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Lumbar Intradiscal Pressure after Posterolateral Fusion and Pedicle Screw Fixation

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Abe, E., Nickel, T., Buttermann, G.R., Lewis, J.L. and Transfeldt, E.E. *Lumbar Intradiscal Pressure after Posterolateral Fusion and Pedicle Screw Fixation.* Tohoku J. Exp. Med., 1998, **186** (4), 243-253 —— In vitro biomechanical testing was performed in single-functional spinal units of fresh calf lumbar spines, using pressure needle transducers to investigate the effect of posterolateral fusion (PLF) and pedicle screw constructs (PS) on intradiscal pressure (IDP), in order to elucidate the mechanical factors concerned with residual low back pain after PLF. IDP of 6 calf lumbar spines consisting of L4 and L5 vertebrae and an intervening disc was measured under axial compression, flexion-extension and lateral bending in the intact spine, PS, PLF and the destabilized spine. Relative to the intact spines, the destabilized spines showed increased IDP in all of lordings and moments. IDP under PS and PLF were significantly decreased in axial compression, extension and lateral bending loads ($p<0.05$). In flexion, IDP under PS and PLF increased linearly proportional to the magnitude of flexion moment and reached as high as IDP of the intact spines. These results demonstrated that despite an increase in the stiffness of motion segments after PLF and PS, significant high disc pressure is still generated in flexion. Flexibility of PS and PLF may cause increased axial load sharing of the disc in flexion and increased IDP. This high IDP may explain patients' persisting pain following PS and PLF.
——— biomechanics; intradiscal pressure; lumbar spine; posterolateral fusion; pedicle screw fixation

A large number of pedicle screw fixation (PS) and spinal fusion operations have been performed as treatment for low back pain with instability or degenerative disc. Posterolateral fusion (PLF) of the lumbar or lumbosacral spine is the most commonly used spinal fusion method among them (Watkins 1953; Stromqvist 1993; Axelsson et al. 1994). However, some patients experience persistent

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low back pain despite an unquestionably solid PLF (62%, reported by Kawakami et al. 1997; 55%, reported by Suk et al. 1997). Coppes et al. (1997) reported observations of extensive disc innervation in degenerated and painful intervertebral discs. Weatherley et al. (1986) described cases of 5 patients with discogenic pain persisting despite solid posterior fusion, whose pain was reproducible by discography and completely relieved after anterior intervertebral fusion. These two reports suggest that the residual degenerated disc causes discogenic pain, if there is large mechanical stress to the disc after PS or solid PLF.

To our knowledge, there have been only a few studies of intradiscal pressure (IDP) within an instrumented segment or fused segment (Weinhoffer et al. 1955; Nachemson and Morris 1964; Rolander 1966; Cunningham et al. 1997), the results showed wide variations and are controversial. The present study was conducted to investigate and analyze changes in IDP on loading unisegmental spine and the effects of spinal destabilization, instrumentation and fusion on IDP, in an attempt to clarify whether or not there is large mechanical stress to the disc which has potential to cause the discogenic pain after solid fusion.

Materials and Methods

Preparation of materials

Fresh-frozen calf lumbar spines harvested from six calves (80 kg to 120 kg body weight) were used in this investigation. The specimens were thawed to room temperature for 12 hours and one functional spinal units of the L2-L3 and L4-L5 segments were isolated from the specimens. Each isolated segment was immediately frozen at $-20°C$ in double thickness plastic bags. Just before the preparation and mechanical testing, the isolated segments were thawed to room temperature for about 12 hours. The surrounding soft tissue and muscles were dissected off the segments, with care being taken to preserve the ligamentous structures, facet joint capsules and discs. The upper and lower vertebrae of each isolated segment were anchored with 4 to 6 stainless steel screws and embedded in metal fixtures using bone cement (methylmethacylate). Great care was taken to place the potted vertebrae in a parallel and coaxial direction to fit into jigs, which were attached to a loading device in a materials testing system (MTS) machine and encompassed a system of six linear variable different transformers (LVDT) (Panjabi et al. 1981) for following motion measurements (Fig. 1).

