INTRODUCTION

In lumbar scoliosis, which mainly appears in elderly people, surgical methods with metal rods or with plates are effective, especially for an excessive deformation. As one of the surgical methods, there is a pedicle screw fixation, which uses spinal instruments such as metal screws, connectors and rods (Figure 1). This method for correcting scoliosis is stronger than the other methods. But if a design of instruments is not good, it might not hold. Then, rod damage, or the loosening of screws may occur. To avoid these problems, the forces applied to the instruments and the lumbar motion must be understood. Additionally, the assemblies of the instruments should be as small as possible in order to reduce the surgical damage. From these points, model analysis methods are available because muscle forces and other forces in daily motions can be represented.

METHOD

The finite element model is useful but analyzing whole lumbar behavior with instruments in three-dimensional motion but has difficulties due to calculation of the load. In this study, a whole lumbar and instruments were modeled simply by rigid bodies and springs. By using this model, corrected postures and pull-out forces of the screws were estimated. Applied muscle forces in this estimation were obtained from the musculoskeletal model developed by previous study (Hase and Yamazaki).

Lumbar And Instruments

A lumbar and instruments were modeled by 15 rigid bodies and 211 springs. The rigid bodies are 5 lumbar vertebrae and 10 screws, where each lumbar vertebra has a screw on their each view is shown in Figure 1.

The springs connect the rigid bodies and represent deformations of rods (Figure 2).

Vertebrae

Since the Young’s modulus of a vertebra (1000 MPa) is large compared with that of a ligament (5 MPa) and that of
an intervertebral disc (10 MPa), a vertebra can be regarded as a rigid body. The length and width of the vertebra, and insertion of ligaments or muscles were derived from the data of human vertebral shape. The vertebral weights are decided from the geometrical approximation of the vertebral bodies as elliptic truncated cones.

**Ligaments**

Six ligaments were modeled as in Figure 2. From the experimental result by Pintar et al., the tensile force is assumed proportional to its extended length, while the compressive force is neglected. Each intertransverse, interspinous and supraspinous ligament is replaced with one spring. By considering the effect from flexion, lateral bending and rotation, each anterior longitudinal, posterior longitudinal and yellow ligament has three springs. The spring constant of a ligament is derived from dividing the product of Young’s modulus and the sectional area by the height.

The spring constant of the translation of the cylinder is determined in a similar way to that of a ligament, that is, when compressed by the weight (250 N) of the torso above. The spring constant of the torque for rotation is determined by the Young’s modulus of the disc and by polar moment of inertia of its area. Table 1 shows the translation and torque spring constants, which were obtained by the above method.

<table>
<thead>
<tr>
<th>Table 1: Intervertebral disc parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring const. (10^4 N/m)</td>
</tr>
<tr>
<td>Flexion</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>L1-2</td>
</tr>
<tr>
<td>L2-3</td>
</tr>
<tr>
<td>L3-4</td>
</tr>
<tr>
<td>L4-5</td>
</tr>
<tr>
<td>L5-S</td>
</tr>
</tbody>
</table>

Let, \( K_{\text{disc}} \) be a matrix whose diagonal elements are translation spring constants, and \( T_{\text{disc}} \) be a matrix whose diagonal elements are torque spring constants. Let \( \mathbf{e}_{\text{disc}} \) and \( \theta_{\text{disc}} \) be a relative translation vector and a relative angle vector, respectively, between superior and inferior vertebral. Then, passive forces \( \mathbf{f}_{\text{disc}} \) and moments \( \mathbf{n}_{\text{disc}} \) of the intervertebral disc are expressed by the following:

\[
\mathbf{f}_{\text{disc}} = -K_{\text{disc}} \mathbf{e}_{\text{disc}} - T_{\text{disc}} \theta_{\text{disc}},
\]

\[
\mathbf{n}_{\text{disc}} = \mathbf{r}_{\text{disc}} \times \mathbf{f}_{\text{disc}}.
\]

**Intervertebral Discs**

The model of an intervertebral disc consisted of three translation springs and three torque springs. The translation springs were set along the \( u \), \( v \) and \( w \)-axes in the local coordinates, respectively. The torque springs were set around them, respectively. Here, among these springs, there was assumed to be no effect on each other.

The shape of an intervertebral disc was considered to be a cylinder whose sectional area is the average of the superior and inferior end plates of the vertebral bodies and whose height without load is the average of the height of the intervertebral disc in the upright posture and the thickness when compressed by the weight (250 N) of the torso above. The spring constant of the translation of the cylinder is determined in a similar way to that of a ligament, that is, dividing the product of Young’s modulus (10 MPa) and the sectional area by the height.

