Facet joint opening in lumbar degenerative diseases indicating segmental instability

Clinical article

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Object. The objective of this study was, using a novel intraoperative measurement (IOM) system, to test the hypothesis that an increased facet joint volume is evidence of spinal instability.

Methods. In 29 patients (male/female ratio 13:16; mean age 67.5 years, range 43–80 years)—17 with degenerative spondylolisthesis (DS) of the lumbar spine (Group DS) and 12 with canal stenosis (CS) of the lumbar spine (Group CS)—DICOM (Digital Imaging and Communications in Medicine) data derived from CT scans were transferred to a workstation. A 3D model of facet joint spaces was reconstructed and the average volume of the bilateral facets was calculated. Segmental properties—stiffness, absorption energy (AE), and neutral zone (NZ)—were measured using an IOM system, and values were compared between groups. Linear regression analyses were performed among biomechanical parameters and average volumes.

Results. Stiffness and AE did not differ significantly between groups. The NZ was significantly greater in Group DS than in Group CS (p < 0.05) and significantly positively correlated with the average volume ($R^2 = 0.141, p < 0.05$). Stiffness tended to negatively correlate with average volume. Absorption energy did not correlate with average volume.

Conclusions. Biomechanical analyses using the IOM system verified that an increased facet joint volume is evidence of spinal instability, represented by NZ, in the degenerative lumbar spine.

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Key Words • facet joint opening • intraoperative biomechanical analysis • lumbar degenerative diseases • segmental instability

SEGMENTAL instability of the lumbar spine is a widely accepted biomechanical concept. The definition of instability in the clinical setting, however, is controversial. The decision to perform a spinal fusion requires evidence of segmental instability. Although radiographic evaluation of degenerative lumbar spines is extensively performed, its usefulness for the diagnosis of segmental instability remains controversial because of the large range of normal motion and the significant overlap of underlying pathological conditions.

The concept of “facet opening” on axial views of T2-weighted MR images was recently proposed to indicate segmental instability. The presence of large, fluid-filled facet joints indicates the likelihood of positional translation in patients with spinal stenosis and spondylolisthesis. A relationship between facet joint findings on MR imaging and the biomechanical properties of the spine, however, has yet to be verified. Since 1997, we have been working to develop an IOM system to evaluate segmental properties with all ligamentous structures intact. In preliminary basic and clinical studies, we confirmed that the system safely and reliably provides measurements of multiple parameters based on continuous load-deformation data obtained during surgery. We also investigated the segmental properties of degenerative spondylolisthesis by using the IOM system and demonstrated that segments with spondylolisthesis were characterized by lower flexion stiffness and a higher NZ compared with normal segments.

The objective of this study was to use the novel IOM system to test the hypothesis that an increased facet joint volume is evidence of spinal instability.
**Methods**

The IOM system comprises spinous process holders (Gi-5, Mizuhoikakikai), a motion generator (RC-RSW-L-50-S, IAI Corp.), and a personal computer. The 2 holders firmly grip adjacent spinous processes. A cyclic displacement in a single direction at a speed of 2.0 mm/second is generated to the tips of the holders with a maximum displacement of 15.0 mm from the neutral position. Neutral position is defined as the position in which no load is recorded between the tips of the holders. Load at the tip of the caudal spinous process holders is measured using a load cell (LUR-A-200NSAI, Kyowadengyo Corp.) and displacement is measured using an optical displacement transducer (LB-080, Keyence). Real-time load-displacement data are obtained via a personal computer. The spinous process holder is connected to the motion generator through a multidirectional ball joint, producing flexion and extension of the segment (Fig. 1). The range of motion induced by 15-mm craniocaudal displacements of the spinous processes is equivalent to approximately 9° of segmental flexion-extension. No adverse effects occur following this compelling motion.13

The patient was placed in the prone position on a Hall's frame, and the paraspinal muscles were detached from the spinous processes in a standard fashion. Two spinous process holders were attached to the adjacent spinous processes. All ligamentous structures of the functional spinal unit, including the supra- and interspinous ligaments and facet joints, were kept intact. The motion generator attached to the tips of the holders loaded the segment, producing 5 flexion-extension segmental motion cycles, and real-time load-displacement data were obtained with a sampling rate of 5 Hz. Data of the third cycle were used for biomechanical analysis. We defined 3 motion parameters using the load-displacement data: stiff-