The specimens were kept moist with saline spray during the preparation of the specimen and the mechanical testing. The L2-L3 segments were almost the same size as the L4-L5 segments. The intervertebral disc sizes of the L2-L3 and L4-L5 specimens were 41.0 ± 6.0 mm in anteroposterior diameter and 48.2 ± 3.0 mm in lateral diameter. These disc sizes are similar to those of human lumbar spines (Cotterill et al. 1986)

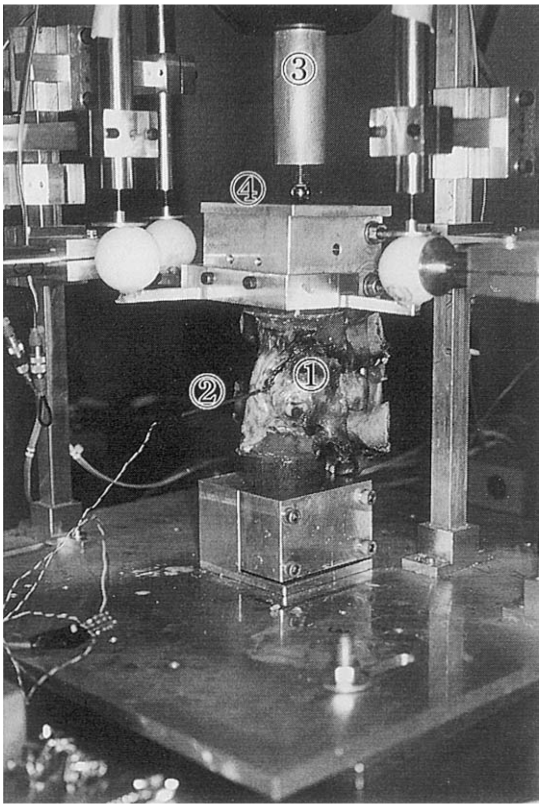

Fig. 1. Intradiscal pressure measurement system
[1]a specimen (calf lumbar spine)
[2]needle-type microtransducer inserted into the intervertebral disc
[3]load cell (MTS machine)
[4]loading plate

Spinal constructs

As a preliminary study, the 300 N and 1000 N loading tests were done with the intact spines and PS constructs in four L2-L3 segments. After then, the following four lumbar fixation constructs were tested in six L4-L5 segments with 300 N loading: 1) the intact (control) spine; 2) PS construct; 3) simulated PLF construct and 4) destabilized spine. PS was done in situ with the Texas Scottish Rite Hospital (TSRH) spinal system (Sofamor Daneck, Memphis, TN, USA), which consists of 4 stainless-steel variable angle screws (6.5 mm in diameter and 40 mm in threaded length) and 2 rods (6.35 mm in diameter) (Fig. 2a). PLF was achieved in situ both by inserting 4 mm threaded Steinman pins across the facet joints and by using methylmethacrylate on the transverse processes (Fig. 2b). The destabilized spines were created by bilateral complete facetectomy and transection of the ligamentous structures in the posterior column.

Material loading system

The biomechanical tests were performed using a servohydraulic materials testing machine (MTS; 858 Bionix Testing System, Minneapolis, MN, USA). The axial compression force of 0 to 300 N or 0 to 1000 N was applied on the loading

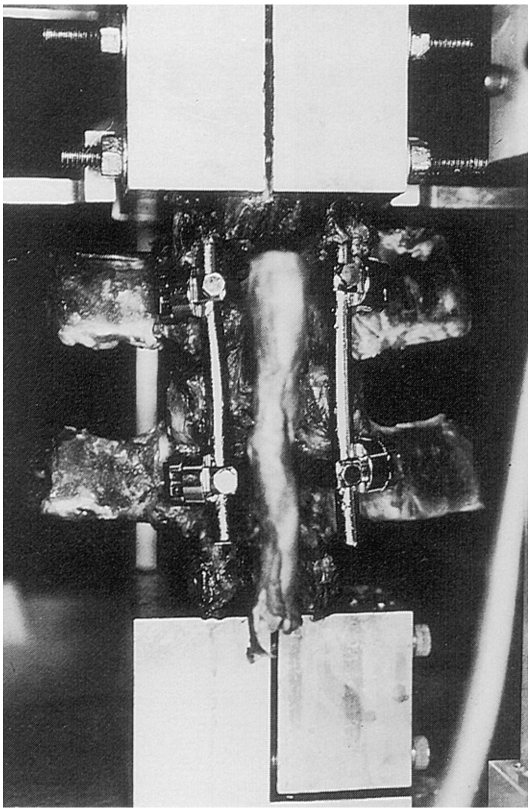
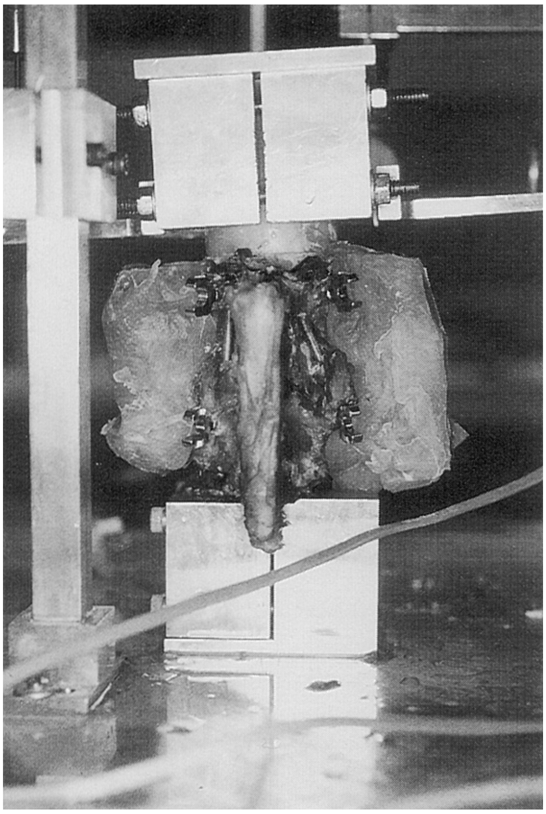

