In vivo 3D kinematic changes in the cervical spine after laminoplasty for cervical spondylotic myelopathy

Clinical article

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Object. Cervical laminoplasty is an effective procedure for decompressing the spinal cord at multiple levels, but restriction of neck motion is one of the well-known complications of the procedure. Although many authors have reported on cervical range of motion (ROM) after laminoplasty, they have focused mainly on 2D flexion and extension on lateral radiographs, not on 3D motion (including coupled motion) nor on precise intervertebral motion. The purpose of this study was to clarify the 3D kinematic changes in the cervical spine after laminoplasty performed to treat cervical spondylotic myelopathy.

Methods. Eleven consecutive patients (6 men and 5 women, mean age 68.1 years, age range 57–79 years) with cervical spondylotic myelopathy who had undergone laminoplasty were included in the study. All patients underwent 3D CT of the cervical spine in 5 positions (neutral, 45° head rotation left and right, maximum head flexion, and maximum head extension) using supporting devices. The scans were performed preoperatively and at 6 months after laminoplasty. Segmental ROM from Oc–C1 to C7–T1 was calculated both in flexion-extension and in rotation, using a voxel-based registration method.

Results. Mean C2–7 flexion-extension ROM, equivalent to cervical ROM in all previous studies, was 45.5° ± 7.1° preoperatively and 35.5° ± 8.2° postoperatively, which was a statistically significant 33% decrease. However, mean Oc–T1 flexion-extension ROM, which represented total cervical ROM, was 71.5° ± 8.3° preoperatively and 66.5° ± 8.3° postoperatively, an insignificant 7.0% decrease. In focusing on each motion segment, the authors observed a statistically significant 22.6% decrease in mean segmental ROM at the operated levels during flexion-extension and a statistically insignificant 10.2% decrease during rotation. The most significant decrease was observed at C2–3. Segmental ROM at C2–3 decreased 24.2% during flexion-extension and 21.8% during rotation. However, a statistically insignificant 37.2% increase was observed at the upper cervical spine (Oc–C2) during flexion-extension. The coupling pattern during rotation did not change significantly after laminoplasty.

Conclusions. In this first accurate documentation of 3D segmental kinematic changes after laminoplasty, Oc–T1 ROM, which represented total cervical ROM, did not change significantly during either flexion-extension or rotation by 6 months after laminoplasty despite a significant decrease in C2–7 flexion-extension ROM. This is thought to be partially because of a compensatory increase in segmental ROM at the upper cervical spine (Oc–C2).

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KEY WORDS • cervical laminoplasty • cervical spondylotic myelopathy • 3D kinematics • volume registration • head rotation

Cervical laminoplasty, a surgical alternative to laminectomy, is widely used to treat cervical spinal cord compression caused by cervical spondylosis or ossification of the posterior longitudinal ligament because it produces good long-term results.1,2,12,22,28 Although laminoplasty has advantages such as a lower incidence of postoperative cervical kyphosis and preservation of range of motion (ROM), many authors have reported a significant decrease in cervical ROM after laminoplasty despite the good postoperative neurological improvements experienced by their patients.1–6,11,12,15–18,20–22,25,26,28 However, they have investigated using only 2D flexion and extension on lateral radiographs. To our knowledge, there has been no report of 3D motion analysis about cervical laminoplasty, including coupled motion and precise intervertebral motion. Coupled motion is defined as combined motions that are mechanically forced to occur; it is difficult to measure it with conventional 2D methods.

For a better understanding of the precise pathophysiological change that occurs after laminoplasty, it is important to clarify the difference in precise kinematics before laminoplasty versus after it. We previously reported accurate in vivo 3D kinematics of the normal and degenerative
cervical spine using our own 3D motion-analysis method.\textsuperscript{7–9,19} In the study we report here, we sought to accurately document 3D kinematic changes in the cervical spine after laminoplasty for cervical spondylotic myelopathy.

