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Basic Science

Biomechanical evaluation of lumbar lateral interbody fusion for the treatment of adjacent segment disease

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Abstract

BACKGROUND CONTEXT: Adjacent segment disease (ASD) is a well-known complication after lumbar fusion. Lumbar lateral interbody fusion (LLIF) may provide an alternative method of treatment for ASD while avoiding the morbidity associated with revision surgery through a traditional posterior approach. This is the first biomechanical study to evaluate the stability of lateral-based constructs for treating ASD in existing multilevel fusion model.

PURPOSE: We aimed to evaluate the biomechanical stability of anterior column reconstruction through the less invasive lateral-based interbody techniques compared with traditional posterior spinal fusion for the treatment of ASD in existing multilevel fusion.

STUDY DESIGN/SETTING: Cadaveric biomechanical study of laterally based interbody strategies for treating ASD.

METHODS: Eighteen fresh-frozen cadaveric specimens were nondestructively loaded in flexion, extension, and lateral bending. The specimens were randomized into three different groups according to planned posterior spinal instrumented fusion (PSF): group 1: L5–S1, group 2: L4–S1, and group 3: L3–S1. In each group, ASD was considered the level cranial to the upper-instrumented vertebrae (UIV). After testing the intact spine, each specimen underwent PSF representing prior fusion in the ASD model. The adjacent segment for each specimen then underwent (1) Stand-alone LLIF, (2) LLIF + plate, (3) LLIF + single screw rod (SSR) anterior instrumentation, and (4) LLIF + traditional posterior extension of PSF. In all conditions, three-dimensional kinematics were tracked, and range of motion (ROM) was calculated for the comparisons.

RESULTS: ROM results were expressed as a percentage of the intact spine ROM. LLIF effectively reduces ROM in all planes of ROM. Supplementation of LLIF with plate or SSR provides further stability as compared with stand-alone LLIF. Expansion of posterior instrumentation provides the most substantial stability in all planes of ROM ($p < .05$). All constructs demonstrated a consistent trend of reduction in ROM between all the groups in all bending motions.

CONCLUSIONS: This biomechanical study suggests potential promise in exploring LLIF as an alternative treatment of ASD but reinforces previous studies' findings that traditional expansion of posterior instrumentation provides the most biomechanically stable construct. © 2018 Elsevier Inc. All rights reserved.

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Introduction

Adjacent segment disease (ASD) refers to the development of new symptoms with its corresponding radiographic changes cranial to the level of a previous spinal fusion [1]. While there is no established standard for the treatment of ASD, it is traditionally managed through a posterior approach by extending the previous construct using pedicle screws and rods, with or without additional interbody fusion [2]. Other possible alternative is lumbar lateral interbody fusion (LLIF), which is a minimally invasive technique for treating ASD that preserves posterior ligamentous structures, minimizes soft tissue dissection, and decreased blood loss as well as potential morbidities compared with traditional posterior approach [3].

In traditional posterior approach, direct decompression of neural elements relies on adequate removal of ligamentum flavum, laminotomy and/or laminectomy, and facetectomy. In contrast, LLIF provides indirect decompression by placement of interbody cages, the disc height would be restored and the foramen opened. A retrospective review of patients who underwent LLIF demonstrated in increase in average foraminal area of approximately 35% and posterior intervertebral height increases of 70% [4]. In the same study, an increase of 33.1% in central canal diameter was noted when treating patients for symptomatic lumbar stenosis with stand-alone LLIF. In a recent retrospective review, Louie et al. reported outcome of 25 patients treated with stand-alone LLIF. Their results indicate significant improvement in the Oswestry disability index (ODI), and visual analog scale (VAS). Also radiographic parameters including segmental and regional lordosis, as well as intervertebral disc height were significantly improved.

The optimal construct for ASD has been evaluated by prior biomechanical studies that examined the stability of lateral-based constructs with supplemental fixation [5–8]. Of these, one study was specifically designed to evaluate lateral-based constructs for treating ASD [5]. These studies concluded that insertion of lateral interbody effectively reduces the range of motion (ROM) of the instrumented segment. Additionally, supplemental fixations to the lateral interbody further decrease the ROM.

