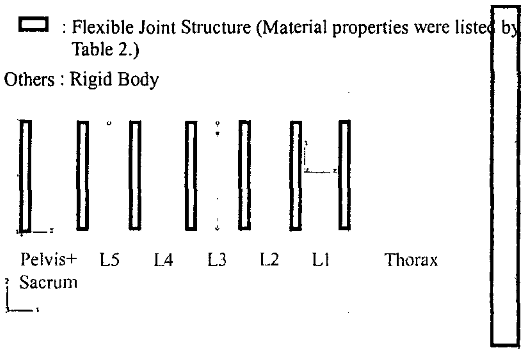


Figure 1. Simplified Spine Beam Model

### 2.3 Determination of Boundary Condition

Our aim is to analyze the fracture behavior of the lumbar No.4 and No.5 spine subjected to PA forces under surgical conditions. To this end, we use the result of a simplified beam spine analysis, with PA static displacements as components, to determine the boundary condition. The analysis proceeds as follows: a static concentrated PA force $F = 100N$ is applied in the negative y-direction on the lumbar No.5 vertebral segment. Then using the simplified beam model, we calculate the PA static displacements of the L5-S1 and L4-L5 flexible joint structures, which are converted to reaction forces using equation (2).

$$\delta = \frac{FL}{AE} \qquad (2)$$

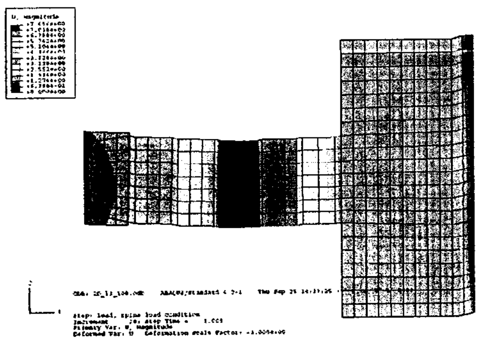

Figure 2. Displacement Distribution of Simplified Beam

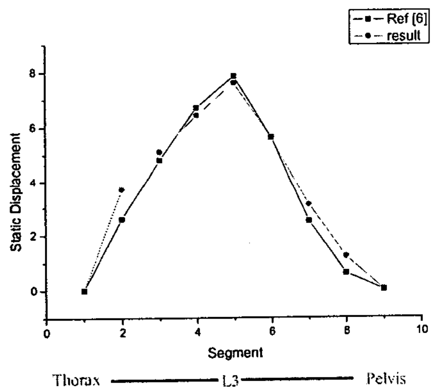


Figure 3. Static Displacement of the Lumbar No.3 vertebra to 100 N

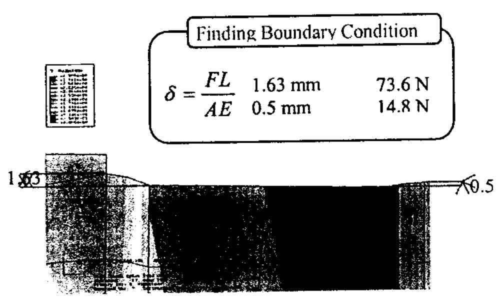


Figure 4. Displacement of L5-S1 and L4-L5 Flexible Joint Structures

The calculated reaction forces are then applied on lumbar No.5 vertebral body of the three dimensional model as static distributed shear forces in the positive y-direction. Finally, the six DOF (degree of freedom) of the load point are constrained. These procedures set the boundary condition. In other words, our procedure is such that the load point was constrained six DOF and supports the force rather than loads the force, and then the inversed reaction force is applied on the supporting region as a distributed shear force, instead of supporting. The analysis procedure for lumbar No.4 vertebra is the same as for No.5.

