Lateral Translation of the Lumbar Spine: 
In Vitro Biomechanical Study

Yuichiro Okushima¹, Nobutoshi Yamazaki², Morio Matsumoto¹, Kazuhiro Chiba¹, 
Takeo Nagura¹, and Yoshiaki Toyama¹

Keio University, Tokyo

A biomechanical study of lateral translation in lumbar spine with human cadavers was performed in order to explore the direction of the force increasing lateral translation and the contributions of discs and facet joints to lateral translation. Whole lumbar spines from 12 fresh cadavers were attached to a specially designed loading apparatus whose five cables simulated the muscles of the trunk without restricting natural movement. Three-dimensional positions of each vertebra were recorded with position-sensitive detectors. Force in the anterolateral direction increased the lateral translation more than force in the posterolateral direction. Lateral translation was increased to a significantly greater extent when the facet joints were removed than when the discs were removed at L4-5 at the levels of shear loading applied in this study.

Key Words: cadaver, scoliosis, degeneration

Degenerative lumbar scoliosis is becoming a more frequent problem in the elderly population (Epstein, Epstein, & Jones, 1979; Robin, Span, Steinberg, Makin, & Menczel, 1982; San Martino, D’Andria, & San Martino, 1983; Simmons & Simmonns, 1992). Lateral listhesis of the lumbar vertebrae is often present in patients with degenerative lumbar scoliosis and can complicate their management (Grubb, Lipscomb, & Coonrad, 1988; Piat, Laredo, & Tassin, 1995). Radiculopathy or neurogenic deficits caused by lateral listhesis are common complaints of patients with degenerative lumbar scoliosis. Recently, Liu et al. (2003) discovered that the lateral listhesis in patients with degenerative lumbar scoliosis in which the L3 or L4 root on the concave side of the curve was affected were larger than in patients in which the L5 or S1 root on the convex side was compressed.

There is controversy regarding the management of degenerative lumbar scoliosis, especially the necessity of fusion surgery (Daffner & Vaccaro, 2003; Grubb, Lipscomb, & Suh, 1994; Gupta, 2003). Tribus (2003) considered posterior fusion to be reasonable in a patient with lateral listhesis > 5 mm. Lateral listhesis is also recognized as an indicator of segmental instability of the lumbar spine and is one of the risk factors related to the progression of scoliosis (Kirkaldy-Willis & Farfan, 1982; Korovesis, Piperos, Sidiropoulos, & Dimas, 1994; Krismer et al., 2000; Nachemson, 1985; Sapkas et al., 1996). Radiological studies have suggested a relationship between loss of lordosis and lateral listhesis. In a study by Pritchett and Bortel (1993) of 200 consecutive patients, 171 had less lordosis than normal, and lateral listhesis ≥ 6 mm was one of the important predictive factors for curve progression, as was a Cobb angle ≥ 30°. Grubb et al. (1992) described 17 of 55 patients with degenerative scoliosis (31%) as having lumbar lordosis ≤ 30°, while 80% had lateral listhesis ≥ 5 mm, predominantly at the L3 and L4 levels.

¹Dept. of Orthopedic Surgery, School of Medicine, and ²Dept. of Mechanical Engineering, Faculty of Science and Technology, Keio University, 35 Shinanomachi, Shinjuku, Tokyo 160-8582, Japan.
Although lateral listhesis in the analysis of roentgenograms is different from the pure lateral translation because horizontal rotation of vertebrae affects roentgenograms (Coleman, Harrison, & Bernard, 2001), a biomechanical experiment to investigate the direction of the force increasing lateral translation revealed the source of lateral listhesis in degenerative lumbar scoliosis. However, no previous biomechanical studies have focused on the details of the relationship between the direction of force and lateral translation.

Spinal motion at each level is regulated by bilateral facet joints and the intervertebral discs. Facet joint laxity and degeneration of the discs are thought to be involved in lateral translation. However, no causal relationship has been established between facet joints or discs and increased lateral translation. The current study was designed to explore the direction of the force increasing lateral translation and the contributions of discs and facet joints to lateral listhesis in vitro.

**Methods**

Whole lumbar spines, from the T12 vertebra to the sacrum, were procured from 12 fresh cadavers. The ages ranged from 60 to 85 years (mean = 76 years) and the male-female ratio was 6:6.

