Biomechanical study on the effect of five different lumbar reconstruction techniques on adjacent-level intradiscal pressure and lamina strain

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Object. The objectives of this study were to compare the biomechanical effects of five lumbar reconstruction models on the adjacent segment and to analyze the effects of three factors: construct stiffness, sagittal alignment, and the number of fused segments.

Methods. Nondestructive flexion–extension tests were performed by applying pure moments to 10 calf spinal (L3–S1) specimens. One-segment (L5–6) or two-segment (L5–S1) posterior fusion methods were simulated: 1) one-segment posterolateral fusion (PLF); 2) one-segment PLF with interbody fusion cages (one-segment PLIF/PLF); 3) two-segment PLF; 4) two-segment PLIF/PLF; and 5) two-segment PLF in kyphosis (two-segment kyphotic PLF).

The range of motion (ROM) of the reconstructed segments, intradiscal pressure (IDP), and lamina strain in the upper (L4–5) adjacent segment were analyzed.

The ROM was significantly decreased in the PLIF/PLF models compared with that in the PLF alone models after both the one- and two-segment fusions. If the number of fused segments was increased, the pressure and strains were also increased in specimens subjected to the PLIF/PLF procedure, more so than the PLF-alone procedure. In the one-segment PLIF/PLF model the authors observed a reduced IDP and lamina strain compared with those in the kyphotic two-segment PLF model despite the latter’s higher levels of initial stiffness.

Conclusions. If the number of fused levels can be reduced by using PLIF to correct local kyphosis, then this procedure may be valuable for reducing adjacent-segment degenerative changes.

KEY WORDS • biomechanical testing • lumbar spine • posterior lumbar interbody fusion • intradiscal pressure • lamina strain • kyphosis

Posterolateral fusion in which a PS system is implanted has been widely used to treat unstable lumbar spine; however, PLF is often unable to restore sagittal-plane alignment or disc space height when the anterior column is injured. Posterolateral interbody fusion combined with PLF (PLIF/PLF) provides anterior-column support, increases construct stiffness, restores spinal alignment, and leads to higher fusion rates compared with conventional PLF alone. Degenerative changes at the levels adjacent to the fusion site, however, are well recognized. It has been proposed that using less rigid fixation, restoring physiological alignment, and undertaking short-segment fusion may reduce the progression of these adjacent-segment degenerative changes. The details of these interactions or the synergistic effects of these factors, however, are not yet fully understood. In our previous biomechanical study we found that PLIF/PLF treatment may lead to an even higher load on the adjacent segments due to increased stiffness in the fixed segments, even if the local kyphosis is corrected by PLIF. This phenomenon was only simulated, however, in a two-segment fixation model, and we did not investigate the effect of the number of fixed segments. The effect of a PLIF short-segment fusion on the adjacent level remains unknown. Hence, it is uncertain whether the existence of any kyphotic deformity after the instrumentation has been applied is acceptable or whether the PLIF procedure should be undertaken to restore the normal physiological alignment or to provide short-segment fixation. No clinical or biomechanical studies have been conducted to address these issues.

The objectives of this study were to compare the biomechanical effects of five different posterior lumbar reconstruction models on the adjacent segments and to analyze the effects of three specific factors: construct stiffness, sagittal alignment, and the number of the fused segments.

Abbreviations used in this paper: IDP = intradiscal pressure; PLF = posterolateral fusion; PLIF = posterior lumbar interbody fusion; PS = pedicle screw; ROM = range of motion.
Materials and Methods

Specimens and Experimental Setup

We tested 10 cadaveric specimens of calf lumbar spines (from L-3 to the sacrum, obtained in 8–10-week-old calves). To exclude specimens with abnormalities or degenerative changes, anteroposterior and lateral radiographs were assessed before testing. The soft tissues were removed, taking care not to damage the disc, ligaments, or joint capsules. The upper half of the L-3 vertebra and the lower half of the sacrum were cast in polyester resin molds (Soler Co., Ltd., Tokyo, Japan) that were reinforced by three 3-mm-diameter screws. The sacrum was then securely fastened onto a testing table. Radiographs were acquired in each case to ensure that the L4–5 intervertebral disc was horizontally oriented. All biomechanical tests were performed with specimens at room temperature. The specimens were wrapped in saline solution–soaked towels to prevent dehydration of the tissue.

