An in Vitro Biomechanical Evaluation of the Mobility of Adjacent Segments after Spinal Instrumentation*

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Abstract
Adjacent segment degeneration (ASD) is an abnormal process that develops at spinal segments adjacent to the fused segment caused by biomechanical changes after spinal fusion. To avoid the adverse effects of spinal fusion on the adjacent segments, various flexible stabilization systems have been developed, of which the Graf system is one of the most widely used. We assessed the biomechanical influence of the Graf system and spinal fusion. The L3–L6 vertebrae were taken from porcine lumbar spines. A spinal motion tester displaced the end of the L3 vertebra to simulate continuous flexion/extension. Three cycles of flexion/extension were applied and the angular motion and intradiscal pressure were recorded during the third cycle for each test. The angular deformity at the flexible stabilized segment was suppressed until 4° of deformation; the deformity gradually increased after 4° and then finally equaled that of the intact spine. The maximum intradiscal pressure increased significantly in each segment fused and in the adjacent spinal segments using the Graf system. In conclusion, the Graf system reduces the motion of adjacent segments and may reduce the risk of ASD. Nevertheless, the relationship between ASD and the increase in the intradiscal pressure remains controversial.

Key words: Spine, Biomechanics, Adjacent Segment Degeneration, Graf System, Spinal Fusion, Instrument

1. Introduction
Spinal fusion with instrumentation is an essential component in the management of spinal degeneration. It is performed to improve the initial stability and uses simplified external fixation to promote early ambulation1–4. Nevertheless, solid fixation often induces adjacent segment degeneration (ASD) above or below the fusion5–9. ASD is defined as any abnormal process of disc degeneration, listhesis, or instability that develops in the mobile segment adjacent to a fused segment. The biomechanical changes in the segment due to the fusion, such as increased intradiscal pressure, increased facet loading, and increased mobility, are thought to contribute to ASD10–13).

To avoid the adverse effects of spinal fusion on the adjacent segments, various flexible stabilization systems have been developed to stabilize the unstable segment without rigid...
Flexible stabilization systems are based on the concept of allowing spinal motion, while restricting the motion within the range of normal motion. The Graf flexible stabilization system is one of the most widely used methods of flexible stabilization. It consists of pedicle screws that are placed in adjacent vertebrae and semielastic ring bands to connect the heads of the screws across the segments and act as ligaments. For stabilization, the bands are pretensioned on application to place the mobile segments into lordosis and lock the facet joints.

Kanayama et al. compared the mobility of adjacent segments between the Graf system and posterolateral fusion clinically using radiographs. Radiographic evidence of adjacent disc deterioration was more frequent in the patients with spinal fusion than in the Graf group. They concluded that the Graf system decreased the risk of ASD compared to spinal fusion with instrumentation. Strauss et al. assessed the biomechanical influence of the Graf system on spinal motion by measuring the main and coupled motions of the mobile segments during loading. They showed that Graf flexible stabilization reduces the range of motion and provides flexibility under some loading conditions. Nevertheless, biomechanical evaluations regarding the influence of flexible stabilization on the adjacent segments remain controversial.

In this study, we assessed the biomechanical influence of flexible stabilization with the Graf system and instrumented spinal fusion on the adjacent segments. In vitro experiments were performed using porcine lumbar spines in a spinal motion tester. The testing apparatus simulated continuous spinal flexion and extension, and the segmental motion and intradiscal pressures of each segment were measured. This study sought to clarify the biomechanical effects of destabilization and to assess one of the risk factors of ASD.

2. Methods

2-1. Specimen preparation

In vitro experiments were performed with fresh-frozen porcine lumbar spines. The lumbar spines were harvested from 15 mature pigs that were approximately 200 days old and ranged in weight from 68.5 to 81.5 kg with a mean ± S.D. of 75.5 ± 2.7 kg at the time of death. After harvest, the spines were wrapped in saline-soaked gauze and plastic bags to prevent drying and kept frozen at –20°C before disarticulation. Each specimen was then thawed in a refrigerator at 7°C for 8 to 10 h and the four adjacent L3–L6 vertebral bodies were dissected, including the posterior elements and intervertebral discs. All musculature and fatty tissues were removed, while preserving the ligamentous tissues, intervertebral discs, facet joint capsules, and osseous structures. After disarticulation, to mount the specimen on the spinal motion tester, both the superior (L3) and inferior vertebra (L6) were immersed to the pars interarticularis (the part between the facet joints) in aluminum potting boxes and fixed with a polyester resin and dental plaster. In addition, screw nails were used to secure the vertebral bodies into the resin. This fixing method provides secure fixation, while allowing the full range of flexion and extension of the specimen. During testing, the spinal columns were kept moist at all times in saline-soaked gauze.