T12 vertebrae were sectioned at the level of the superior surface of the vertebral body. The sacrum was sectioned at 5 cm below the L5-S1 disc in the transverse plane. All ligaments, facet joints, and discs were left intact. The iliolumbar ligaments and the intertransverse process ligaments were also preserved bilaterally. The specimens were examined radiographically. No compression fractures or osteophytes, of the 3rd or 4th degree based on Nathan’s (1962) method, were recognized. Neither slipping nor lateral listhesis was detected. The specimens were stored frozen at −20 °C, then thawed at room temperature for 24 hours before testing. For rigid fixation of the specimen, muscle and fat were removed and 2.0 mm diameter Kirschner wires were inserted into the T12 vertebra and the sacrum.

In order to confirm that translation or angulation occurred when the human lumbar spine was bent laterally, a natural bending force was loaded onto the specimen. Thus, a loading apparatus was specially designed and natural lateral bending motion of the specimen was reproduced by a pulley system (Figure 1). Five cables served as the *M. obliquus externus abdominis*, *M. obliquus internus abdominis*, and the back muscles, which were attached to an aluminum plate imitating the lower level of the thoracic cage at the points measured in an actual human skeleton. Two cables pulling the specimen simulated the *M. obliquus externus abdominis*, producing the lateral bending and anterior flexion (LAF) at the same time. The other two cables created traction for lateral bending and posterior flexion (LPF). The remaining cable produces posterior flexion (PF). Three LEDs were attached to the anterior side of each vertebral body and the 3D positions of each vertebra were recorded with two position-sensitive detectors.

![Image](image-url)
When the specimen was pulled in the LAF or LPF direction, it showed anterior or posterior bending motion as well as a lateral bending motion, which enabled us to investigate the influences of forces in the anterior and posterior directions on lateral translation of the lumbar spine. The remaining cable was for posterior flexion (PF) representing the back muscles. A specimen was attached to each part of the device using a polyester resin. First, the apparatus was modified to assure that the specimen was placed straight in the coronal view and that the superior aspects of the L4 vertebra was situated parallel to the horizontal line as viewed from the side.

To measure the position of each vertebra, we attached three LEDs to the anterior side of each vertebral body. Three-dimensional positions of each vertebra were recorded 200 times during a 2-second period with two PSD (position sensitive detectors, PSS-3570, Hamamatsu Photonics, Hamamatsu City, Japan). The measurement error of the PSDs was 0.64 mm according to the measurements in the previous experiment. We constructed the metal frame on which 16 LEDs were placed. The position of the each LED was accurately measured with a 3D digitizer (Micro-scribe 3D, Immersion Corp., San Jose, CA). Before starting the test, we measured 3D positions of the bilateral transverse processes and the upper anterior portion of each vertebral body.

The first experiment was carried out to determine which direction of force increases lateral translation, LAF or LPF. After placing the specimen in the apparatus as described above, we loaded a 1000-g weight in a predetermined order: left side of the LAF cable, right LAF, left LPF, and finally the right LPF, with 30 seconds of creep at each loading step. Each specimen was subjected to the same series of tests three times.

Three-dimensional positions of the bilateral transverse processes and the upper anterior portion of each vertebral body were calculated from the measured LED positions using software specially designed to make the calculations. The origin of axes of each vertebra was defined as the median point of the bilateral transverse processes. The X axis on the horizontal plane was defined as passing through the bilateral transverse processes. The Z axis was defined as the line from the origin to the upper anterior portion of each vertebral body. The lateral translation was defined as the movement of the origin along the X axis. The lateral flexion angle was determined by the rotation around the Z axis, and the rotation angle was the rotation around the Y axis (Figure 2). The range of motion was defined as the absolute value of the remainder from the values when the weight was loaded onto the left cable to the values of the right cable.

A further experiment using 6 specimens was performed in order to investigate the contributions of facet joints and intervertebral discs to lateral translation. After the previous series of studies were done, a 1000-g weight was applied to the PF cable to prevent extreme anterior flexion of the specimen. Then a 1000-g weight was loaded onto the cable in the LAF direction, as in the previous study. For three specimens (Group A), the experiment was repeated after the intervertebral discs at L2-3, L3-4, L4-5, and L5-S had been removed (Step 1). Subsequently, the experiment was repeated after bilateral facetectomy at L2-3, L3-4, L4-5, and L5-S (Step 2). The Group B specimens were sectioned conversely, after removing the bilateral facet joints (Step 1). Then the intervertebral discs were removed (Step 2). To protect the anterior longitudinal ligament, we excised the discs from the lateral sides of the intervertebral spaces with scalpel and surgical puncher. The entire laboratory procedure was performed on each specimen and required no more than 6 hours.