Fig. 2. a) Posterior view of the spine with pedicle screw fixation (TSRH system).
b) Posterior view of the spine with simulated posterolateral fusion.

board secured to the upper end of a specimen with a 10 mm diameter iron ball at a loading rate of 60 N/seconds. Before the loading tests, each specimen was preconditioned with axial compression (0–300 N or 0–1000 N) four or five times until stabilization under monitoring of IDP was observed. Each test condition was replicated three times to ensure repeatability.

In the preliminary study, the loading tests were performed with the intact spines and the PS constructs of four L2-L3 segments by 0 to 300 N, after then by 0 to 1000 N. The testing modes included axial compression and flexion-extension.

The 0–300 N loading tests of six L4-L5 segments were first done with the intact spine, then with PS construct, and with PLF construct, and last with the destabilized spine. Those testing modes included axial compression, flexion-extension and lateral bending. The order of the tests was not randomized because of the violation of the facet joint and ligamentum flavum.

The axis of rotation of the specimen was determined by LVDT output monitoring on the intact spine of each specimen. The loading point of axial compression is at the axis of rotation; those of flexion, extension and lateral bending were at 10 mm, 20 mm, 30 mm and partially 40 mm anterior, posterior, lateral from the axis of rotation in each intact spine, respectively. The terms Flexion 1, 2, 3 and 4 indicate 300 N loading or 1000 N loading at 10, 20, 30 and 40 mm anterior from the axis of rotation of the intact spine, i.e., 3, 6, 9 and 12 Nm at 300 N loading, or 10, 20, 30 and 40 Nm at 1000 N loading anteriorly. Extension

1, 2, 3 and Lateral bending 1, 2, 3 indicate 3, 6 and 9 Nm in 300 N loading or 10, 20, 30 Nm in 1000 N loading posteriorly and laterally, respectively.

Intradiscal pressure measurement

IDP was measured directly by a specially designed needle-type micro-pressure transducer (Model 3521-500 with an outer diameter of 2.11 mm, Robert A. Denton Co., Rochester Hill, MI, USA). The pressure transducer voltage output is linearly related to pressure for values up to 3.4 MPa for 0 to 1000 N loading. The transducer was placed into the center of the disc through the anterior portion of the annulus and attached with sutures and super-glue to maintain stationary positions between tests. The position of the tip of the transducer was confirmed by 2-directional x-ray before the measurements. Pressure data were recorded by computer data acquisition. IDP changes (net IDP) was defined as the difference between the maximum IDP at loading and the lowest IDP before loading.

Motion monitoring

The motion of the specimen was measured with a six-degree-of-freedom LVDT system. This tester describes the motion of the segment in the form of three rotations, i.e., axial rotation, flexion/extension bending, and lateral bending, and three translations, i.e., anterior/posterior shear, axial extension/compression, and lateral shear. The system's measurement errors are 0.4% for rotation, and 0.9% for translations (Panjabi et al. 1981). These data were recorded simultaneously with the pressure data by computer data acquisition.