**Methods**

Our study included 11 consecutive patients (6 men and 5 women, mean age 68.1 years, age range 57–79 years) with cervical spondylotic myelopathy who had undergone open-door laminoplasty that used a modification of the Ito\textsuperscript{10}–Tsuji\textsuperscript{27} technique. In most patients, decompression extended from C-3 to C-6 or C-7. A full-thickness trough was drilled on one side of the lamina with a small bur and a high-speed drill. On the contralateral side, a partial-thickness trough was drilled. The lamina was then elevated toward the partial-thickness trough. The resected spinous process was placed into the space made after laminoplasty of C-4 and C-6 to keep the space open (Fig. 1). Of the 11 patients, 7 had disease that involved C3–6 and 4 had disease that involved C3–7. Patients with ossification of the posterior longitudinal ligament, diffuse idiopathic skeletal hyperostosis, rheumatoid arthritis, and trauma were excluded from the study. The duration of the period for which study participants wore a cervical collar after surgery ranged from 0 to 2 weeks. The average pre- and postoperative modified Japanese Orthopaedic Association scores were 10.7 $\pm$ 1.7 and 13.2 $\pm$ 1.6, respectively. The Hirabayashi recovery rate was 38.7% $\pm$ 20.3%.\textsuperscript{3} All study protocols were approved by our institution’s review board.

**Acquisition of 3D CT Images**

Computed tomography scans were obtained for 5 positions for each patient using a commercial CT system (LightSpeed VCT, GE Healthcare) with the following parameters: slice thickness 0.625 mm, pixel size 0.352 mm, tube rotation speed 0.5 seconds, beam collimation 40 mm, tube pitch 0.9, tube current 50 mA, and voltage 120 kV. Patients were placed in the supine position on the scanning table and in a neutral position, with their trunk at maximum flexion and extension and 45° axial rotation to the left and right achievable without pain or discomfort (Fig. 2). A supportive device was used to keep the head in flexion and rotation. When scanning patients with their trunk in extension, we took special care not to reproduce their neurological symptoms. The scans were performed before surgery and at 6 months after surgery. To reduce radiation exposure, scans done in positions other than neutral were performed with a lower tube current: 15 mA for rotation and extension and 30 mA only for flexion. Total exposure was 90 dose–length products, which is less than that specified for routine CT by our hospital, and CT data were transferred via a DICOM network into a computer workstation, where image processing was performed using Virtual Place software (M series, Medical Imaging Laboratory).

**Motion Analysis**

The method we used for motion analysis is fully described in our previous reports.\textsuperscript{7–9,19} First, each vertebra was semi-automatically extracted using intensity threshold techniques. Second, the segmented images of the vertebrae in the neutral position were superimposed over images in other positions using voxel-based registration. As a result of this registration, the 3D migration of each vertebra was expressed by a matrix. Third, segmental motions from Oc–C1 to C7–T1 were calculated by converting the matrix obtained by the registration into a matrix representing relative motion with respect to the inferior adjacent vertebra both in flexion-extension and in rotation. Oc–T1 ROM (Oc motion relative to T-1, represented as total cervical ROM) and C2–7 ROM (C-2 motion relative to C-7, equivalent to a C2–7 angle measured on lateral radiographs) were also calculated. The results were expressed in 6 degrees of freedom by Euler angles, with the sequence of pitch (X), yaw (Y), and roll (Z), and in translations using a previously defined coordinate system\textsuperscript{7–9,19} (Fig. 3). The ROM for flexion-extension was calculated as the sum of the flexion (+RX) and extension (–RX) angles, and the ROM for rotation was calculated as the sum of the right (–RY) and left (+RY) rotation angles. Coupled motion (lateral bending; ± RZ) during rotation was also...
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Accuracy Validation

We performed in vitro validation of the accuracy of our experimental CT method for the cervical spine using fresh-frozen vertebrae. More than 8 tantalum beads with a radius of 1.0 mm were implanted in the vertebrae. Subsequently, CT scans were performed 8 times in different positions with the same imaging parameters. Each vertebra was then superimposed by voxel-based registration. The true value of the migration was measured by marker-based registration, providing gold-standard data, and accuracy was defined as the closeness to the true value. The root mean square distance for migration was 0.19° in flexion-extension, 0.13° in axial rotation, 0.21° in lateral bending, 0.13 mm in lateral translation, 0.15 mm in superoinferior translation, and 0.31 mm in anteroposterior translation.

Statistical Analysis

All statistical analyses were performed with Excel 2007 for Windows XP (Microsoft) with the add-in software Statcel 2 (OMS Publishing Ltd.). The data were analyzed using the nonparametric Mann-Whitney U-test where indicated. A probability value of p < 0.05 was considered statistically significant.

