Degenerative lumbar scoliosis is defined as lateral lumbar curvature caused by asymmetrical disc space narrowing, olisthesis, and rotation of vertebrae resulting from degenerative changes of lumbar discs without evidence of previous scoliosis. The prevalence of degenerative lumbar scoliosis has been reported to be increasing with increasing life expectancy. The prevalence of lumbar scoliosis of at least 11° in individuals 40 years of age or older has been reported to be 8.9%. In addition, the prevalence of scoliosis has been shown to increase dramatically with age (3.1% in people 40–50 years of age, 22.5% in those 80 years and older). Patients with degenerative lumbar scoliosis sometimes suffer from neurogenic claudication and/or radicular pain because of neural compression resulting from...
Degenerative lumbar scoliosis

accompanying spondylolisthesis, rotatory olisthesis, and/or spinal canal stenosis. Lumbar fusion with instrumentation is an option for patients in whom these symptoms are refractory to conservative treatment. Pedicle screws are one of the most effective and preferred means of anchorage in posterior instrumentation, but malposition can cause loss of fixation strength and sometimes neural complications.²,¹³,¹⁷,¹⁸,²³ It is essential to acquire precise morphometric data on the lumbar pedicle for appropriate insertion of pedicle screws.

There have been several reports on the asymmetry of pedicle in adolescent idiopathic or symptomatic scoliosis.⁷,⁸,¹⁵,²¹ The morphometric differences between the pedicles on the concave and convex sides can result in an increased risk of malpositioned pedicle screws. Some authors have suggested that surgeons should give special attention to the insertion of pedicle screws on the concave side in idiopathic scoliosis.⁷,⁸,¹⁵,²¹ However, whether pedicle asymmetry also occurs in degenerative lumbar scoliosis has been unclear. The limited space available for lumbar pedicles or axial load imbalanced by asymmetrical disc space narrowing can cause asymmetrical remodeling changes of lumbar pedicles in patients with degenerative lumbar scoliosis. The purpose of this study was to investigate the asymmetry of the lumbar pedicle in degenerative scoliosis by radiographic assessment using CT with multiplanar reconstruction.

Methods

The study group comprised 16 consecutive patients (1 man and 15 women) with degenerative lumbar scoliosis and a Cobb angle of at least 30° who underwent lumbar surgery at our hospital between January 2009 and December 2011. All patients had undergone preoperative helical CT scans. None of the patients had a history of previous scoliosis, and all cases were classified as Aebi Type I (Table 1).¹⁹ The patients were between 63 and 81 years of age (mean age 70.9 ± 4.5 years) when the CT scans were performed. The patient characteristics are shown in Table 2. The Cobb angle was measured, and the Nash and Moe classification²⁶ was used to characterize the rotation of the apical vertebra from anteroposterior radiographs taken in the standing position for each patient. A LightSpeed Plus (GE Healthcare) was used for the CT scans (helical mode, slice thickness 1.25 mm, tube voltage 120 kVp, tube current 300 mA, window level 300 HU, and window width 2000 HU).

Measurement of Morphometric Parameters

The CT scan data, in DICOM standard format, were imported into a 3D image reconstruction software package (ExaVision Lite, Ziosoft Inc.). The first author (T.M.) measured the morphometric parameters (described below) in the lumbar spine between the end vertebrae (a total of 124 pedicles; L-1, 26 pedicles in 13 patients; L-2, 32 pedicles in 16 patients; L-3, 32 pedicles in 16 patients; L-4, 28 pedicles in 14 patients; L-5, 6 pedicles in 3 patients) once on the 2 different planes described below. The linear and angular precisions of the measurements using the software were 0.01 mm and 0.01°, respectively. We defined the pedicle axis as the line bisecting the pedicle isthmus on both the axial and sagittal planes.⁶,²⁴

**Axial Plane.** The axial plane was defined as the plane parallel to the cranial endplate of the vertebral body or the line connecting the cranial edges of both sides of the pedicles if wedge deformity of the vertebral body existed. The following parameters were measured on the axial plane: 1) transverse pedicle width (Fig. 1, left), defined as the minimum inner cortical distance (inner cortical transverse pedicle width [TPWi]) and outer cortical distance (outer cortical transverse pedicle width [TPWo]) perpendicular to the pedicle axis on the axial plane; 2) the cortical thickness of the pedicle on the axial plane (CT[TPWo]), calculated as TPWo – TPWi; 3) the cortical ratio of the pedicle on the axial plane (CR[TPWo]), calculated as CT[TPWo]/TPWo; 4) the axial angle (Fig. 1, left)—the angle made by a line of the pedicle axis and the sagittal midline of the vertebral body.