Statistical Analysis

The statistical analysis of the biomechanical data included descriptive statistics, repeated-measures analysis of variance, and the *post hoc* Student-Newman-Keuls method for multiple comparisons between groups (Fisher's protected least significant difference). Probability values less than 5% were considered significant.

Results

Preliminary study

IDP of the intact spines and PS constructs showed a linear response to the magnitude of applied axial load for 0 to 1000 N at the axis of rotation. In comparative studies of 300 N and 1000 N loading at flexion-extension, net IDP of the intact spines and those of the PS constructs changed in proportion to the magnitude of each loading and moment. Mean IDP values under 1000 N loading increased by 3.1 to 4.8 times as high as those under 300 N loading in each moment (Fig. 3).

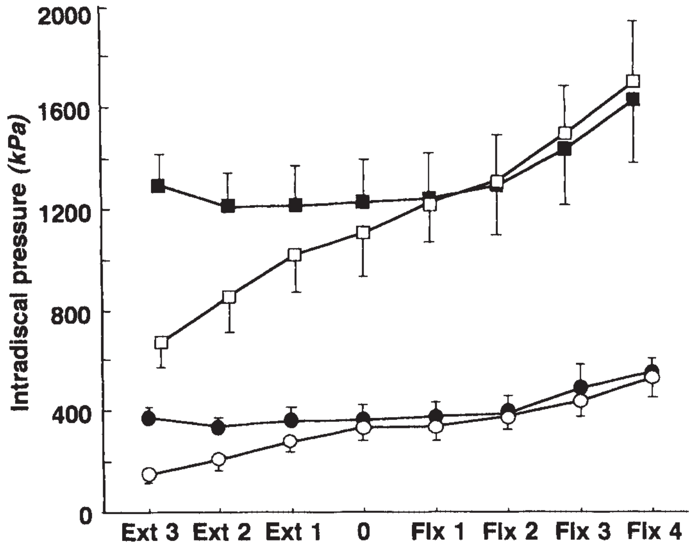

Fig. 3. Intradiscal pressure changes in flexion-extension on the intact spine and the pedicle screw fixation construct under 300 N and 1000 N loading. The data are mean±S.E. of four specimens. The error bar signifies S.E. Ext: Loading at 30 mm posterior from the center of motion. Flx 3: Loading at 30 mm anterior from the center of motion. y-axis: interadiscal pressure. ●, control(intact spine) at 300 N loading; ○, pedicle screw fixation at 300 N loading; ■, control at 1000 N loading; □, pedicle screw fixation at 1000 N loading.

Axial compression

IDP showed a quite linear response to the magnitude of applied axial load at the center of rotation in the different six spines under the different four stabilized conditions. IDP of the destabilized spines increased by 15% on average compared to the intact spines under 300 N loading, but this difference was not significant ($p=0.068$). IDP of the PS constructs decreased significantly by 23% ($p<0.01$), and that of the PLF constructs decreased by 19% ($p<0.05$). Compared to the destabilized spines, IDP of the PS constructs decreased by 33%, and that of the PLF constructs decreased by 29% (PS and PLF: $p<0.001$) (Fig. 4).

Flexion and extension

From extension to flexion, IDP values of the intact spines and those of the destabilized spines increased almost in parallel in proportion to the size of each moment. The lowest IDP of the intact spines was at the center of rotation, while that of the destabilized spines shifted anteriorly to Flexion 1. IDP of the destabilized spines was higher than that of the intact spines by 14-36%, which was significant from Extension 1 to Extension 3 ($p<0.05$ to $p=0.0001$), but was not significant from Flexion 3 to the neutral position ($p>0.068$). IDP under PS showed almost the same changing pattern as that of PLF. IDP values of PS and PLF were significantly lower than the intact spines from Extension 1 to 3 (PLF and PS: $p<0.05$ to $p<0.0001$). Those values increased almost linearly from