Nondestructive biomechanical testing was performed by applying two types of pure moments to the specimens, as has been reported (Fig. 1).1,3,8,20,21 The flexion and extension moments ranged from 0 to 6 Nm, which include the ranges of moments used in previous biomechanical studies of lumbar reconstruction models.1,2,9,10,18,21 Because the authors of pilot studies have previously demonstrated that load-displacement and load-strain or pressure data after the second load-unload cycle were almost identical to the second, the loading procedure involved the application of a three load-unload cycle. Information obtained during the third loading cycle was used for data analysis of all biomechanical parameters. The specimen was allowed to creep for 30 seconds between load application and data collection.6,9,10,18,21

Both one- (L5–6) or two- (L5–S1) segment posterior fusion methods were simulated. A displacement gauge (Model 25C-20; MTS Systems, Inc., Minneapolis, MN) spanning the operative segment was used to quantify segmental displacement6,9,18 (if two-segment fusion was simulated, the gauge was placed over the entire fusion length from L-5 to S-1). The displacement gauge was attached longitudinally, bridging the anterior aspects of the vertebral bodies through the anterior longitudinal ligament. The gauge was consistently oriented vertical to the segment. The ROM was measured with respect to the corresponding anterior longitudinal ligament displacement to determine the stability of the fused segments.9,10,18 A pressure needle transducer (R. Denton, Inc., Rochester Hills, MI) was inserted into the L4–5 intervertebral discs to determine IDP and investigate the biomechanical effects on the superior adjacent segment.2,9 The needle was 2.1 mm in diameter. Its tip housed a waterproofing-coated single-strain gauge containing a 1.5-mm-diameter sensing area. The needle was initially calibrated to 1.36 MPa with a hydraulic test. The pressure needle was inserted from the lateral side of the L4–5 intervertebral disc into the center of the nucleus pulposus.2,18 The insertion point and depth of the needle were controlled using both anteroposterior and lateral radiographs. Uniaxial surface-strain gauges (KFG-02-120-C1-11L3MR; Kyowa Dengyo Co., Tokyo, Japan) were sagittally mounted on the bilateral L-4 laminae just cranial to the L4–5 facet joint by using cyanoacrylate.4,9,18 The lamina strains indirectly indicated the load transmission through the posterior column of the adjacent segment.18 For the lamina strain analysis, the mean values of right and left gauges were calculated to minimize the effects of coupled motions.21

Data were acquired through the pressure transducer and strain gauges connected to a multichannel signal-conditioning amplifier (PCD-200/A; Kyowa Dengyo Co.) interfaced with a personal computer (PC-LMS500I; NEC Inc., Tokyo, Japan) and recorded simultaneously with segmental displacement data.

Experimental Protocol

After testing in the intact state, a bilateral partial facetectomy and partial discectomy were performed at the L5–6 level, and the supra- and interspinous ligaments were transected. For the partial facetectomy, the medial half of the facet joint and the ligamentum flavum were resected. The partial discectomy was defined as transection of the posterior longitudinal ligament and posterior part of the anulus fibrosus combined with removal of the nucleus pulposus. The effectiveness of these sequential destabilization procedures in creating spinal instability has been demonstrated in the literature.1 After destabilization, spinal reconstructions were sequentially performed using PSs with or without interbody fusion cages. The PLF was simulated by PS fixation and the PLIF by insertion of interbody cages: 1) L5–6 PLF (one-segment PLF), and 2) L5–6 PLF with interbody fusion cages (one-segment PLIF/PLF). After testing one-segment fusion, destabilization was also performed at the L6–S1 level and three types of two-segment constructs were randomly assembled: 3) L5–S1 PLF (two-segment PLF), 4) L5–S1 PLF with interbody fusion cages (two-segment PLIF/PLF), and 5) L5–S1 PLF in kyphosis (two-segment kyphotic PLF). The order of this sequence was randomized among specimens. The Isola spinal system (screw, 6.25 × 45 mm; rod, 6.35 mm in diameter; Depuy-AcroMed, Boston, MA) was used for PS fixation. For the interbody fusion, two Brantigan carbon cages (10 × 9 × 21 mm; Depuy-AcroMed) were used in each disc. For simulating the in situ PLF, straight rods were used. For in situ PLIF/PLF, two cages were inserted into each disc and straight rods were placed. For kyphotic PLF, prebent rods were applied over the region of kyphosis (Fig. 2).

To standardize the compressive preload on the interbody cages, 125 N of compressive preload was applied to the specimen by using a Bionix 858 biaxial servohydraulic materials test machine (MTS Systems) while the screw–rod junctions were tightened. This pre-loading value was chosen after referring to a previous study involving intervertebral cages.16,18,21 The same biomechanical testing was repeated after each reconstruction procedure.