**Plane Perpendicular to the Pedicle Axis.** The second plane of measurement was the oblique coronal plane that is perpendicular to the pedicle axis (Fig. 2). The following parameters were measured on this plane: 1) minimum pedicle diameter (Fig. 1, right), the maximum diameter of the circle whose center is on the pedicle axis and whose perimeter does not extend beyond the outer cortex of the pedicle through the planes perpendicular to the pedicle axis (inner cortical minimum pedicle diameter [MPDi]) and the maximum diameter of the circle whose center is on the pedicle axis and whose perimeter does not extend beyond the outer cortex of the pedicle (outer cortical minimum pedicle diameter [MPDo]); 2) cortical thickness of the pedicle on the plane perpendicular to the pedicle axis (CT[MPDo]), calculated as MPDo – MPDi; 3) cortical ratio of the pedicle on the plane perpendicular to the pedicle axis

<table>
<thead>
<tr>
<th>TABLE 1: Aebi adult deformity classification*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>II</td>
</tr>
<tr>
<td>IIIa</td>
</tr>
<tr>
<td>IIIb</td>
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</tbody>
</table>

* Based on Smith et al.¹⁹
(CR<sub>MPD</sub>), calculated as CT<sub>MPD</sub>/MPDo; 4) cephalocaudal inclination (Fig. 1, right), the angle made by the major axis of the pedicle section on the plane perpendicular to the pedicle axis and the line perpendicular to the upper vertebral endplate.

**Postoperative Evaluation of Pedicle Screw Diameter and Placement**

To analyze the difference in the inserted pedicle screw diameters and the accuracy of the placement between the convex and concave sides, the diameter of inserted pedicle screws was investigated from the operation records, and the accuracy of the pedicle screw placement was analyzed on postoperative multiplanar reconstructions of CT scans in 11 patients who underwent lumbar operation with pedicle screws inside the curves (a total of 74 pedicle screws in 37 vertebrae). The postoperative CT scans were performed with the same equipment and settings as the preoperative scans. We defined accurate pedicle screw insertion as placement of a screw completely within the pedicle.

**Statistical Analysis**

The Wilcoxon signed-rank test was used to compare parameters of the concave and convex sides. Results were considered statistically significant at p < 0.05. Intraobserver and interobserver ICCs in TPWi, TPWo, axial angle, MPDi, MPDo, and cephalocaudal inclination were calculated in 30 pedicles of 4 patients. For the analysis of intraobserver ICC, the first author (T.M.) measured these parameters twice with a 1-week interval. For the analysis of interobserver ICC, 2 authors (T.M. and H.F.) measured these parameters. Statistical analysis was performed using StatView Version 5.0 (SAS Institute Inc.) for all statistics except ICC. Intraclass correlation coefficient analysis was performed using R version 2.8.1 (The R Foundation for Statistical Computing).

**Results**

**Measurement of Morphometric Parameters**

The data measured on the axial plane are shown in Table 3, and the data on the plane perpendicular to the pedicle axis are shown in Table 4. Among the target vertebrae, the values of TPWi, MPDi, and MPDo were significantly smaller on the concave side than on the convex side (TPWi and MPDi, p < 0.01; MPDo, p < 0.05). At L-3, the MPDi values were significantly smaller on the concave side than on the convex side (p < 0.01); in 5 of 16 vertebrae the MPDi was more than 1.5 mm smaller on the concave side than on the convex side (Fig. 3). At L-4, the values for TPWi, TPWo,
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MPDi, and MPDo were all significantly smaller on the concave side than on the convex side (TPWi, TPWo, and MPDi, \( p < 0.05 \); MPDo, \( p < 0.01 \)); in 5 of 14 vertebrae, the TPWi was more than 1.5 mm smaller on the concave side than on the convex side; in 3 of 14 vertebrae, the TPWo was more than 1.5 mm smaller on the concave side than on the convex side (Fig. 4); in 7 of 14 vertebrae, the MPDi was more than 1.5 mm smaller on the concave side than on the convex side; and in 4 of 14 vertebrae, the MPDo was more than 1.5 mm smaller on the concave side than on the convex side (Fig. 3).