To our knowledge, no study has analyzed the biomechanical stability of lateral-based constructs adjacent to progressive multilevel preexisting fusion for treating symptomatic ASD. Therefore, our primary aim was to determine the biomechanical stability of four different laterally based lumbar interbody fusion techniques for treating ASD. We also aimed to evaluate if superiority of one laterally based construct exists over another at various ASD levels.

Materials and methods

Specimen preparation

Eighteen fresh-frozen cadaveric lumbar spines (L1–Pelvis) were procured from an approved tissue bank and stored at −30°C. The specimens were thawed out several hours before testing. In all specimens, anterior-posterior and lateral radiographs were obtained to confirm that the samples were devoid of deformity or excessive degeneration due to etiologies other than age-related wear and tear such as tumors or infection. Dual-energy x-ray absorptiometry (DEXA; Discovery C, Hologic Inc., Bedford, MA) scans were also performed to quantify the bone

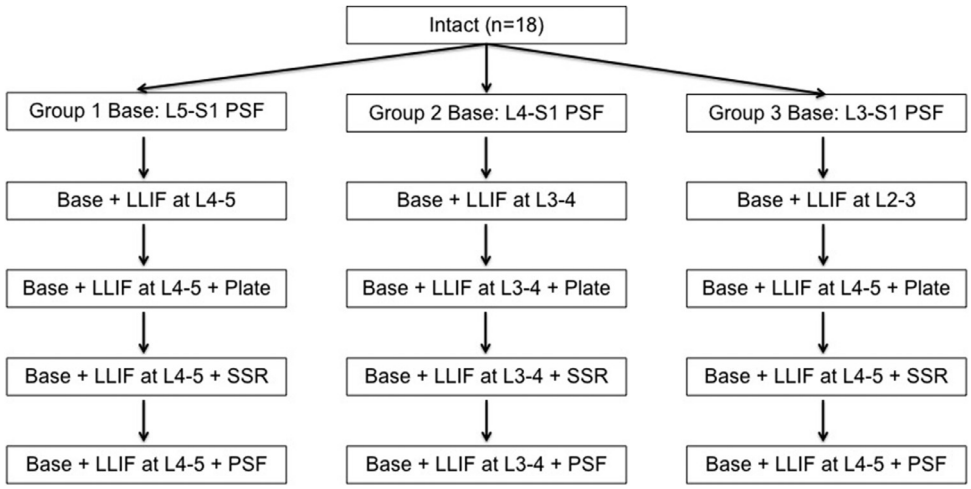

Fig. 1. Chart outlining the order in which testing was performed. After testing in intact state, the specimens were randomly assigned to one of the three groups. After insertion of the LLIF, the subsequent instrumentation with plate or SSR or PSF was randomized to eliminate bias.

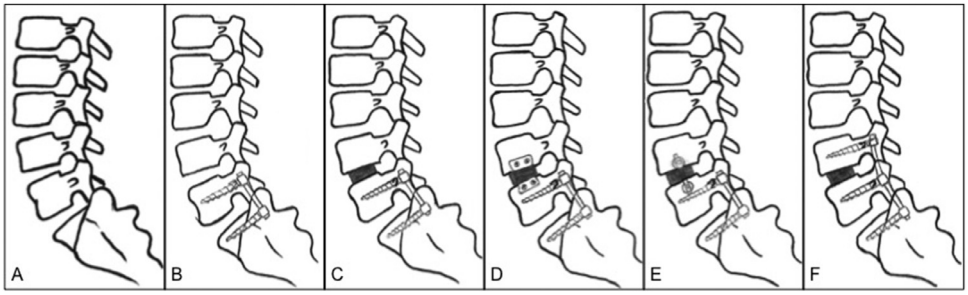

Fig. 2. Schematic diagram of the biomechanical design. This figure represents the instrumentation of the specimen in group 1 in which ASD was assumed at L4–5 level. (A) Intact specimen, (B) L5–S1 posterior spinal instrumented fusion (PSF) (base), (C) Stand-alone lumbar lateral interbody fusion (LLIF), (D) LLIF + plate, (E) LLIF + single screw rod (SSR) anterior instrumentation, and (F) LLIF + traditional extension PSF.

mineral density (BMD) of the specimens. Severely osteoporotic spines were eliminated utilizing BMD and T-scores which were averaged over the L1–S1 vertebrae with cutoff value of T = −2.5.