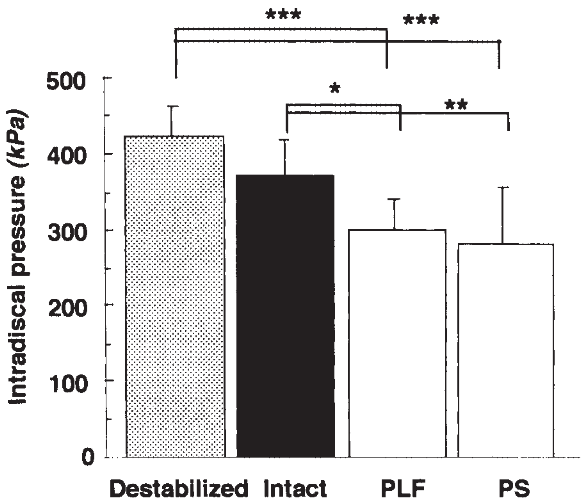

Fig. 4. Lumbar intradiscal pressure under axial compression loading in response to pedicle screw fixation (PS), simulated posterolateral fusion (PLF), and spinal destabilization (Destabilized) under 300 N loading. The data are mean ± S.E. of six specimens. The error bar signifies S.E., and $*p<0.05$, $**p<0.01$, $***p<0.001$.

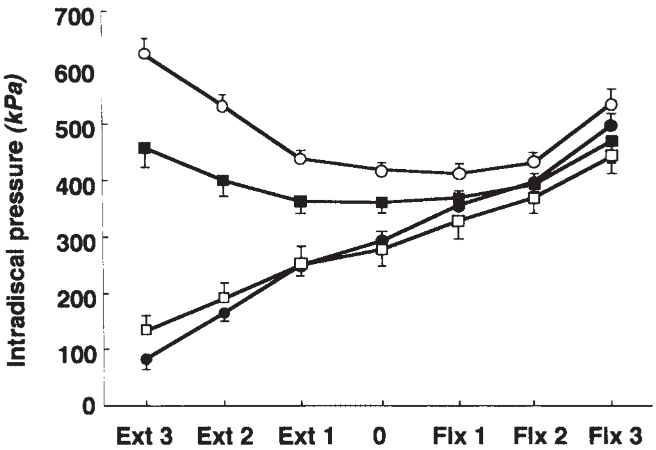

Fig. 5. Intradiscal pressure changes in flexion-extension with different stabilization and moment conditions under 300 N loading. The data are mean ± S.E. of six specimens. Ext 3: 300 N loading at 30 mm posterior point from the center of motion, i.e., -9 Nm. Flx 3: 300 N loading at 30 mm anterior point from the center of motion, i.e., +9 Nm. Y-axis: intradiscal pressure. ○, destabilized spine; ●, posterolateral fusion; □, pedicle screw fixation; ■, control (intact spine).

Extension 3 (−9 Nm) to Flexion 3 (9 Nm) and reached as high as that of the intact spines in flexion. IDP of PS increased by 326% and that of PLF increased by 612% at Flexion 3 from the lowest values of extension (Fig. 5).

Lateral bending

Bilateral side-bending produced symmetrical changes of IDP, and the eccen-

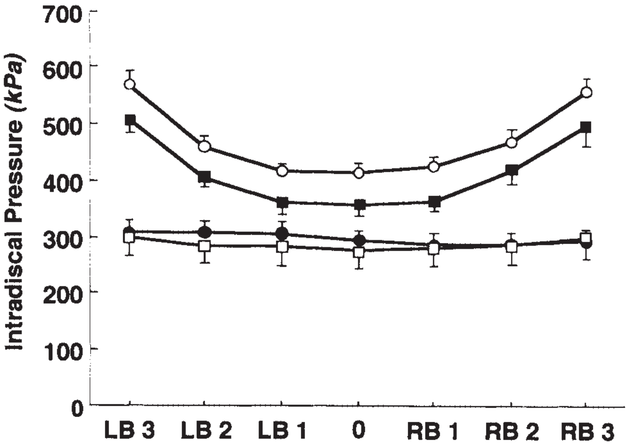

Fig. 6. Intradiscal pressure changes in lateral bending in different stabilization and moment conditions. The data are mean ± S.E. of six specimens. LB 3: 300 N loading at 30 mm left lateral point from the center of motion. y-axis: intradiscal pressure.
○, destabilized spine; ●, posterolateral fusion; □, pedicle screw fixation; ■, control (intact spine).

tric loading apart from the center of rotation resulted in increased IDP in the intact spines and the destabilized spines. In contrast, few changes in IDP were observed in the PLF and PS constructs compared with the axial loading to the center of rotation (Fig. 6).