Among the target vertebrae, neither the CT TPW nor the CT MPD values differed between the concave and convex sides, but both the CRTPW and the CRMPD were significantly larger on the concave side than on the convex side (CRTPW, \( p < 0.05 \); CRMPD, \( p < 0.01 \)). At L-3, the CRMPD was significantly larger on the concave side than on the convex side (\( p < 0.01 \)). At L-4, both the CRTPW and the CRMPD were significantly larger (\( p < 0.05 \)) on the concave side than on the convex side.

The axial angle was significantly larger on the concave side than on the convex side among the target vertebrae (\( p < 0.01 \)) and at L-2 and L-3 respectively (\( p < 0.05 \)). The cephalocaudal inclination did not differ between the concave and convex sides among the target vertebrae at each level.

The ICC for TPWi was 0.985 (95% CI 0.968–0.993) in the intraobserver measurements and 0.962 (95% CI 0.919–0.982) in the interobserver measurements. TPWo, 0.984 (95% CI 0.966–0.992) and 0.960 (95% CI 0.918–0.981); axial angle, 0.786 (95% CI 0.600–0.891) and 0.689 (95% CI 0.433–0.840); MPDi, 0.943 (95% CI 0.884–0.972) and 0.912 (95% CI 0.825–0.957); MPDo, 0.957 (95% CI 0.912–0.979) and 0.948 (95% CI 0.894–0.975); cephalocaudal inclination, 0.978 (95% CI 0.955–0.990) and 0.856 (0.715–0.930).

**Postoperative Evaluation of Pedicle Screw Diameter and Placement**

In 5 (13.5%) of 37 vertebrae, pedicle screws of different diameters were used on the concave and convex sides.

<table>
<thead>
<tr>
<th>Parameter &amp; Side</th>
<th>L-1</th>
<th>L-2</th>
<th>L-3</th>
<th>L-4</th>
<th>L-5</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td><strong>TPWi (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>concave</td>
<td>4.91 ± 1.59</td>
<td>5.14 ± 1.77</td>
<td>6.37 ± 1.98</td>
<td>7.71 ± 1.76†</td>
<td>13.01 ± 1.58</td>
<td>6.37 ± 2.56‡</td>
</tr>
<tr>
<td>convex</td>
<td>4.91 ± 1.06</td>
<td>5.09 ± 1.59</td>
<td>6.72 ± 1.55</td>
<td>8.60 ± 1.68</td>
<td>14.08 ± 1.55</td>
<td>6.70 ± 2.66</td>
</tr>
<tr>
<td><strong>TPWo (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>concave</td>
<td>6.94 ± 1.84</td>
<td>7.62 ± 1.70</td>
<td>8.59 ± 1.94</td>
<td>10.20 ± 1.91†</td>
<td>15.83 ± 1.17</td>
<td>8.71 ± 2.69</td>
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<tr>
<td>convex</td>
<td>6.99 ± 1.39</td>
<td>7.33 ± 1.62</td>
<td>8.88 ± 1.46</td>
<td>10.70 ± 1.82</td>
<td>17.00 ± 1.29</td>
<td>8.89 ± 2.79</td>
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<tr>
<td><strong>CTTPW (mm)</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>concave</td>
<td>2.03 ± 0.42</td>
<td>2.48 ± 0.55</td>
<td>2.22 ± 0.54</td>
<td>2.49 ± 0.67</td>
<td>2.82 ± 0.48</td>
<td>2.34 ± 0.59</td>
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<tr>
<td>convex</td>
<td>2.08 ± 0.47</td>
<td>2.25 ± 0.46</td>
<td>2.16 ± 0.38</td>
<td>2.11 ± 0.55</td>
<td>2.92 ± 0.27</td>
<td>2.19 ± 0.49</td>
</tr>
<tr>
<td><strong>CRTPW</strong></td>
<td></td>
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<tr>
<td>concave</td>
<td>0.30 ± 0.05</td>
<td>0.34 ± 0.11</td>
<td>0.27 ± 0.09</td>
<td>0.25 ± 0.06†</td>
<td>0.18 ± 0.04</td>
<td>0.29 ± 0.09†</td>
</tr>
<tr>
<td>convex</td>
<td>0.30 ± 0.04</td>
<td>0.32 ± 0.07</td>
<td>0.25 ± 0.06</td>
<td>0.20 ± 0.05</td>
<td>0.17 ± 0.03</td>
<td>0.26 ± 0.08</td>
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<tr>
<td>axial angle (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>concave</td>
<td>8.60 ± 2.52</td>
<td>10.10 ± 3.67†</td>
<td>12.54 ± 4.00†</td>
<td>13.52 ± 4.31</td>
<td>22.51 ± 5.37</td>
<td>11.79 ± 4.88‡</td>
</tr>
<tr>
<td>convex</td>
<td>8.75 ± 3.29</td>
<td>8.35 ± 3.48</td>
<td>10.47 ± 2.38</td>
<td>12.66 ± 4.46</td>
<td>20.79 ± 4.83</td>
<td>10.56 ± 4.52‡</td>
</tr>
</tbody>
</table>