2-2. Instrumented models

The spines were first tested intact, and then after bilateral medial facetectomy (MF), augmented by the Graf flexible stabilization system (Graf) or instrumented spinal fusion. Figure 1 shows posterior and lateral views of intact, MF, flexible stabilization, and instrumented spinal fusion specimens. Flexible stabilization was achieved by applying the Graf flexible stabilization system (Graf System; Showa Ika Kohgyo, Aichi, Japan), which consists of pedicle screws that are placed in the vertebral body and semielastic ring bands that connect the heads of the screws. A tensile load of approximately 50 N was applied to
the Graf bands using a special tension measurement device, shifting the spinal segment to a
new extended position. For instrumented spinal fusion, the transpedicle screw system
(Global System; Showa Ika Kohgyo) was applied to the segment to keep the spine in the
neutral position. MF and spinal instrumentation were performed at L4/5, the middle
segment of the spinal column specimens.

Fig. 1 Instrumented models of the porcine lumbar spine. Posterior view (left) and lateral view (right) of the
specimens were shown. A: Intact spine. B: Bilateral medial facetectomy (MF). C: Graf flexible stabilization
system (Graf). D: Instrumented spinal fusion.

2-3. Experimental setup

The spinal columns were assessed using a spinal motion tester designed to displace the
L3 vertebra and simulate sequential flexion and extension of the spine (Figure 2). A linear
actuator (RCP-SMA-M-300-S; IAI Corporation, Shizuoka, Japan), which generates
displacement, was attached to the top of the testing apparatus. The displacement of the
linear actuator can be controlled at speeds of 5 to 333 mm/sec using a speed controller
(RCP-C-SM; IAI Corporation) and personal computer. The linear actuator was connected to
an articulating arm, which consisted of a linear ball spline (SMT30UU-E; Nippon Bearing,
Niigata, Japan) and a linkage system. The articulating arm, which could rotate in the frontal
and axial axes and move vertically, was able to convert the reciprocating motion of the
linear actuator into flexion/extension motion of the spine. The L3 vertebral body was
connected to the articulating arm, and the L6 vertebral body was mounted in a potting box
rigidly attached to the test machine frame.

To observe the results of the segmental motion of each vertebra, three sets of markers
were mounted on the cranial fixture box and L4 and L5 vertebrae bodies. As the spine was
displaced, the locations of these markers were tracked with a charged-coupled device
(CCD) camera (DCR-TRV900; Sony, Tokyo, Japan). Based on the locations of these
markers, the two-dimensional angular motion in the sagittal plane of each segment and the
entire specimen was calculated using motion analysis software (DIPP-Motion Ver.1.30;
Ditect, Tokyo, Japan).

To measure the intradiscal pressure, a miniature fiber optic pressure sensor (FOP-M;
FISO Technologies, Quebec, Canada) was used for each intervertebral disc. A
1.0-mm-diameter stainless-steel guide needle was directed into the central region of the
nucleus pulposus of each disc from a 45° right-anterior approach. The guide needle was
then removed and replaced with the pressure probe, with the pressure-sensing portion at the
tip of the pressure probe located in the nucleus pulposus. The pressure sensor was 1.6 mm
in diameter, equivalent to the sensors used in previous studies and has been shown not to
influence the pressures produced by the nucleus pulposus.

2-4. Experimental procedure

During testing, an axial compressive load of 70 N was applied to the column by the
weight of the articulating arm and fixture box. The actuator reciprocated at a speed of 5.0
mm/sec with displacement of ±20 mm to bend the vertebral column. Three cyclic flexion/extension motions were applied from a neutral position to approximately 8° of extension and then to 8° of flexion. The neutral position of the sagittal plane was defined as the middle region in which the load was zero. During the initial two cycles of flexion/extension, each specimen was preconditioned to minimize the viscoelastic effect of the specimen. The intradiscal pressure and angular motion of the specimen were recorded during the third cycle of each test.

Fig. 2 A schematic diagram of the test configuration. This configuration enables to simulate sequential flexion and extension of the spine. A caudal vertebra is moved with the actuator, intradiscal pressure is measured with a pressure sensor, a segmental motion is tracked with a CCD camera.