A set of 200 data points was obtained in one series of tests, and after three series of tests had been performed, the average values of all 600 data points were adopted. The significance of the mean difference among L2-3, L3-4, L4-5, and L5-S was examined by ANOVA and the Scheffé test as a post hoc test, while a paired Student’s t-test was used to determine the significance of the mean difference between the LAF and LPF direction forces. Taking the range of motion at Step 2 into consideration, we used repeated-measures ANOVA to analyze the pattern difference between Groups A and B statistically, with the aim of evaluating the
contributions of discs and facet joints in preventing lateral translation, the lateral flexion angle and the rotational angle in the removal experiment. A $p$ value of $\leq 0.05$ was taken to indicate statistical significance.

**Results**

In the first experiment, i.e., loading of the 1000-g weight, lateral translation was increased by traction in the LAF direction as compared to that in the LPF direction at L2-3 ($p = 0.025$), L3-4 ($p = 0.022$), and L4-5 ($p = 0.018$) (Figure 3). Lateral translation at L2-3 was significantly greater than that at L5-S ($p = 0.015$) when the specimen was pulled in the LAF direction. The same tendency could be seen when the specimen was pulled in the LPF direction; lateral translation at L2-3 was significantly greater than at L5-S ($p = 0.034$).

Traction in the LAF direction increased the lateral flexion angle more than in the LPF direction at L3-4 ($p = 0.019$). There were no significant differences among L2-3, L4-5, and L5-S regardless of whether the specimen was pulled in the LAF or the LPF direction.

In terms of the rotation angle, traction in the LAF direction was greater than in the LPF direction at L2-3 ($p = 0.022$) and L4-5 ($p = 0.021$). The rotation angle at L2-3 was significantly greater than at L5-S ($p = 0.033$ in LAF, $p = 0.011$ in LPF).

The anterior flexion angle of the intervertebral disc was significantly greater when the specimen was pulled in the LAF direction than when the specimen was pulled in the LPF direction at L2-3 ($p = 0.011$) and L3-4 ($p = 0.041$).

In the removal experiment, lateral translation at all intervertebral spaces increased significantly following resection of discs and facet joints (L2-3, $p = 0.004$; L3-4, $p = 0.001$; L4-5, $p = 0.003$; and L5-S, $p = 0.005$), as shown in Table 1. The lateral flexion angle at all intervertebral spaces increased significantly following resection of discs and facet joints (L2-3, $p < 0.0001$; L3-4, $p = 0.0002$; L4-5, $p < 0.0001$; and L5-S, $p < 0.0001$). The rotation
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Figure 3—Result of first experiment with loading of a 1000-g weight. (a) Lateral translation was significantly greater in the LAF direction than in the LPF direction at L2-3, L3-4, and L4-5. Lateral translation at L2-3 was significantly greater than at L5-S. (b) Lateral flexion angle. Traction in the LAF direction increased the lateral flexion angle more than in the LPF direction at L3-4. There were no significant differences at L2-3, L4-5, and L5-S regardless of whether the specimen was pulled in the LAF or the LPF direction. (c) The rotation angle at L2-3 was significantly greater than at L5-S. Traction in the LAF direction was greater than in the LPF direction at L2-3 and L4-5.