* Values are expressed as the means ± standard deviations.
† \( p < 0.05 \) versus convex side.
‡ \( p < 0.01 \) versus convex side.
In all 5 vertebrae, the smaller diameter was used on the concave side.

Five (6.8%) of the 74 pedicle screws were judged as malpositioned on postoperative CT scans. Four of these 5 screws were on the concave side.

**Discussion**

The findings of this study revealed that, in degenerative lumbar scoliosis, both the inner and outer cortical minimum pedicle diameters were significantly smaller on the concave side than on the convex side. Furthermore, the axial angle and cortical ratio of the pedicle on both the axial plane and the plane perpendicular to the pedicle axis were significantly larger on the concave side than on the convex side. These asymmetrical changes were most evident at L-4, which was not always the apex of the scoliotic curve.

Recently, advancements in imaging techniques have made it possible to reconstruct images on specific planes and measure parameters on those planes. Even when 3D rotation or deformity of a vertebral body exists in scoliotic spines, multiplanar reconstruction enables measurement of the pedicle morphometrics precisely with good intra- and interobserver reliability. Our study also revealed good to excellent intra- and interobserver reliability by ICC analysis. Li et al. proposed a new measurement method for pedicle diameters that uses the reconstructed plane that is entirely vertical to the pedicle axis, and they insisted that this plane is more appropriate for measuring the narrowest diameter of the lumbar pedicle than the axial plane that is used in conventional measurement methods. Therefore, we included the same method for measuring the minimum pedicle diameter.

There have been several reports on the use of multiplanar reconstruction for measuring asymmetries of the vertebral bodies and pedicles in patients with adolescent idiopathic scoliosis. Liljenqvist et al. used multiplanar reconstruction of MRI to analyze the vertebral morphometrics in idiopathic scoliosis with a thoracic major curve (Type 2, 3, or 4 by the King classification) (average patient age 15.4 years; average Cobb angle of the thoracic spine 66°; average Cobb angle of the lumbar spine 46°). They reported that at the apical region of the thoracic curve, the transverse pedicle width was smaller on the concave side than on the convex side, and this asymmetry diminished approaching the neutral vertebra. They found no significant difference in the transverse pedicle width between the concave and convex sides in the lumbar curve. Takeshita et al. used multiplanar re-
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construction of CT scans to analyze the vertebral morphometrics in idiopathic or symptomatic scoliosis (average patient age 17.4 years; average Cobb angle of the major curve 65.7°). Although one-quarter of the patients (11 of 41) had a major curve in the lumbar spine, there was no significant difference in the transverse pedicle width of the lumbar spine between the concave and convex sides.21 The reason why asymmetry of the pedicle morphometry is apparent only in the thoracic spine in adolescent idiopathic scoliosis is unclear. In contrast, for degenerative lumbar spinal conditions such as lumbar disc herniation, lumbar spinal canal stenosis, or lumbar spondylolisthesis, no significant difference in the transverse pedicle width between the left and right sides has been reported.15 However, to the best of our knowledge, there has been no report on an investigation of lumbar pedicle morphology in patients with degenerative lumbar scoliosis. Thus, this is the first report to demonstrate the asymmetry of pedicles in diameters and angles in that condition.