Statistical Analysis

Statistical significance was determined using a repeated-measurement analysis of variance in addition to a post hoc multiple comparison using Fisher Protected Least Significant Difference test at 95% of confidence. Values are presented as the means ± standard deviations.

Fig. 1. Schematic showing the experimental apparatus and measurement system. Pure moments were applied to the specimen with a system of weights and pulleys. Anterior segmental displacement was recorded using a displacement gauge. The IDP and lamina strain within the superior adjacent segment were measured using a pressure needle transducer and uniaxial surface-strain gauges, respectively.
Results

Sagittal Alignment at the Reconstructed Segments

On plain lateral radiographs the actual sagittal angle at the reconstructed segments in each specimen was measured using the Cobb angle technique. The mean lordotic angle was 0.4° ± 0.8° in the intact group, 2.0° ± 0.5° in the one-segment PLF group, 2.4° ± 0.6° in the one-segment PLIF/PLF group, 2.3° ± 0.6° in the two-segment PLF group, and 2.8° ± 0.7° in the two-segment kyphotic PLF group. Excluding the kyphotic PLF group, statistical differences were not detected among the other groups (p > 0.05).

Range of Motion of the Reconstructed Segments

Analysis of the ROM at the reconstructed segments demonstrated significant differences among the six groups under both flexion (F = 86.971, p < 0.0001) and extension loading (F = 8.855, p < 0.0001). A significant decrease in ROM was observed in the PLIF/PLF models compared with that in specimens subjected to PLF alone in both one- and two-segment fixation models under flexion–extension loading (p < 0.05). In the two-segment fusion models, both PLIF/PLF and PLF were associated with a more restricted ROM than that of any of the one-segment fusion models (Fig. 3A).

Intradiscal Pressure in the Adjacent Segment

Statistical differences were detected among the six reconstruction types in terms of flexion (F = 3.212, p = 0.0131) and extension (F = 4.810, p = 0.0010) strain in the adjacent segment. Similar to the IDP results, statistical significance in the lamina strain was not found between the PLIF/PLF and PLF procedures in the one-segment fusion model (p > 0.05). Under flexion loading, the two-segment PLIF/PLF model was associated with significantly higher lamina strain than the one-segment fusion models (p < 0.05). Under extension loading, a significant increase in the lamina strain occurred in the two-segment PLIF/PLF and kyphotic PLF groups compared with the one-segment fusion groups (p < 0.05). There were no significant differences between the two-segment PLF and any of the one-segment models under flexion–extension loading (p > 0.05) (Fig. 3B).

Lamina Strain in the Adjacent Segment

Study Background

With the increase in the use of instrumentation in spinal fusion surgery, most surgeons have come to recognize that early breakdown of the adjacent segments can occur in some cases. Using a load-controlled testing protocol, Oda, et al. created an in vitro spinal fusion model and demonstrated that the placement of additional interbody cages significantly increased construct stiffness and adjacent-segment segmental motion compared with PLF alone. They suggested that the greater stiffness provided by instrumentation might accelerate degenerative changes in the adjacent motion segments.
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Fig. 3. Bar graphs showing results of statistical comparisons. A: The mean ROM of the reconstructed segments from the intact spine and five reconstruction models under flexion–extension loading. B: The mean IDP within the superior adjacent segment of the intact spine and five reconstruction models under flexion–extension loading. C: The mean lamina strain within the superior adjacent segment for the intact spine and five reconstruction models under flexion–extension loading. All the data have been normalized for the initial, intact spine. Bars indicate the standard deviations.
The authors of clinical studies have documented that lumbar fusion in a nonanatomical sagittal alignment could also cause adjacent-segment degenerative changes. In an in vitro load-controlled biomechanical study, Akamaru, et al. documented increased flexion-extension motion at the segment above the fixation site when the fixed level was aligned in a hypolordotic fashion. These clinical and biomechanical findings emphasized the importance of sagittal realignment and the maintenance of lordosis during fixation.

It has also been reported that reduction in the number of mobile segments increases the load in the adjacent unfused segments and causes these early degenerative changes. Using a displacement-controlled testing protocol, Nagata, et al. investigated the biomechanical effects of long-segment thoracolumbar instrumentation on the remaining motion of adjacent segments. They found that lumbrosacral motion and facet joint loading were significantly increased after surgical immobilization and that the extent of the increase depended on the number of immobilized segments. In a retrospective clinical and radiographic study, Edwards, et al. examined patients in whom thoracic fusion extended to L-5 and reported that subsequent advanced degeneration of the L5–S1 disc was common after such a long-spanning fusion, which often requires further operations. Therefore, the surgeon is often required to make an important choice early in treatment planning—what is the most appropriate fusion level?