Table 1 Result of Removal Experiment

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<thead>
<tr>
<th></th>
<th>L5/S</th>
<th>L4/5</th>
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<td>Lateral Translation</td>
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<td>Intact (mm)</td>
<td>1.2 ± 1.6</td>
<td>2.5 ± 2.0</td>
<td>2.6 ± 2.3</td>
<td>3.4 ± 3.5</td>
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<td>After discectomy</td>
<td>4.3 ± 3.0</td>
<td>7.5 ± 4.5</td>
<td>10.3 ± 6.3</td>
<td>9.9 ± 9.2</td>
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<td>and facetectomy (mm)</td>
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<td>0.001</td>
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<td>Lateral Flexion Angle</td>
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<td>2.2 ± 1.9</td>
<td>4.6 ± 1.6</td>
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<td>After discectomy</td>
<td>8.6 ± 2.7</td>
<td>12.0 ± 3.3</td>
<td>14.7 ± 5.2</td>
<td>16.5 ± 5.4</td>
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<td>and facetectomy (°)</td>
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<td>Intact (°)</td>
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<td>1.6 ± 1.1</td>
<td>1.4 ± 0.8</td>
<td>3.6 ± 2.0</td>
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<tr>
<td>After discectomy</td>
<td>7.9 ± 4.7</td>
<td>11.0 ± 8.3</td>
<td>10.9 ± 9.2</td>
<td>14.5 ± 7.9</td>
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<td>and facetectomy (°)</td>
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<tr>
<td>p</td>
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<td>0.020</td>
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Note: The lateral translation, lateral flexion angle, and rotation angle increased significantly following resection of discs and facet joints.
Figure 4a – Rate of increase with resection compared with the range of motion of the intact specimen. Lateral translation. There was a significant pattern difference at L4-5 between Group A and Group B. At other intervertebral spaces, the pattern of increase with resection in Group A was not significantly different from that in Group B.

angle also increased significantly at all intervertebral spaces (L2-3, $p = 0.005$; L3-4, $p = 0.035$; L4-5, $p = 0.020$; and L5-S, $p = 0.003$).

When the range of motion of the intact specimen was assumed to be 1, the rate of increase in lateral translation with resection [(ROM of each status) / (ROM of intact) –1] showed a significant pattern difference at L4-5 ($p = 0.020$) between Group A and Group B. At other intervertebral spaces, the pattern of increase with resection, in Group A, was not significantly different from that in Group B.

The rate of increase in the lateral flexion angle showed a significant difference in pattern at L2-3 ($p = 0.026$). At other intervertebral spaces, the patterns of increase with resection, in Group A, were not significantly different from those in Group B. As for the rate of increase in the rotational angle, there were no significant differences between Group A and Group B at any of the intervertebral spaces (Figure 4). Throughout all resection steps, lateral translation, lateral flexion and rotation angle at L5-S were smaller than those at other intervertebral spaces.

Discussion

Degenerative lumbar scoliosis is often accompanied by lateral listhesis. Some radiological studies have shown diminution of lordosis to be related to lateral listhesis. Liu, Ray, and Hirsch (1975) attempted to explain the relationship between the loss of lordosis and lateral listhesis.

Some previous biomechanical studies of cadaveric specimens on which pure shear force was loaded demonstrated that the stiffness of the motion segment unit of the lumbar spine ranged from 53 to 643 N mm$^{-1}$ (Liu et al., 1975; Miller, Schultz, Warwick, & Spencer, 1986; Panjabi, Krag, & Chung, 1984). The stiffness of the motion segment was not
Figure 4 b – Rate of increase with resection compared with the range of motion of the intact specimen. The rate of increase in the lateral flexion angle showed a significant pattern difference at L2-3. At other intervertebral spaces, the patterns of increase with resection in Group A were not significantly different from those in Group B.

determined in the present study because the simulated muscle forces were applied to the specimens instead of pure shear force. However, none of the previous studies focused on the precise relationship between the direction of force and lateral translation, or between facet joints or discs and increased lateral translation.

In our first experiment, traction in the LAF direction increased lateral translation more significantly than in the LPF direction at L2-3, L3-4, and L4-5. Although the actual force and moment loading each vertebra cannot be calculated in this experimental system, it is clear that the anterior flexional moment of the traction in the LAF direction is greater than that of the traction in the LPF direction.

Traction in the LAF direction increased the lateral flexion angle more significantly than in the LPF direction at L3-4. At other intervertebral spaces, there were no significant differences in the lateral flexion angle. The anterior flexion angle of each intervertebral space was significantly greater when the specimen was pulled in the LAF direction than when it was pulled in the LPF direction. A difference was seen in lateral translation according to the tractional direction, LAF or LPF, but not in lateral flexion. This result indicates that force in the anterior direction increases lateral translation more than force in the posterior direction.

The question of which component restrains lateral translation more, facet joints or intervertebral
Figure 4 c – Rate of increase with resection compared with the range of motion of the intact specimen. Rotational angle. There were no significant differences between Group A and Group B at any of the intervertebral spaces examined.

disks, remained. Therefore, we performed further removal experiments in order to measure the contributions of discs and facet joints to lateral translation, the lateral flexion angle, and the rotation angle. The removal experiments were carried out using cables because the LAF direction showed larger numerical values than the preceding LPF direction.