Fig. 3 Typical whole specimen motion-segmental motion curves for each instrumented model. The angular deformity of each segment increased linearly in the intact spine and MF in both positions. With the Graf system, the angular deformity of L4/5 was suppressed until 4° of deformation, and then gradually increased after 4° of deformation, ultimately equaling that of the intact spine.
3. Results

The typical relationships between each spinal segment (L3/L4, L4/L5, and L5/L6) and the whole specimens (L3–L6) are shown graphically in Figure 3. The curves were calculated based on the locations of the markers tracked using the CCD camera.

The angular deformity of each segment increased linearly in the intact spine. After MF, the angular deformity of each segment increased in a manner similar to that of the intact spine in both positions. With the Graf system, the angular deformity of L4/5 was suppressed until 4° of deformation, and then gradually increased after 4° of deformation, ultimately equaling that of the intact spine. During the change in L4/5 deformation with the Graf system, the deformation of the L5/6 segment decreased compared to the fused spine when the spine was flexed more than 4°.

![Graph showing range of motion for each instrumented model.](image)

**Fig. 4** Data on the range of motion for each instrumented model. For the superior adjacent segment, in both instrumentation groups, the ROM was significantly greater than in the intact or MF spine in both positions. For the inferior segment (L5/6), the ROM increased in flexion with spinal fusion, in extension with the Graf system and with spinal fusion. At L4/5, while in extension, the ROM decreased with the Graf system and with spinal fusion; both differences were significant compared to the intact or MF spines.

The range of motion (ROM) was defined as the unilateral angular deformation of each segment during bending of the spinal column from the neutral position to 8° of flexion and to 8° of extension. In the intact spine, the mean ROM (±standard deviation) during flexion was 1.3 ± 0.4°, 1.8 ± 0.4°, and 4.9 ± 0.6° at L3/4, L4/5, and L5/6, respectively, during flexion, and the mean ROM during extension was 2.0 ± 1.0°, 3.7 ± 1.1°, and 2.3 ± 1.0°, respectively. In MF, the mean ROM in the flexed position was 1.3 ± 0.4°, 2.0 ± 0.5°, and 4.7 ± 0.7° at L3/4, L4/5, and L5/6, respectively, and the respective mean ROM in the extended position was 2.0 ± 1.0°, 4.1±1.1°, and 1.8±1.0°. No significant differences were detected between the intact and MF spine at each segment. For the superior adjacent segment (L3/L4), the ROM increased 54% with the Graf system and 46% with the fused spine compared to the intact spine in the flexed position, while the respective changes in the extended position were 30 and 75%. In both instrumentation groups, the ROM was significantly greater than in the intact or MF spine in both positions. For the inferior...
segment (L5/6), no significant differences were observed in the ROM among the intact, MF, and Graf spines in the flexed position, while the ROM increased 18% with spinal fusion. In contrast, the ROM increased 117% in extension with the Graf system and 74% with spinal fusion. At L4/5, no significant differences were found in the ROM among the intact, MF, and Graf spines in flexion, while in extension, the ROM decreased 117% with the Graf system and 74% with spinal fusion; both differences were significant compared to the intact or MF spines (Figure 4).

Fig. 5  Distribution of the range of motion for each instrumented model. At L4/5, the ROM with the Graf system was significantly less than in the intact and MF groups, while with spinal fusion, the ROM was significantly less than in all three other groups.

Fig. 6  Data on the intradiscal pressure for each instrumented model. With the Graf system, the intradiscal pressure in the neutral position was increased significantly. The maximum intradiscal pressure was measured at the position of maximum flexion. The maximum intradiscal pressure increased significantly at L3/4 to L5/6, respectively, with the Graf system. With spinal fusion, the maximum intradiscal pressure increased significantly at L3/4 and at L5/6.
The ROM of the MF spine was not significantly different from that of the intact spine, while the total motion at the adjacent segments (L3/4 and L5/6) was significantly greater in the Graf and spinal fusion groups than in the intact or MF groups. At L4/5, the ROM with the Graf system was significantly less than in the intact and MF groups, while with spinal fusion, the ROM was significantly less than in all three other groups (Figure 5).

Examining the intradiscal pressure, in the neutral position, the mean intradiscal pressure (±standard deviation) was 0.27 ± 0.03, 0.25 ± 0.01, and 0.23 ± 0.02 MPa at L3/4 to L5/6, respectively, in the intact spine. In the MF group, the intradiscal pressure was not significantly different at any segment. With the Graf system, the intradiscal pressure was increased significantly by 47% at L4/5 and by 33% at L5/6, while with spinal fusion, it was significantly reduced by 46% at L4/5. The maximum intradiscal pressure was measured at the position of maximum flexion. In the intact spine, the maximum intradiscal pressure was 0.35 ± 0.04, 0.37 ± 0.07, and 0.39 ± 0.06 MPa at L3/4 to L5/6, respectively. With MF, the maximum intradiscal pressure did not differ significantly from the intact spine at each segment. The maximum intradiscal pressure increased significantly by 96, 90, and 67% at L3/4 to L5/6, respectively, with the Graf system. With spinal fusion, the maximum intradiscal pressure increased significantly by 54% at L3/4 and 67% at L5/6 (Figure 6).