In addition, before testing, each specimen was thoroughly cleaned of nonstructural soft tissue while preserving the disc, facet joint capsules, and ligamentous structures. The cranial and caudal ends of each specimen were mounted in polymethylmethacrylate. To minimize tissue degradation, all testing for each specimen were performed on the same day.

Biomechanical testing

Biomechanical testing was conducted on an 858 Mini-Bionix II Testing System (Eden Prairie, MN). Pure moment flexibility testing was performed on a custom built jig, servohydraulic actuated six degree-of-freedom spine testing system, applying unconstrained moments of 7.5 Nm about each axis (flexion, extension, and lateral bending) for three cycles, with the final cycle used in data analysis. The sequence of testing for each bending mode was randomized among the specimens to eliminate bias. The axial load was maintained at 0 N. These parameters are consistent with existing literature [9,10]. Motion tracking markers were placed on the ventral and lateral side of each vertebral body for three-dimensional digital motion capture to allow for direct, accurate measurement of displacement of each vertebrae. Three-dimensional vertebral kinematic response was measured via an optical infrared camera system (Vicon Nexus Motion System, Centennial, CO). All data collected were recorded with the use of LabVIEW data acquisition software (National Instruments, Austin, TX).

All specimens were initially tested in the intact, uninstrumented condition in order to obtain baseline characteristics. Onwards, all instrumentations were performed by fellowship-trained spine surgeons according to accepted surgical techniques. The specimens were then divided into three groups (six specimens per group) based on vertebral levels posteriorly instrumented (PSF), ie, group 1: L5–S1, group 2: L4–S1, and group 3: L3–S1 (Fig. 1). Bilateral pedicle screw fixation (The Everest Degenerative Spinal System, K2M Inc., Leesburg, VA) was utilized for the posterior instrumentation. The posterior screws were connected using 5.5 mm cobalt chromium alloy spinal rod. Specimens were then retested with the base fusion according to their assigned group. Subsequently, the cranial adjacent segment for each of the specimens underwent the following instrumentation and tested accordingly: (1) stand-alone LLIF (The Aleutian Lateral Interbody System, K2M Inc., Leesburg, VA), (2) LLIF + plate (The CAYMAN Minimally Invasive (MI) Plate System, K2M Inc., Leesburg, VA), (3) LLIF + single screw rod (SSR) anterior instrumentation, and (4) LLIF + traditional extension PSF (Fig. 2). The purpose of extension of PSF in addition to LLIF was to emulate the traditional approach when treating ASD.

Data analysis

Relative vertebral motion at the adjacent segment level was interpreted as ROM data on the sagittal, coronal, planes relative to the initial neutral position. The ROM was

Table 1
Group 1 summary of median ROM as a percentage of the intact spine with ranges

Test condition	Flexion	Extension	Lateral bending
Base	116.56 (79.4–151.6)	120.8 (78.7–150.4)	112.8 (89.8–145.5)
LLIF	59.9 (26.6–97.6)	93.2 (38.2–177.7)	88.7 (30.3–90.5)
Plate	46.2 (33.3–107.0)	60.2 (30.0–117.6)	25.5 (8.6–54.0)
SSR	57.1 (31.3–87.7)	86.9 (34.4–105.0)	57.9 (32.1–94.9)
PSF	21.6 (6.9–227.9)	31.0 (15.4–65.8)	23.4 (6.1–46.7)

ROM, range of motion; LLIF, lumbar lateral interbody fusion; SSR, single screw rod; PSF, posterior spinal fusion.