We speculated that there could be several reasons for asymmetrical changes of lumbar pedicles in degenerative lumbar scoliosis. First, when there is severe progression of the wedging deformity of the intervertebral space, the pedicles on the concave side can be in contact with the caudal endplate of the adjacent lower vertebra in the sagittal plane (left, arrow) and the superior articular process of the adjacent lower vertebra in the sagittal plane (right, arrow) become closer to the pedicle on the concave side. Therefore, when there is a difference in the diameter of the concave-side and convex-side pedicles. As to the axial angle, which is an index for the axial direction of pedicle screw, our study revealed that the axial angle was larger on the concave side than on the convex side. In addition, in patients with scoliosis, vertebral rotation requires surgeons to consider these differences when inserting pedicle screws for the treatment of degenerative lumbar scoliosis, to prevent pedicle screw misplacement, especially on the concave side.

Limitations of this study include the fact that our differentiation of degenerative lumbar scoliosis from the progression of previous scoliosis, such as adolescent idiopathic scoliosis, depended on patients’ awareness of lumbar deformity in their childhood. However, almost all of our patients met the criteria of degenerative lumbar scoliosis of Grade 2 or less according to the Nash-Moe classification, or with curves having an apex at L2–3 or L3–4.1 Even if some of our patients had progression of previous scoliosis without being aware that they had the condition, we think the effect of degenerative changes on pedicles overcomes that of previous scoliosis because it has been reported that asymmetry of the pedicle morphometry is not apparent in the lumbar spine in adolescent idiopathic scoliosis.

In scoliotic spines, plain radiographs do not show the pedicles clearly because of the vertebral rotation, and so CT scans should be performed to evaluate the pedicle morphology for accurate pedicle screw insertion. The measurement of transverse pedicle diameter is a conventional index for the choice of screw diameter, but recent research indicates that significant differences exist between the transverse pedicle width and the minimum pedicle diameter, and the minimum pedicle diameter is an optimal index for the choice of pedicle screw diameter.6 Our study revealed that the minimum pedicle diameter was significantly smaller on the concave side than on the convex side; 31% of the L-3 vertebrae and 50% of the L-4 vertebrae studied had a difference in MPDi of more than 1.5 mm between the concave and convex side. This difference is critical for the selection of optimal pedicle screw diameter. In 13.5% of vertebrae in this study, there was a difference in the diameter of the concave-side and convex-side pedicle screws. As to the axial angle, which is an index for the axial direction of pedicle screw, our study revealed that the axial angle was larger on the concave side than on the convex side. Therefore, the trigger of degenerative lumbar scoliosis at L4–5.22 Therefore, the pedicle at L-4 can suffer from this unbalanced load from the early stage of degenerative lumbar scoliosis. This can account for the asymmetrical changes of the pedicles that were most evident at L-4 compared with the other levels. Third, the duration of the exposure to a scoliotic deformity is usually longer than that encountered in adolescent idiopathic scoliosis. This can explain why the asymmetry of the lumbar pedicle is evident in patients with degenerative lumbar scoliosis but not in patients with adolescent idiopathic scoliosis.
scoliosis. The degenerative asymmetrical changes in lumbar pedicles may be apparent earlier in patients with previous scoliosis than in those without it.

Conclusions

In this study, we used multiplanar reconstruction of CT scans to analyze pedicle morphology in degenerative lumbar scoliosis. Although the TPWd did not differ between the concave and convex sides, the TPWI and inner and outer minimum pedicle diameters (MPDi and MPDo) were smaller and the axial angle was larger on the concave side than on the convex side. This is the first report to describe the asymmetry of the lumbar pedicle in degenerative lumbar scoliosis using multiplanar reconstructed CT. Surgeons should keep these differences in mind and carefully determine the screw size and direction when inserting pedicle screws on the concave side.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Makino. Acquisition of data: Makino, Kaito, Fujiwara. Analysis and interpretation of data: Makino, Kaito. Drafting the article: Makino. 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: Makino. Statistical analysis: Makino. Study supervision: Yonenobu.

References