The spring constant of the torque for flexion and lateral bending is determined by Young’s modulus of the disc and the calculated moment of inertia of the area of the disc about the center of the disc. By comparison, the spring constant of the torque for rotation is determined by the Young’s modulus of the disc and by polar moment of inertia of its area.
When the screw is rotated, a set torsion friction spring is 1.1Nm because the average inserted torque is 1.1Nm. The values in Table 2 are the spring constants used in this study.

Table 2: Contact face spring parameters

<table>
<thead>
<tr>
<th>Bone</th>
<th>Pull-out (10^3 N/m)</th>
<th>Contact (10^3 N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancellous</td>
<td>4.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Sub-cortical</td>
<td>11.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Cortical</td>
<td>2.9</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Now, with these spring constants, screw’s force $f_{screw}$ is expressed by

$$f_{screw} = -k_{pull} \mathbf{e}_{screw}$$

where $k_{pull}$ is pull-out spring constant.

Screw’s moment $n_{screw}$ is expressed as follows:

$$n_{screw} = r_{screw} \times f_{screw} - \alpha \mathbf{e}_{trq}$$

where

$$\alpha = \text{sign}(\theta_{screw}) \times \frac{\theta_{screw}}{\theta_{screw} = 0}$$

and $r_{screw}$ is a direction vector from the center of gravity in a rigid body to the insertion attached to spring’s end, $t_{trq}$ (=1.1 Nm) is the inserted torque, and $\theta_{screw}$ is an angle vector around the longitudinal of a screw.

Rod

The rod was regarded as a column beam with the uniform sectional area and the uniform material property. Consider the rod coordinates, where the $\hat{z}$-axis is set along the column beam (Figure 3). When $[\delta \hat{x} \ \delta \hat{y} \ \delta \hat{z}]^T$ is the relative translation vector and $[\delta \hat{\phi} \ \delta \hat{\theta} \ \delta \hat{\psi}]^T$ is the relative angle vector between the superior and inferior linkage points between the connector and the rod, the reaction forces and moments $[f_{rod} \ n_{rod}]^T$ are expressed as follows:

$$[f_{rod} \ n_{rod}]^T = \mathbf{K} \begin{bmatrix} \delta \hat{x} \\ \delta \hat{y} \\ \delta \hat{z} \\ \delta \hat{\phi} \\ \delta \hat{\theta} \\ \delta \hat{\psi} \end{bmatrix}$$

where the large matrix is the stiffness matrix of a rod, whose elements $c_i L$ are the constants decided by the shape and the material property of a rod. Set $c_1 = 12E/L^3$, $c_2 = 6E/L^2$, $c_3 = E/L$, $c_4 = 4E/L$ and $c_5 = G I / L$, where $L$ is the distance between superior and inferior of the linkages, $E$ is modulus of longitudinal elasticity (110 GPa), $G$ is modulus of transverse elasticity (42 GPa), $d (=6$ mm) is the diameter of the rod and $S (= \pi d^2 / 4)$ is the sectional area. Since (6) is expressed by the rod coordinates, it should be translated into the coordinate of each rigid body.

Muscle

Muscles surrounding the lumbar were modeled as 8 muscles as shown in Figure 2 (c). Muscle forces, which are estimated with the three-dimensional musculoskeletal model reported by Hase and Yamazaki (1995), are obtained under the condition of simple daily motions such as flexion (30 degrees), right lateral bending (20 degrees) and left rotation (10 degrees).

A moment $n_{muscle}$ is expressed with a muscle force $f_{muscle}$ as follows:

$$n_{muscle} = r_{muscle} \times f_{muscle}$$

where $r_{muscle}$ is a direction vector from the center of gravity in a rigid body to a insertion of the muscle. The obtained forces and moments apply to the rigid body at the insertion.
Upper Body and Intra Abdominal Pressure

A head, thorax and arms were assumed to be one rigid body. Put $f_{\text{upper}}$ to be the gross weight of the upper body. Then, a moment of the upper body weight $n_{\text{upper}}$ is expressed in the following equation:

$$ n_{\text{upper}} = r_{\text{upper}} \cdot f_{\text{upper}}, \quad (8) $$

where $r_{\text{upper}}$ is a direction vector from the center of gravity of L1 to the center of the upper part. Therefore, $f_{\text{upper}}$ and $n_{\text{upper}}$ applies to the rigid body as L1. Denote by $p_{\text{abd}}$ as the intra abdominal pressure obtained from an estimate by Chaffin (1969), then the force due to the intra abdominal pressure $f_{\text{abd}}$ is represented by

$$ f_{\text{abd}} = s_{\text{abd}} \cdot p_{\text{abd}}, \quad (9) $$

where $s_{\text{abd}}$ is a vertebral projection area to abdomen.