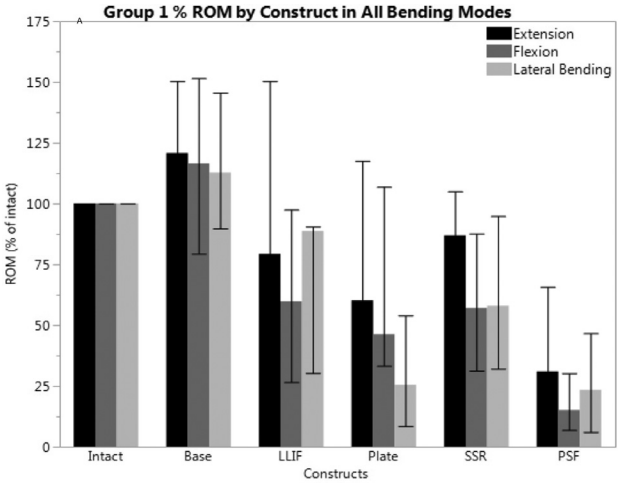

Fig. 3A. Normalized mean (± range) ROM in specimens with ASD at L4–5. L5–S1 posterior spinal instrumented fusion (PSF) (base), stand-alone lumbar lateral interbody fusion (LLIF), LLIF + plate, LLIF + single screw rod (SSR) anterior instrumentation, and LLIF + traditional extension PSF. Stand-alone LLIF reduced ROM at ASD level. Supplementing LLIF with plate and SSR further reduced the ROM in all bending motions. Augmentation of stand-alone LLIF with bilateral pedicle screw fixation (PSF) results in greatest reduction in ROM in all bending motions ($p < .05$).

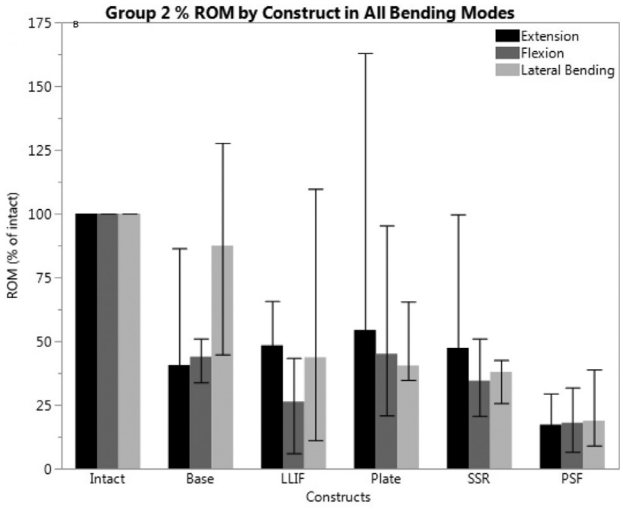

Fig. 3B. Normalized mean (± range) ROM in specimens with ASD at L3–4. L4–S1 posterior spinal instrumented fusion (PSF) (base), stand-alone lumbar lateral interbody fusion (LLIF), LLIF + plate, LLIF + single screw rod (SSR) anterior instrumentation, and LLIF + traditional extension PSF. Stand-alone LLIF reduced ROM at ASD level. Supplementing LLIF with plate and SSR further reduced the ROM in all bending motions. Augmentation of stand-alone LLIF with bilateral pedicle screw fixation (PSF) results in greatest reduction in ROM in all bending motions ($p < .05$).

normalized to the intact condition (% intact) to control for differences in flexibility among specimens.

Statistical analyses, including median and range for the ROM at the index level calculated for each test condition and loading direction, were conducted with JMP, Version 13 (SAS Institute Inc., Cary, NC). The alpha level for statistical significance was set a priori at 0.05. All ROM data were assessed for normality through observation of