Discussion

We used 8-week-old calf lumbar spines to measure IDP of the functional spinal unit consisting of two vertebrae and an intervening disc, because they are simlar size to adult human lumbar spines and have no disc degeneration (Cotterill et al.1986). However, the anatomy of the calf spine differs from that of the adult human spine in several respects. The calf lumbar spine has slight kyphosis (0–5 degrees), different contours of the facet joints, a smaller range of motion, six lumbar vertebrae, immature vertebral endplates and larger transverse processes. The first three points may have affected the results of the present biomechanical testing. Especially, its kyphotic curvature may have decreased load-sharing by the posterior column compared to that of the lordotic human lumbar spine.

Nachemson (1981) reported that the approximate loads on the L3/4 disc in a person weighing 70 kg are as follows; supine and awake: 250 N; standing at ease: 500 N, 40° forward bend: 1000 N. Compared with these in vivo loads at standing or forward bending, the magnitude of our loading was slightly small. In our preliminary study, IDP in the intact spines and the PS constructs showed quite linear increases to the magnitude of applied axial load from 0 to 1000 N, and IDP by 1000 N loading showed the same changing pattern as IDP by 300 N loading in flexion and extension. IDP under 1000 N loading showed 3.1 to 4.8 times as high as those under 300 N loading in each moment. These results suggest that we can anticipate the results under 1000 N loading untested from those under 300 N loading.

In the axial compression loading, IDP of the destabilized spines increased by 15% on average compared to the intact spines in the present calf spine model. Cunningham et al. (1997) reported that IDP increased by 22% in a lordotic multisegmental human cadaver spine. This smaller increase may be due to anatomical discrepancies between the kyphotic calf spine and the lordotic human spine, because load sharing of the posterior column in the kyphotic spine is smaller than that of the posterior column in the lordotic lumbar spine. IDP under PS was reduced by 23% and that under PLF was reduced by 19% ($p<0.05$) compared to that of the intact spine in the present study. The reduction of these IDP values is smaller than those of studies by Cunningham et al. (1997), Rolander (1966) and Nachemson and Morris (1964). Cunningham et al. (1997) reported that IDP was reduced by 55% under PS compared with the intact spine, and Rolander (1966) reported that it was reduced by 50% under PLF in human cadaver studies. Nachemson and Morris (1964) reported that the IDP was reduced by 30% in posterior fusion in an in vivo study. These discrepancies seem to depend mainly on the rigidity of each spinal construct (i.e., PS or PLF), the difference of the curvature of the spine (i.e., kyphotic or lordotic spine) and single-functional spinal units vs. multiple-functional units.

In flexion-extension and lateral bending in the present model, IDP of the destabilized spines showed similar changing pattern as the intact spines, and it was always higher than IDP of the intact spines. The eccentric loading apart from the center of rotation resulted in increased IDP in both the intact spine and the destabilized one. IDP values under PS and PLF showed the same patterns of changes. PS and PLF markedly decreased IDP in extension loading, and increased it linearly from Extension 3 to Flexion 3. These results are consistent with Rolander's (1966) finding that under a simulated posterior fusion condition, IDP decreased with the loading axis closer to the posterior column and increased with a more anterior positioned loading axis. Although Cunningham et al. (1997) reported that IDP under PS was decreased even in flexion, its maximal flexion angle was only 12.5° in spite of the specimen with 5 motion segments. In such a small flexion angle, flexion force seems not to work effectively in the intervening discs of the fixed motion segments. Weinhoffer et al. (1995) reported that IDP in a segment fixed with Wiltse-type pedicle screws was elevated above that under the non-instrumented condition at a flexion angle more than around 15°. Adams et al. (1994) reported that in their IDP study using one-functional spinal units of the human cadaver spine, flexion angle greater than about 75% of the full range of flexion generated high tensile forces in the posterior ligaments and caused substantial increases in IDP. These two reports are consistent with our results that significant high disc pressures exist in flexion in the intervening disc of the fixed segment.

Adams et al. (1996) investigated the pressure distribution in the human intervertebral disc and reported that disc degeneration increased the stress concentration within the annulus. Coppes et al. (1997) reported extensive innervation in degenerated and painful intervertebral discs. These findings suggest that degenerated discs cause discogenic pain if there is any large mechanical stress to the disc after PS or solid PLF. In the present study, we revealed high disc pressure in flexion under PS or PLF, which may be generated through the flexibility of the spine. This high disc pressure in flexion is most likely one of mechanical factors causing discogenic low back pain after PLF in some patients, which was speculated by Weatherley et al. (1986), Kawakami et al. (1997) and Suk et al. (1997).

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