Results

Oc–T1 and C2–7 Angle

Mean Oc–T1 flexion-extension ROM was 71.5° ± 8.3° preoperatively and 66.5° ± 8.3° postoperatively (Table 1; Fig. 4). Mean C2–7 flexion-extension ROM was 45.8° ± 8.3° preoperatively and 35.3° ± 8.2° postoperatively. Although C2–7 ROM decreased significantly (p < 0.01), total cervical ROM did not change significantly after laminoplasty during flexion-extension. Mean Oc–T1 rotation ROM was 83.7° ± 5.2° preoperatively and 79.8° ± 6.0° postoperatively. Mean C2–7 rotation ROM was 15.1° ± 4.4° preoperatively and 12.6° ± 3.1° postoperatively. Neither Oc–T1 nor C2–7 rotation ROM changed significantly after laminoplasty during rotation.
TABLE 1: Segmental range of motion (°), means ± SD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oc–C1</th>
<th>C1–2</th>
<th>C2–3</th>
<th>C3–4</th>
<th>C4–5</th>
<th>C5–6</th>
<th>C6–7</th>
<th>C7–T1</th>
<th>Oc–T1</th>
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<td><strong>flexion-extension</strong></td>
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</tr>
<tr>
<td>preop</td>
<td>8.1 ± 8.9</td>
<td>7.1 ± 9.1</td>
<td>5.9 ± 9.8</td>
<td>6.4 ± 8.2</td>
<td>8.1 ± 8.8</td>
<td>9.3 ± 8.5</td>
<td>11.1 ± 7.9</td>
<td>12.5 ± 8.0</td>
<td>12.2 ± 7.6</td>
</tr>
<tr>
<td>postop</td>
<td>12.5 ± 8.9</td>
<td>10.8 ± 9.1</td>
<td>8.9 ± 9.8</td>
<td>9.4 ± 9.5</td>
<td>9.9 ± 9.4</td>
<td>8.8 ± 9.5</td>
<td>9.8 ± 9.5</td>
<td>10.7 ± 9.2</td>
<td>11.6 ± 9.0</td>
</tr>
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<td>rotation</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>preop</td>
<td>3.1 ± 2.0</td>
<td>4.2 ± 2.1</td>
<td>5.3 ± 2.4</td>
<td>4.3 ± 2.2</td>
<td>5.4 ± 2.4</td>
<td>4.5 ± 2.5</td>
<td>5.6 ± 2.6</td>
<td>5.7 ± 2.7</td>
<td>6.0 ± 2.8</td>
</tr>
<tr>
<td>postop</td>
<td>3.1 ± 1.4</td>
<td>4.2 ± 2.1</td>
<td>5.3 ± 2.4</td>
<td>4.3 ± 2.2</td>
<td>5.4 ± 2.4</td>
<td>4.5 ± 2.5</td>
<td>5.6 ± 2.6</td>
<td>5.7 ± 2.7</td>
<td>6.0 ± 2.8</td>
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<td>coupled motion</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>preop</td>
<td>−1.4 ± 0.8</td>
<td>−3.6 ± 2.4</td>
<td>−5.7 ± 3.5</td>
<td>−3.7 ± 3.4</td>
<td>−5.8 ± 3.5</td>
<td>−3.9 ± 3.4</td>
<td>−5.8 ± 3.5</td>
<td>−6.0 ± 3.6</td>
<td>−6.2 ± 3.7</td>
</tr>
<tr>
<td>postop</td>
<td>−1.3 ± 0.9</td>
<td>−3.6 ± 2.4</td>
<td>−5.7 ± 3.5</td>
<td>−3.7 ± 3.4</td>
<td>−5.8 ± 3.5</td>
<td>−3.9 ± 3.4</td>
<td>−5.8 ± 3.5</td>
<td>−6.0 ± 3.6</td>
<td>−6.2 ± 3.7</td>
</tr>
</tbody>
</table>

* p < 0.05.
** p < 0.01.

Segmental ROM During Flexion–Extension

Mean pre- and postoperative segmental ROM during flexion-extension were calculated (Table 1; Fig. 5). Segmental ROM decreased significantly at the proximal adjacent level (C2–3) and all operated levels (C3–6 laminoplasty, from C3–4 to C5–6; C3–7 laminoplasty, from C3–4 to C6–7) (p < 0.05, Table 2). In compensation, segmental ROM tended to increase at the upper cervical levels (Oc–C1 and C1–2) during flexion-extension and at C7–T1 during rotation, but these increases were not statistically significant (Table 2). No new abnormal slippage occurred after laminoplasty. However, preoperative abnormal slippage, which was observed at only 1 segment, could not be decreased by laminoplasty (Fig. 6).