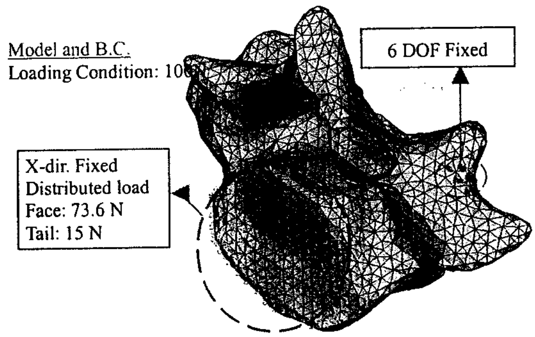


Figure 5. Three Dimensional L5 Model and Loading Condition

## 3. RESULTS

To analyzes the response to the static concentrated PA force of $F = 100N$ applied in the negative y-direction on the lumbar No.5 vertebral segment, we performed a FE analysis using our simplified spine beam model. Figure 4 shows that the displacements of the L5-S1 and L4-L5 flexible joint structures, which consist of intervertebral disc and other soft connective tissues (ligaments, muscles, tendons, and cartilage), are respectively 1.63 and 0.5 mm, which correspond to reaction forces of 73.6 and 14.8 N. These results were then used inversely as a loading condition of distributed shear forces on the lumbar No.5 vertebral body, equal to the static concentrated PA force $F = 100N$. Figure 5 shows the three dimensional lumbar No.5 vertebra model and the loading condition. To the face side of the vertebral body was applied 73.6 N of distributed shear force, and to the tail side 14.8 N. The material properties of the lumbar No.5 and No.4 vertebra are listed in Table 3, taken from the literature [1]. Figure 6 shows the Von mises stress distribution of the lumbar No.5 vertebra. From Figure 6, it was found that the load point stress under surgical conditions is 47 MPa and is the greatest, however 47 MPa is much less than the ultimate strength of cortical bone (800 MPa). We therefore increased the static concentrated PA force linearly up to $F = 1500N$

linearly. Figure 7 shows that the stress on the lumbar No.5 vertebra is 800 MPa at $F = 1500N$ and that the cortical bone fractured.

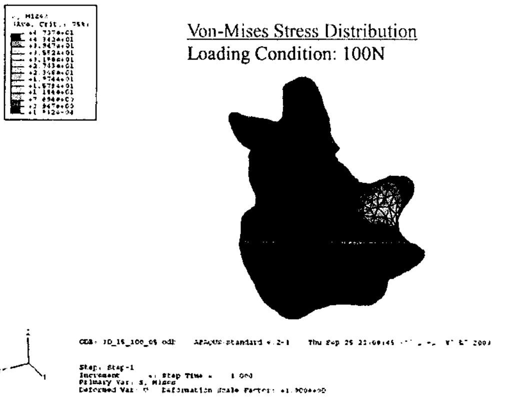


Figure 6. Von Mises Stress Distribution of 3-D Lumbar No.5 Vertebra

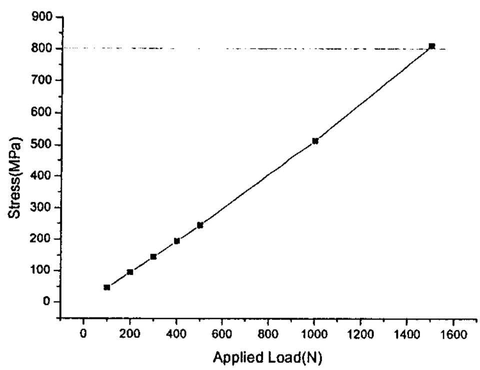


Figure 7. Stress-Load Curve of L5 Vertebra

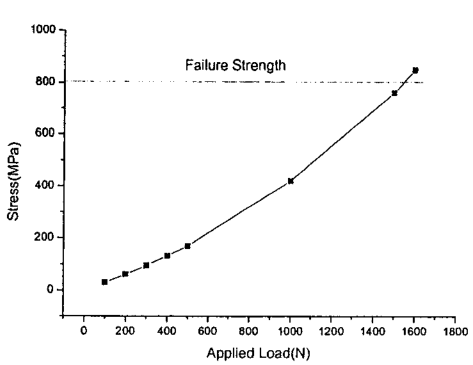


Figure 8. Stress-Load Curve of L4 Vertebra

The analysis of lumbar No.4 is the same as for No.5. The displacements of the L4-L5 and L3-L4 flexible joint structures were respectively 1.64 and 1.06 mm, which correspond to reaction forces of 49 N and 31.8 N. These reaction forces were applied on the lumbar No.4 vertebra. The load point stress is 30 MPa. The fracture load of lumbar No.4 is 1550 N, as shown in Figure 8.

## 4. DISCUSSION

Our FE analysis has found the fracture load of the lumbar No.5 and No.4 vertebrae. The fracture load of No.4 (1550 N) is larger than for No.5 (1500 N), as a result of the total stress difference. In other words, by considering spine column as beam model, the moment of the No.5 vertebra section is larger than for No.4, so that the total stress on No.5 vertebra is larger than on No.4. Using this fact, we can predict that fracture load of lumbar No.3 is large than No.5 and No.4.

In this work, we applied on the static force, but in real surgical conditions, the lumbar vertebra is loaded several times impact load until fracture occurs. Therefore in real conditions, we predict that the impact fracture load is less than static load.

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