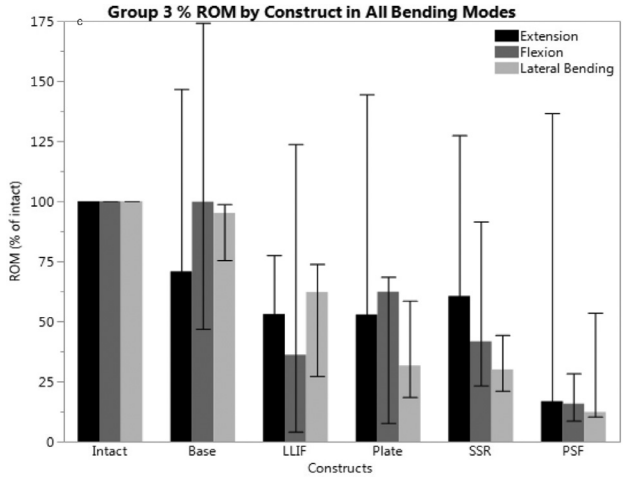

Fig. 3C. Normalized mean (± range) ROM in specimens with ASD at L2–3. L3–S1 posterior spinal instrumented fusion (PSF) (base), stand-alone lumbar lateral interbody fusion (LLIF), LLIF + plate, LLIF + single screw rod (SSR) anterior instrumentation, and LLIF + traditional extension PSF. Stand-alone LLIF reduced ROM at ASD level. Supplementing LLIF with plate and SSR further reduced the ROM in all bending motions. Augmentation of stand-alone LLIF with bilateral pedicle screw fixation (PSF) results in greatest reduction in ROM in all bending motions ($p < .05$).

plots and with Shapiro-Wilk tests. In cases where normality assumptions were not met, nonparametric testing was conducted. Statistical differences in ROM within each group (L5–S1, L4–S1, and L3–S1) tested in flexion, extension, and lateral bending were determined using one-way Analysis of Variance (ANOVA), followed by Tukey-Kramer post hoc pairwise comparison testing to examine differences in ROM between individual constructs as they compared with the intact state. Statistically, significant pairwise comparisons between any constructs and the "base" are reported.

We then tested for statistical differences in ROM between all groups for each testing motion (flexion, extension, lateral bending) using one-way ANOVA, followed by Tukey-Kramer post hoc testing to examine differences in ROM between individual constructs as they compared with the intact state. For those distributions that did not demonstrate a normal distribution, Kruskal-Wallis and Dunn all pairs tests for joint ranks were used as the nonparametric alternatives for ANOVA and Tukey-Kramer, respectively. Global reduction in ROM for each group (L5–S1, L4–S1, and L3–S1), as compared with the intact state, was calculated as follows. The mean ROM in flexion, extension, and lateral bending was summed for each construct, and this value was divided by the sum of the mean ROM in flexion, extension, and lateral bending for the intact state. These values were expressed as percent reduction in ROM as compared with the intact state (Fig. 4).

Results

A total of 18 specimens, 9 male and 9 female, were included in the study with mean of 77.6 years of age (range, 52–106

Table 2
Group 2 summary of median ROM as a percentage of the intact spine with ranges

Test condition	Flexion	Extension	Lateral bending
Base	43.9 (33.9–51.1)	40.7 (22.7–86.4)	87.4 (44.9–127.7)
LLIF	26.3 (6.1–43.4)	48.4 (38.2–65.8)	43.7 (11.2–109.7)
Plate	45.0 (20.9–95.4)	54.5 (3.1–163.0)	40.4 (34.9–65.6)
SSR	34.5 (20.7–51.1)	47.4 (6.3–99.7)	38.0 (25.7–42.6)
PSF	18.0 (6.7–31.8)	17.3 (3.2–29.5)	18.8 (9.2–38.9)

ROM, range of motion; LLIF, lumbar lateral interbody fusion; SSR, single screw rod; PSF, posterior spinal fusion.

years). The average BMD was 0.093 g/cm^2 (range, 0.08–1.4 g/cm^2), and the mean T-score was −0.79 (range, −2.3 to 2.5) as determined by DEXA. Male and female spines were evenly distributed between the groups, and there were no significant differences in bone quality parameters (BMD or T-score) between the groups ($p > .05$).

Group comparisons

Group 1 median ROM as a percentage of the intact spine with ranges is summarized in Table 1. The data for this group demonstrate that in all bending modes, the average ROM was significantly reduced after the extension of PSF ($p < .05$). Addition of plate to LLIF significantly reduced ROM in lateral ($p < .003$). When comparing PSF to LLIF, ROM was significantly reduced in extension ($p < .01$) (Fig. 3A). When comparing global ROM reduction LLIF, plate, SSR, and PSF reduced ROM from the intact state 20%, 50%, 36%, and 63%, respectively (Fig. 4).