Segmental ROM During Rotation

Main Motion. The mean values for pre- and postoperative segmental ROM of main axial rotation during rotation were calculated (Table 1; Fig. 7). Segmental ROM decreased significantly at C2–3 and did not change significantly at the operated levels or the distal adjacent level (Table 2). No significant laterality of main motion was observed.

Coupled Lateral Bending. The mean values for pre- and postoperative segmental ROM of coupled lateral bending during rotation were calculated (Table 1; Fig. 8). Coupled lateral bending during rotation was observed in the opposite direction at the upper cervical level and in the same direction at the subaxial spine, and this coupling pattern did not change after laminoplasty (Fig. 8). Although ROM showed no significant change after laminoplasty for any segment, only C2–3 segmental ROM had a strong tendency to decrease after laminoplasty (Table 2).

Discussion

Many researchers have reported that cervical ROM decreases significantly after laminoplasty.1–6,11,13,15–18,20–22,25,26,28 According to a representative review by Ratliff and Cooper20 of cervical laminoplasty, this decrease is an average of 50% (range 17%–80%). In one of the most recent reports, Hyun et al.5 described a 20% decrease of ROM at 6 months after laminoplasty. However, almost all of these studies assessed neither total cervical ROM nor segmental ROM but only partial cervical flexion-extension ROM (C2–7 angle), using lateral radiographs.1–6,11,13,15,16,18,21,22,26,28 That assessment method is useless when the C-7 vertebra is masked by shoulder girdle shadows. We obtained similar results in our study; we found that C2–7 ROM during flexion-extension decreased significantly by 23% after laminoplasty. Interestingly, however, we found little change in Oc–T1 ROM (total cervical ROM) because of a compensatory increase at the upper cervical spine (Oc–C2).

As for rotation ROM after laminoplasty, we found only 2 prior reports. Takeuchi et al.,25 in evaluating cervical rotation using digital photographs, reported that rotational motion is significantly larger in laminoplasty that preserves the semispinalis cervicis inserted into C-2 than in conventional laminoplasty. Sugimoto et al.,24 in evalu-
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ating cervical rotation using 2D CT, reported that C1–T1 rotation ROM had not changed by 6 months after laminoplasty. Similarly, we found that neither Oc–T1 nor C2–7 rotation ROM changed significantly within the same head rotation angle. However, unlike previous studies, which investigated the change in total cervical ROM, our study mainly focused on the change in segmental kinematics, including coupled motion, within the same 45° head rotation angle after laminoplasty.

As for segmental ROM after laminoplasty, only Baba et al.1 evaluated segmental ROM using flexion-extension lateral radiographs. They reported a significant decrease in ROM at all levels except C2–3 and C7–T1, based on values obtained at mean of 5.8 years after laminoplasty.1 However, their data were unreliable because it is impossible to quantify small segmental ROM accurately on functional radiographs. No study has investigated segmental ROM during rotation after laminoplasty. Our precise measurements showed that segmental ROM at the operated levels was reduced significantly during flexion-extension and did not change significantly during rotation. Segmental ROM at C2–3, which is the proximal adjacent segment, showed the most significant decrease during both flexion-extension and rotation. Segmental ROM at C2–3, as Iizuka et al.6 suggested, the lifted C-3 lamina appeared to collide with the inferior edge of the C-2 lamina during both extension and rotation (see Videos 1 and 2, which demonstrate the reduction of ROM both in flexion-extension and in rotation by the collision of lifted laminae).

Video 1. Video clip showing a 3D animation of the C2–3 segment during flexion-extension. The left side of the video shows preoperative status; the right half shows postoperative status. Copyright Yukitaka Nagamoto. Published with permission. Click here to view with Quicktime.

Video 2. Video clip showing a 3D animation of the C2–C3 segment during rotation. The left side of the video shows preoperative status; the right half shows postoperative status. Copyright Yukitaka Nagamoto. Published with permission. Click here to view with Quicktime.