In this resection experiment, the pattern of increase in lateral translation differed significantly between Groups A and B at L4-5. The fact that Group B showed a larger rate of increase and that the bilateral facet joints and discs were ultimately removed in both groups indicates that lateral translation increases more when the facet joints are removed than when the discs are removed. Sharma et al. (Sharma, Langrana, & Rodriguez, 1995) reported that the facet joints play an important role in resisting the anterior shear displacement (translation) which accompanies flexion in the sagittal plane. There are no previous detailed studies on the role of the facet joints in resisting lateral translation in the coronal plane. Facet joints are tightened when the lumbar spine is extended posteriorly, preventing the vertebrae from translating laterally, but they are loose when the lumbar spine is bent forward to permit lateral translation between the vertebrae.

Several limitations in our study should be noted. Since the specimens used in this study were obtained from the cadavers of elderly persons, the results may have been affected by degeneration of the discs and the facet joints. However, we think that the results are meaningful because lateral translation of the lumbar spine mostly occurs in the elderly.

In the first experiment, as we designed an apparatus that simulated natural lateral bending motion, it was impossible to calculate the actual force loaded on each vertebra, and the four vector pairs of the cable representing abdominal oblique muscles do not act on each vertebra as pure lateral translational forces. In the second removal experi-
ment, we completely resected facet joints and discs in order to facilitate lateral translation. However, such a situation is unlikely to occur in vivo.

Previous reports have focused on the relationship between discs and lateral translation. Goel et al. (Goel, Goyal, Clark, Nishiyama, & Nye, 1985) reported that lateral translation increased after discectomy in vitro. Recently Krismer et al. (2000) demonstrated with cadaveric specimens that after application of an axial rotation moment, lateral translation increased as the degree of degeneration increased. However, the current study showed lateral translation to be more closely related to facet joints than to discs, because greater translation was seen when the facet joints were removed than when the discs were removed.

The lateral flexion angles were affected more strongly by the removal of discs than by the removal of facet joints at L2-3. Abumi et al. (1990), in an experiment using fresh human lumbar functional spinal units, found that bilateral total facetectomy leads to spinal instability in flexion, but not in lateral bending. The current results are in accordance with those of Abumi et al. in that the range of motion was not affected in lateral bending even after total facetectomy. Mimura et al. (1994) assessed the relationship between spinal instability and disc degeneration. They found the range of motion in lateral bending, which was the sum for the neutral and elastic zones, to decrease with increasing macroscopic and radiographic disc degeneration. The result explained the change in disc height with degeneration. In our experiment, the weight loaded onto the PF cable was attached to the specimen to avoid extreme flexion, which prevented loss of the disc height at the same time. Thus the range of lateral bending increased after discectomy.

There is controversy as to whether rotational torsion of the lumbar spine is resisted by the facet joints or the disc (Adams & Hutton, 1983; Gunzburg, Hutton, & Fraser, 1991). The facet joints prevent extreme rotation by the concave surface of the superior processes and the convex surface of the inferior processes. Gunzburg et al. indicated that the facet joint capsules are more important in resisting rotation in the neutral position than in flexion. In the current study, the rotational angle was very small when the specimen was intact, but the traction in the LAF direction increased the rotational angle more than that in the LPF direction at L3-4 and L4-5, a result which supports the study of Gunzburg et al. In the removal experiments, the rotational angle was affected by the excision of both discs and facet joints. A causal contribution to the rotational angle could not be assumed in the current study.

Some reports have described L5-S1 as being stiffer than other lumbar segments affected by posterior elements: facets, interspinous ligaments, and the ligamentum flavum (McGlashen, Miller, Schultz, & Andersson, 1987; Tsai et al., 2003). The specimens used in the current study were harvested with bilateral preservation of the iliolumbar ligaments. Yamamoto et al. (1990) used cadaveric specimens to demonstrate that the iliolumbar ligament restricts lateral bending and axial rotation at the L5-S1 joint. In our study, lateral translation and the rotational angle at L5-S were smaller than those of other intervertebral spaces. This result indicates that the iliolumbar ligament restricts not only lateral bending and the rotational angle but also lateral translation.

In conclusion, force in the anterolateral direction increased the lateral translation more than force in the posterolateral direction, and lateral translation was greater when the facet joints were removed than when the discs were removed at the levels of shear loading applied in this study.

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