Group 2 median ROM as a percentage of the intact spine with ranges is summarized in Table 2. In this group, the average specimen ROM was significantly reduced in lateral bending after the extension of PSF (Fig. 3B). When comparing global ROM reduction LLIF, plate, SSR, and PSF reduced ROM from the intact state by 56%, 47%, 59%, and 81%, respectively (Fig. 4).

Group 3 median ROM as a percentage of the intact spine with ranges is summarized in Table 3. The average specimen ROM was significantly reduced in flexion after the extension of PSF ($p < .018$; Fig. 3C). When comparing global ROM reduction LLIF, plate, Rod, PSF reduced ROM from the intact state by 46%, 46%, 49%, and 72%, respectively. All constructs demonstrated a consistent trend

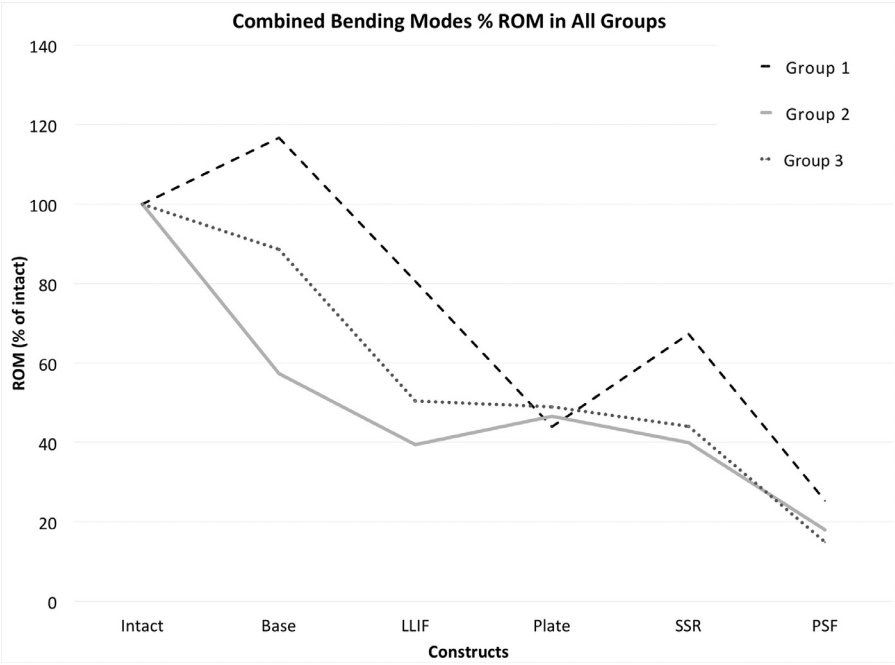

Fig. 4. Normalized mean ROM in all bending modes. Stand-alone LLIF reduced ROM at ASD level in all three groups. Supplementing LLIF with plate and SSR further reduced the ROM in all three groups. Augmentation of stand-alone LLIF with bilateral pedicle screw fixation (PSF) results in greatest reduction in ROM in all bending motions ($p < 0.05$).

Table 3
Group 3 summary of median ROM as a percentage of the intact spine with ranges

Test condition	Flexion	Extension	Lateral bending
Base	99.9 (46.9–174.3)	70.8 (37.6–146.7)	95.1 (75.5–98.8)
LLIF	36.1 (4.1–123.9)	53.1 (25.0–77.6)	62.2 (27.3–73.9)
Plate	62.4 (7.8–68.6)	52.8 (20.1–144.5)	31.6 (18.6–58.6)
SSR	41.7 (23.4–91.5)	60.5 (29.5–127.5)	29.9 (21.1–44.3)
PSF	15.8 (8.7–28.4)	16.8 (8.1–136.6)	12.3 (10.4–53.6)

ROM, range of motion; LLIF, lumbar lateral interbody fusion; SSR, single screw rod; PSF, posterior spinal fusion.

of reduction in ROM between all the groups in all bending motions (Fig. 4).