We think that this is the mechanism by which the segmental ROM at C2–3 decreased omnidirectionally and that this is one of reasons C2–3 is the level most frequently involved in laminar fusion.6,22,28

No study has investigated coupled motion in the cervical spine after laminoplasty. Normal coupled lateral bending during rotation occurs in the opposite direction at the upper cervical level and in the same direction at the subaxial spine, and coupled motion is thought to be driven by the oblique orientation of the apophyseal joint.8,9 In our

<table>
<thead>
<tr>
<th>Level</th>
<th>Cervical Level</th>
<th>Flexion-Extension</th>
<th>Rotation: MM</th>
<th>Rotation: CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper</td>
<td>Oc–C2</td>
<td>37.2% (p = 0.146)</td>
<td>-13.0% (p = 0.370)</td>
<td>-1.4% (p = 0.999)</td>
</tr>
<tr>
<td>PA</td>
<td>C2–3</td>
<td>-24.2%* (p = 0.039)</td>
<td>-21.8%* (p = 0.028)</td>
<td>-16.2% (p = 0.082)</td>
</tr>
<tr>
<td>operated</td>
<td>C3–6 or C3–7</td>
<td>-22.6%* (p = 0.023)</td>
<td>-10.2% (p = 0.600)</td>
<td>-16.8% (p = 0.262)</td>
</tr>
<tr>
<td>DA</td>
<td>C6–7 or C7–T1</td>
<td>-8.4% (p = 0.674)</td>
<td>7.1% (p = 0.870)</td>
<td>-5.1% (p = 0.597)</td>
</tr>
</tbody>
</table>

* p < 0.05.
† CM = coupled motion; DA = distal adjacent level; MM = main motion; PA = proximal adjacent level; upper = upper cervical level.
study, we observed a normal coupled pattern both before and after surgery. This is because cervical laminoplasty can preserve the apophyseal joint, which drives coupled motion.

None of our study participants had abnormal slippage after surgery or deterioration of a preexisting slip as early as 6 months after laminoplasty despite early postoperative removal of cervical collars. Postoperative segmental ROM tended to be reduced more severely at the middle cervical levels (from C2–3 to C4–5) than at the lower cervical levels (from C5–6 to C7–T1) (Figs. 5, 7, and 8). Shigematsu et al. reported that 87% of cervical degenerative spondylolisthesis had stabilized after laminoplasty, and Kawasaki et al. reported that in 93% of cases, degenerative spondylolisthesis occurred at C3–4 or C4–5. Given our results, we believe that cervical laminoplasty preserves cervical ROM without harmful intervertebral instability and is a reasonable and beneficial procedure for the treatment of elderly patients with myelopathy who have degenerative spondylolisthesis of the middle cervical spine.

In our study, total cervical kinematics had not changed significantly during either flexion-extension or rotation by

![Fig. 6. Vertebral slippage during flexion-extension (horizontal axis, preoperative; vertical axis, postoperative). A positive value indicates anterior slippage, and a negative value indicates posterior slippage.](image1)

![Fig. 7. Preoperative and postoperative segmental range of motion for main axial rotation during rotation, Oc–C1 to C7–T1. *p < 0.05.](image2)
6 months after laminoplasty. Actually, no patient in our study reported loss of neck motion. In addition, we have never encountered any patients reporting disabling loss of neck motion after laminoplasty. This may be explained by early removal of cervical collars, postoperative neck exercises, and some surgical modifications in comparison with procedures performed from the late 1990s to the early years of the 21st century. Meanwhile, Hyun et al. reported that post-laminoplasty cervical ROM continues to decrease for up to 18 months after surgery. Therefore, a follow-up kinematic study of cervical laminoplasty over the long term will provide more conclusive results.

Conclusions

We produced the first accurate documentation of 3D segmental kinematic changes after laminoplasty. At 6 months after laminoplasty, C2–7 flexion-extension ROM, equivalent to cervical ROM in all previous studies, showed a statistically significant 33% decrease, a result similar to that of previous studies. In focusing on each motion segment, we found that the most significant decrease occurred at C2–3, both during flexion-extension and rotation. However, we observed a statistically insignificant 37.2% increase at the upper cervical spine (Oc–C2) during flexion-extension. Oc–T1 ROM, which represented total cervical ROM, showed an insignificant 7% decrease in flexion-extension and an insignificant 4% decrease in rotation despite the significant decrease in C2–7 flexion-extension ROM. This is thought to be partly because of a compensatory increase in segmental ROM at the upper cervical spine.

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Disclosure

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Author contributions to the study and manuscript preparation include the following. Conception and design: Nagamoto, Iwasaki. Acquisition of data: Nagamoto, Sugiura, Matsuo. Analysis and interpretation of data: Nagamoto, Fujimori. Drafting the article: Nagamoto. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Nagamoto. Statistical analysis: Nagamoto. Administrative/technical/material support: Iwasaki, Kashii, Murase, Yoshikawa, Sugamoto. Study supervision: Iwasaki, Yoshikawa, Sugamoto.

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