4. Discussion and Conclusions

Biomechanical changes consisting of increased intradiscal pressure, facet loading, and mobility after fusion are implicated in causing ASD. In this study, we evaluated the changes in segmental mobility and intradiscal pressure during extension and flexion after instrumentation.

The angular deformity at the segment stabilized by the Graf system was suppressed until 4° of flexion of the whole spinal segment; the ROM gradually increased after 4° of deformation and then finally equaled that of the intact spine. This characteristic segmental motion reduced the motion of the adjacent segments by up to 4°. In contrast, with spinal fusion, a continuous increase in L5/6 segmental motion occurred even after 4° of flexion. These results suggest that the Graf system reduces the motion of the adjacent segment in flexion.

Table 1 Segmental Lordosis to Intact(Deg.). Application of the Graf system forces the segment in lordosis compared to the intact spine, and to compensate for the extended alignment, the adjacent segment flexed and its lordosis decreased.

<table>
<thead>
<tr>
<th></th>
<th>L3/4</th>
<th>L4/5</th>
<th>L5/6</th>
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<tbody>
<tr>
<td>MF</td>
<td>0±0.3</td>
<td>−0.2±0.4</td>
<td>0.3±0.2</td>
</tr>
<tr>
<td>Graf</td>
<td>−1.6±0.6</td>
<td>5.8±0.7</td>
<td>−4.1±0.4</td>
</tr>
<tr>
<td>SF</td>
<td>−1.0±0.7</td>
<td>2.1±0.8</td>
<td>−1.2±0.7</td>
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The intradiscal pressure with the Graf system in the neutral position increased 47% at L4/5 and 33% at L5/6 compared to the intact spine, while no such change in the intradiscal pressure was observed with spinal fusion. The Graf system consists of pedicle screws and Graf bands that connect the screws with a 50-N tensile load. Application of the Graf bands to the screws forces the disc in compression to produce a high intradiscal pressure and stability in extended alignment, which results in segmental lordosis compared to the intact spine, as shown in Table 1. The lordosis at L4/5 increased with the Graf system, and to compensate for the extended alignment, the adjacent segment flexed and its lordosis decreased. Consequently, while the segment (L4/5) stabilized by the Graf system underwent some flexion, the adjacent segments (L3/4 and L5/6) could be flexed excessively, increasing
the intradiscal pressure. In this study, a bending moment was applied using displacement control methods. Although displacement control methods can adjust the maximum angle, they cannot adjust the maximum load required to bend the specimen. With spinal fusion, the instrumentation provides rigid fixation and changes the spinal alignment. Although the rigid fixation immobilized the instrumented segment (L4/5), it increased the ROM at the adjacent segments, producing high intradiscal pressures.

This study has certain limitations. The specimens were porcine spines, not human lumbar spines, and although porcine lumbar spines are similar to those of humans in size and shape, the human spine does not always behave in the manner observed in this study. Furthermore, the specimens were harvested from normal mature porcine spines that lacked degeneration, instability, or osteoporosis. A destabilized segment subjected to instrumentation does not necessarily perform like the segments in this study. Another major limitation was the lack of a temporal evaluation, as we evaluated the initial mobility after spinal instrumentation. After instrumentation, the unstable segment tends to stabilize due to excessive disc degeneration or vertebral body fusion, but these progressive degenerative changes were not considered. Since the objective of this study was to clarify the primary effect of instrumentation on the adjacent segment, using the porcine spine was a reasonable choice.

The clinical study of Kanayama observed radiographic evidence of adjacent disc deterioration more frequently in patients with posterolateral fusion than in those with the Graf system, and they concluded that the Graf system decreased the risk of ASD compared to spinal fusion with instrumentation\(^\text{16}\).

It has been suggested that the advantage of the Graf system is that it stabilizes the unstable segment without rigid spinal fusion and maintains mobility at the stabilized segment. This remaining mobility is the main difference between the Graf system and spinal fusion, and by suppressing the motion of the adjacent segment, we may be able to reduce the consequent risk of ASD. Nevertheless, the relationship between the increase in intradiscal pressure and ASD remains controversial.

References


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