![Diagram](image.png)

**Fig. 1.** This novel new IOM system comprises spinous process holders, a motion generator, an optical displacement transducer, and a personal computer.
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TABLE 1: Characteristics of patients with lumbar degenerative spondylolisthesis (Group DS) and lumbar canal stenosis (Group CS)*

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean Age (yrs)</th>
<th>M/F Ratio</th>
<th>L3–4</th>
<th>L4–5</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS</td>
<td>71.6 ± 5.8†</td>
<td>6:11</td>
<td>5</td>
<td>12</td>
<td>2</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>CS</td>
<td>61.7 ± 11.4</td>
<td>7.5</td>
<td>7</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

* Mean values are presented ± SDs.
† p < 0.05, Wilcoxon rank-sum test.

Stiffness, NZ, and AE. Stiffness was defined as the slope of the line fitting the load-displacement curve from −15 mm to −10 mm on flexion. Neutral zone was defined as the reciprocal of the load necessary to displace the 2 tips of the holders from a distance of −5 mm (flexion) to 5 mm (extension). All the lines used for measuring stiffness and NZ were calculated using the least-squares method. The AE was defined as the area of a hysteresis loop (Fig. 1).

Twenty-nine patients (13 men and 16 women) with degenerative lumbar diseases (17 with DS [Group DS] and 12 with CS [Group CS]) were included in this study (Table 1). Group DS included more degenerated discs than Group CS, although it was not statistically tested because of the small sample size. Biomechanical evaluation was performed at all levels using the IOM system. Informed consent for this study was obtained from all patients following the approval of the Committee of Medical Ethics of Niigata University (approval No. 182, 2003).

Lateral radiographs were obtained under the following conditions: lines between bilateral acromion processes and iliac crests were perpendicular radiographs with a 2.5-m distance between the x-ray generator and the film, and the voltage and electric current of the x-ray generator were 110 kV and 140 mA, respectively. Range of motion was determined using the Dupuis procedure. Disc height was calculated as the mean anterior and posterior disc height divided by the anteroposterior width of the upper vertebra. We obtained 1.5-T MR images in all patients. Using the Thompson classification, disc degeneration was graded on midsagittal T2-weighted fast spin echo images (TR 5000 msec, TE 130 msec). The 29 discs were classified as follows: Grade III (inhomogeneous gray nucleus with unclear distinction of nucleus and anulus), 10 discs; Grade IV (inhomogeneous gray to black nucleus without distinction of nucleus and anulus), 18 discs; and Grade V (black nucleus with collapsed disc space), 1 disc. Computed tomography was performed after MR imagi-
ing to identify bone structure. Computed tomography (an axial 2.5-mm thin-slice scan) data in DICOM format were transferred to a Windows-based computer workstation running MIMICS 9.11 (Materialise). The MIMICS software converted the DICOM data into 2D axial images in which the facet joint space was separated from the osseous margin. These 2D images were stacked to create a 3D reconstructed model. The volume of the facet joint space was calculated from the 3D reconstructed model in the bilateral facets in all patients.

The value of each biomechanical parameter and average volume of the bilateral facet joint spaces were compared between Group DS and Group CS using a non-parametric Wilcoxon rank-sum test. Linear regression analyses were performed to identify relationships among biomechanical parameters (stiffness, NZ, and AE) and the average volume of the bilateral facet joint spaces. The JMP software package (ver.5.0.1a, SAS Institute) was used for all statistical analyses. A p < 0.05 was considered to indicate statistical significance.

Results

There were no complications related to the measurement procedure. The spinous process holders were stable even after the 5 cycles of loading in all cases. We routinely performed intraoperative functional spinal cord monitoring to prevent IOM-related adverse effects to nerves. Functional spinal cord monitoring allows multichannel measurement including compound muscle action potentials of quadriceps, tibialis anterior, extensor hallucis longus, flexor hallucis longus, and perianal muscles; we are alerted promptly if there is new nerve impairment. There was no significant change of compound muscle action potentials during the measurement in any case. The symptoms in all patients, even those with severe nerve compression due to stenosis, did not deteriorate and a new lesion such as disc hernia did not develop.