Evaluation of the aforementioned studies suggests that all of these parameters—construct stiffness, sagittal alignment, and the number of fused segments—are important factors affecting adjacent-segment degenerative changes. Few investigators, however, have examined these interactions or the synergistic effects of these factors. In particular, no clinical or biomechanical studies have been undertaken to address these issues in relation to PLIF. It remains undetermined whether adjacent-segment degenerative changes can be reduced by PLIF in which sagittal alignment and short-segment fixation are achieved.

Biomechanical Data and Clinical Relevance

In this study, the ROM of the operative segments was significantly decreased in the PLIF/PLF models compared with that in segments subjected to PLF alone, both in cases of one- and two-segment fusion. For two-segment fusion procedures, both PLIF/PLF and PLF alone reduced the ROM more than the one-segment fusion. These results were consistent with those previously reported by authors who found that the implantation of intervertebral cages increased the overall construct stiffness and that the immobilization afforded by long segmental instrumentation also produced greater overall construct stiffness.

There was no statistical difference in adjacent-segment IDP and lamina strain when assessing one-segment fusion procedures. If the number of fused segments was increased, however, the pressure and strains were also increased more by the PLIF/PLF procedure than by the PLF procedure. These results suggest that there is no biomechanical difference between any of the one-segment fusion procedures in terms of their effects on the adjacent segment; however, if the number of fused levels was increased, the effects on the adjacent segment were also amplified when using PLIF/PLF rather than PLF alone.

In the present study, the one-segment PLIF/PLF model demonstrated a reduced IDP and lamina strain compared with the kyphotic two-segment PLF model despite greater initial stiffness. These results suggest that if the number of fused levels can be reduced by using PLIF to correct local kyphosis, then adjacent-segment degenerative changes may be decreased. Furthermore, our findings suggest that the PLIF/PLF procedure with kyphotic deformity may be associated with the worst biomechanical effects on the adjacent segment. As a general overview, it appears that the stiffer a segment is, the more one can expect increased adjacent-segment IDP and lamina strain. The one exception to this rule is if there is a kyphotic deformity. Hence, when PLIF/PLF is performed, the local kyphotic deformity must be corrected and fusion levels should be minimized.

Study Limitations and Future Directions

A calf spine model was used in this investigation. There are some differences in the anatomical characteristics of human and calf spines. The calf spine, however, has been reported to exhibit similar mechanical responses to those of the human spine under a range of loading conditions. Furthermore, compared with human cadavers, small interspecimen variability in size, bone mineral density, and age in the calf spine provide significant advantages in consistency for the materials used in these biomechanical tests. The calf model, however, does not represent the normal patient who would undergo the type of operation described in this study. The significant disc height (with a normal disc) at the fusion level is atypical; all of the disc spaces were of normal height in the present model. In a patient who undergoes surgery, the disc would not be of normal height nor would the adjacent levels. In many patients in whom there is loss of disc interspace height, the anterior column is much more stable and stiff (in axial loading).

In the present study, PS fixation was used in the PLF model. This procedure did not precisely represent PLF because in PLF the fusion is across the transverse processes, not through the pedicle. To evaluate the stability of the fused segment, we used a displacement gauge. The gauge could only detect linear displacement data and not the location of the axis of rotation and real rotational motion, which might change depending on the type of spinal reconstruction. Therefore, only a rough estimate may be provided by comparing absolute displacement values for the same specimen.

In the present study, the sacrum was included in two-segment fusion models. Using a human cadaveric spine, Untch, et al. showed that a statistically significant increase in L3–4 motion occurred in flexion-extension loading in the L4–S1 fusion model compared with the L4–5 model. The biomechanical difference at the superior or adjacent level might be easier to detect in the present two-segment fusion models than in typical two-segment fusion models in which the sacrum is not included.

Conclusions

With the reconstruction models in our study, we were able to address the immediate postoperative condition of lumbar fusion in a nonanatomical sagittal alignment.
the spinal construct. The effects of osseous fusion on the adjacent segments, however, remain unclear. We were unable to detect any difference in the biomechanical effects on the adjacent segment between one-segment PLIF/PLF and PLF, although in the PLIF/PLF model we observed statistically greater construct stiffness. The setting of the cages into the vertebrae over time, however, may affect the stability of the motion segment. The authors of a previous in vivo study demonstrated that solid osseous interbody fusion provided greater spinal construct stiffness. Additional clinical or animal studies are required to investigate the long-term effects of osseous fusion on the adjacent segments.

References