Calculation Method

In each rigid body, both the total forces and moments must be balanced. Under this condition, relative displacements $(3' 15)$ and angles $(3' 15)$ among rigid bodies were calculated by the quasi-Newton method. The upper weight was added to the lumbar and instruments model as an initial load. The program was written in C language. For the calculation, TAKERU2000 (NABE3 International, OS: Linux, CPU: Pentium III 850MHz) was used. The program took about 120 minutes for one calculation.

RESULTS AND DISCUSSION

Comparison with Corrected Postures

In order to evaluate the effect of inserted pedicle positions and vertebrae level, three types of fixation in Figure 4 were compared: (a) screws are inserted into the pedicles of the both sides of L1-5, (b) screws are inserted into the both sides of L1, L3 and L5 and (c) screws are inserted into the only right side of L1-5. Initial scoliosis was set with a Cobb angle of 10 degrees to the right, as in the typical posture. Then, the scoliosis was compared with the normal lumbar posture, where the force was determined from the reaction forces of the instruments and the restitutive forces of soft tissues.

In this study, the forces are calculated in the corrected posture using the fixation method. Figure 5 shows the initial scoliosis posture and corrected postures. The fixations of (a) and (b) in Figure 4 were almost the same in terms of the relative translations and rotation angles. Therefore, the extent of corrective effects of them were also seemed to be the same. Conversely, (c) was inferior to (a) and (b) in their translations and angles, especially the differences in the frontal plane and the rotation angles between (c) and (a) (or (b)) were large. These results agreed with the clinical reports.

Comparison Among Pull-Out Forces

From the spring forces of the contact surfaces between vertebrae and screws, the pull-out forces at each fixation method in Figure 4 were estimated. Figure 6 (c) shows when the screws are inserted into only the right side, where the load of the screws in the radial direction become large and the cancellous bone might be broken. Figure 6 (b) shows in the case of Figure 4 (b), a large pull-out force (1000N) which is almost the maximum limitation applies to the screw on L3. When the screws are inserted in both sides of the vertebra as in Figure 4 (a), the scoliosis is corrected without loosening of the screws.

Connectivity Among Assemblies in Simple Motions

Muscle forces in simple daily motions (Table 3) were applied to the corrected lumbar as shown in Figure 4 (a). Bending motion occurred only at L5-S joint and in the condition of other discs translate less than 1 mm and rotate less than 0.2 degrees. Figure 7 shows those forces and torques applies to the linkage between the connector and the rod. In this figure, the ends of the track are the minimum
and the maximum values of forces and torques in simple motions, and the circles mean the value of forces and torques in correcting the posture.

The largest connectable force was 1230 N on L3, and torque was 1.8 Nm on L5. From the standard mechanical test by ASTM, connectable forces of each instrument were from 1600 to 3400 N and connectable torques of the instruments were from 1.8 to 8.2 Nm. This results shows that some kinds of instruments have little connectable forces. From the fatigue stress (Ti-6Al-4V, 540MPa) of the instruments, the smallest diameter of the rod is 4.2 mm in simple motions.

**SUMMARY**

In order to correct the typical scoliosis (Cobb’s angle 10 degrees), pedicle screws should be inserted into both the left and right pedicles of all vertebrae. In other conditions, the pull-out forces of the screws approaches the limit and a large force is applied to the lateral direction of the screws. In simple daily motions, the connectable forces between a connector and a rod needs at least 1230 N and the connectable torque between them needs at least 1.8 Nm.

**REFERENCES**

ASTM F1798 Annual Book of ASTM Standards, 13.01, 1222-1231


Oda, I., Cunningham, B.W., et al. (2000). *Spine*, 25(18), 2303-2311


**Table 3:** Muscle forces in simple motion and muscle forces (N)

<table>
<thead>
<tr>
<th>Muscle forces (N)</th>
<th>Flex. (30 degrees)</th>
<th>Late. Bend. (20 degrees)</th>
<th>Rot. (10 degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectus abdominus</td>
<td>0</td>
<td>99</td>
<td>13</td>
</tr>
<tr>
<td>Erector muscles of spine</td>
<td>1100</td>
<td>350</td>
<td>800</td>
</tr>
<tr>
<td>Internal. Oblique(right)</td>
<td>2</td>
<td>90</td>
<td>140</td>
</tr>
<tr>
<td>Internal. Oblique(left)</td>
<td>2</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>External. Oblique(right)</td>
<td>2</td>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td>External. Oblique(left)</td>
<td>2</td>
<td>160</td>
<td>300</td>
</tr>
<tr>
<td>Psoas major(right)</td>
<td>200</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Psoas major(left)</td>
<td>200</td>
<td>15</td>
<td>300</td>
</tr>
</tbody>
</table>

**Figure 6:** Pull-out forces in each fixation

**Figure 7:** Connective force and torque at linkage between connector and rod