There was no significant difference between Group DS and Group CS in stiffness or AE. The NZ in Group DS was, however, significantly higher than that of Group CS (p < 0.05, Table 2). Although average volume of the joint spaces did not correlate with AE, it tended to negatively correlate with stiffness and to significantly positively correlate with NZ (Fig. 2).

Variation of grade of the disc generation may affect the biomechanical analyses. Therefore, a subgroup analysis of Grade IV disc degeneration, in which the largest numbers of the discs were included, was performed. Although there were no significant difference between Group DS and Group CS in stiffness and AE, NZ in Group DS was significantly higher than that in Group CS (Table 2, Fig. 3). This suggests that even though the grade of disc degeneration is identical, segmental instability may be different due to the difference of the facet degeneration.

In a previous study, we investigated the relationship between NZ and stiffness in the patients with spondylolisthesis and normal discs. The results showed that NZs of the segments with spondylolisthesis were mostly ≥ 2 mm/N and those of normal disc were all > 2 mm/N. Therefore, we determined the surgical procedure intraoperatively using the biomechanical data as follows: if the NZ of the segment is < 2 mm/N, the segment was considered to be stable and decompression alone was scheduled; if the NZ was ≥ 2 mm/N, the segment was considered unstable and decompression and dynamic stabilization or TLIF were indicated. In case of simple olisthesis without laterality of the facet osteoarthrosis with cauda equina symptom, dynamic stabilization was added, and in cases with laterality of the facet osteoarthrosis, scoliosis, or lateral listhesis with radiculopathy, TLIF through the symptomatic site was indicated. Following this algorithm, decompression alone was performed in 17 patients, decompression with dynamic stabilization in 6 patients, and TLIF in 6 at the pathological levels in the present study. All the patients were followed more than 2 years and the results were satisfactory.

Illustrative Case

This 76-year-old woman with L-4 degenerative spondylolisthesis presented with neurogenic intermittent claudication and cauda equina syndrome. Flexion-extension radiography showed spondylolisthesis and an intradiscal vacuum phenomenon on extension (Fig. 4A). Magnetic

![Table 3: Summary of the biomechanical parameters in reference to diagnosis in the patients with Grade IV disc degeneration*](chart)

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Group (no. of patients)</th>
<th>DS (14)</th>
<th>CS (4)</th>
</tr>
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<tbody>
<tr>
<td>stiffess (N/mm)</td>
<td>0.58 ± 0.37</td>
<td>0.78 ± 0.51</td>
<td></td>
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<tr>
<td>NZ (mm/N)</td>
<td>3.12 ± 1.29†</td>
<td>1.74 ± 0.41</td>
<td></td>
</tr>
<tr>
<td>AE (J)</td>
<td>0.23 ± 0.06</td>
<td>0.29 ± 0.10</td>
<td></td>
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</table>

* Values are presented as means ± SDs.
† p < 0.05, Wilcoxon rank-sum test.

![Graph comparing NZ between Group DS and CS in the patients with Grade IV disc degeneration.](chart)
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resonance imaging demonstrated a central-type canal stenosis at the olisthetic segment (Fig. 4B). A CT myelogram at L4–5 showed canal stenosis and facet opening on the right side, with an anisotropic change of the facets. The facet joint spaces were reconstructed using MIMICS software, and calculated volumes were 344.4 mm³ in the left facet and 656.2 mm³ in the right (average 500.3 mm³) (Fig. 4C). The IOM was performed at the L4–5 segment and biomechanical data were as follows: stiffness 0.27 N/mm; NZ 2.87 mm/N; and AE 0.16 J. The hysteresis loop of the load-deformation data were notably flattened (Fig. 4D).

Discussion

The facet joint is a crucial component of lumbar spine stability. The facet joints prevent excessive movement from damaging the discs: the posterior anulus is protected during torsion by the facet surfaces and during flexion by the capsular ligaments. The compliance of the joint for torsion in a normal segment, however, is quite low. The physiological range of rotational motion is approximately 10° for the entire lumbar spine, or approximately 1° to each side for each joint. Joint failure can occur after approximately 1–3° of torsion and irreversible damage to the joints will occur when torsion exceeds 3°. Therefore, abnormal findings of facet joints in radiological evaluation contribute to a diagnosis of segmental instability.

Recent MR imaging studies of degenerative lumbar spine have demonstrated that the presence of a large fluid-filled joint—a high signal change on T2-weighted axial images, especially in the upright position—is related to the segmental instability. Rihn et al. reported a close linear association between the facet fluid index (the ratio of the sum of the width of the fluid in each facet to the sum of the width of each facet) and the amount of radiographic instability (percentage of anterior slippage) at L4–5. Furthermore, Chaput et al. investigated MR imaging and standing lateral flexion-extension radiography studies ob-
retained in 54 patients with degenerative spondylolisthesis and compared these studies with those acquired in 139 patients without degenerative spondylolisthesis. They concluded that large (>1.5-mm) facet effusions are highly predictive of degenerative spondylolisthesis at L4–5 in the absence of measurable anterolisthesis on supine MR images. Nonetheless, the biomechanical significance of “facet opening” remains unclear because a relationship between the MR imaging findings and the biomechanical properties of the segment has not been demonstrated.

In the present study, we investigated the direct relationship between facet opening, the volume of the facet joint space, and the biomechanical properties. Using the IOM system, which is the first clinically available method that allows for measurement of multiple parameters based on continuous load-deformation data during surgery with all ligamentous structures intact,12,13 we found that the NZ, the most sensitive available biomechanical parameter,18,19 in Group DS was significantly higher than that in Group CS (Table 2) and that the NZ in the degenerative segment positively correlated with facet volume (Fig. 2). There was a direct positive relationship between the volume of the facet joint space and segmental instability. Furthermore, a subgroup analysis of Grade IV disc degeneration to eliminate the effect disc degeneration showed that the NZ in Group DS was significantly higher than that in Group CS (Fig. 3), suggesting that even though the disc degeneration grade is identical, segmental instability due to the facet degeneration may differ. Therefore, the radiological findings of facet joint degeneration (for example, facet opening) are more important than disc degeneration in terms of segmental instability. The physician should routinely pay attention to the condition of the facet joints, which can be evaluated using axial MR imaging or helical CT scanning (Fig. 4).

Fujiwara et al.10 investigated the relationship between the grade of degeneration (disc and facet joint) and segmental motion, reporting that segmental motion increased with increasing severity of disc degeneration up to Grade IV, but that it decreased in both sexes when disc degeneration advanced to Grade V. Axial rotational motion increased with cartilage degeneration of the facet joints, suggesting that cartilage degeneration, especially thinning of the cartilage, may cause capsular ligament laxity, allowing for abnormal motion or hypermobility of the facet joint. We detected no relationship between MR imaging grade and facet volume, likely due to the limited number of patients with Grade V disc degeneration in the present study. In patients with MR imaging Grade III or IV discs (Fig. 4), there is generally facet opening together with a relatively high NZ. Interestingly, age also significantly positively correlated with NZ ($R^2 = 0.148$, $p < 0.05$). A normal facet joint space is fairly narrow with a thick articular cartilage and a tight capsule. The biomechanical results of the present study are compatible with the hypothetical pathology of the aging spine, such that tears gradually accumulate in the articular cartilage and joint capsule resulting in loosening of the joint that can be verified on MR or CT imaging as an opening facet, in association with loosening of the segment that should be demonstrated by biomechanical analyses.

**Conclusions**

Biomechanical analyses using the IOM system verified that an increased facet joint volume is evidence of spinal instability, represented by increased NZ, in the degenerative lumbar spine.

**Disclosure**

The authors have applied for a patent for the IOM system. Author contributions to the study and manuscript preparation include the following. Conception and design: K Hasegawa. Acquisition of data: K Hasegawa, K Kitahara, H Shimoda. Analysis and interpretation of data: K Hasegawa. Drafting the article: K Hasegawa. Critically revising the article: K Hasegawa. Reviewed final version of the manuscript and approved it for submission: K Hasegawa. Statistical analysis: K Hasegawa. Administrative/technical/material support: K Hasegawa, K Kitahara, T Har. Study supervision: K Hasegawa.

**References**

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