Discussion

Less invasive techniques such as LLIF may provide a viable alternative when managing symptomatic ASD with potential benefits of reduction of blood loss, length of stay, and complication profile compared with traditional posterior approach in revision surgery [11–14]. Studies on clinical and radiographic outcomes following LLIF for ASD are just appearing in the current literature [11], but there is paucity of evidence in the current literature for studies investigating the biomechanical stability of LLIF alone or other lateral-based fixation techniques in treating ASD patients with previous multilevel PSF. To our knowledge, this study is the first and largest biomechanical analysis of several different lateral-based interbody strategies for treating ASD in multilevel preexisting posterior fusion patient.

The results of our study demonstrate that LLIF instrumentation alone reduces ROM in all bending planes when implanted proximal to an existing fusion model. The reduction of ROM is also evident on previous multilevel fusion (L4–S1 and L3–S1) model. Addition of a lateral plate or SSR construct to the LLIF provided further reduction in all bending modes most apparent in lateral bending. Consistent with previous studies, the most stable construct was found to be the traditional extension of PSF. But our results suggest that LLIF can be a successful alternative from a biomechanical standpoint in the treatment of lumbar ASD, while theoretically preventing the complications associated with traditional posterior instrumentation extension.

One of the first biomechanical studies evaluating the stabilizing effects of LLIF with various supplemental internal fixation options done was by Cappuccino et al. [15]. Their study included 10 fresh-frozen cadaveric specimens and tested the intact spine, stand-alone extreme lateral interbody implant, interbody implant with lateral plate, and unilateral and bilateral pedicle screw fixation. Similar to our findings, their study showed that LLIF reduces ROM in flexion-extension and lateral bending by 31.6%. Addition of the lateral plate to LLIF further decreases the ROM to 32.5%, whereas the effects of lateral reinforcement were less pronounced in our study. Unilateral and bilateral pedicle screws further reduced ROM to 20.4% and 13.0 %, respectively. As demonstrated by our data, ROM is most reduced by pedicle screw fixation over other methods.

More recently, Metzger et al. [5] studied LLIF with and without supplemental instrumentation, to determine the stability of the rostral segment adjacent to a two-level fusion when compared with a traditional posterior revision approach. In their study, after testing the intact state, 12 fresh-frozen cadaveric specimens underwent two-level (L3–L5) transforaminal lumbar interbody fusion (TLIF) and PSF as base construct. This was followed by LLIF at ASD level (L2–L3) with subsequent supplemental fixation with the following constructs: lateral plate, spinous process plate, cortical screws, and pedicle screw fixation. A three-level TLIF was the final instrumented condition. Similar to our findings, LLIF reduced ROM in all bending planes, but when supplemented with the plate, results were more pronounced and comparable to TLIF with PSF. Their findings further strengthen our findings, and support the hypothesis that LLIF with supplemental fixation would provide comparable stability in treating ASD superadjacent to previously multilevel fused spine.

While there are potential benefits to LLIF that have attracted clinicians to pursuing this approach when treating ASD, a number of complications should also be considered. Salzmann et al. reviewed the outcomes and complications of LLIF and reported several possible complications associated with this procedure [16]. The most commonly reported complications were transient neurologic injuries. Hip flexion weakness, result of trauma to the psoas muscle during the approach and is probably not related to direct nerve injury. Although vascular injuries are rare, they are still possible. Another common phenomenon is subsidence, which may be prevented by careful endplate preparation. Other rare complications include vertebral body fractures, pseudohernia, and visceral injury.

There are several limitations to the current study, most inherent to cadaveric biomechanical studies. Despite this study being the largest cohort available in this topic, the small sample size of 18 directly affects statistical power and reflects the fragility of our data. Also, from a clinical perspective, segmental fusion is the important goal of the operation. Hence, cadaveric models are not able to determine fusion rates, as in vivo environment is required for such analyses. In addition, given the limited availability of specimens, the posterior instrumented expansion was

performed on cadavers, which already had lateral procedures inserted, tested and subsequently removed; however, we tested motion and not load to failure, which should not vary by using the same specimen. Furthermore, due to the cadaveric nature of this study, we are not able to comment about the relationships between future ASD and biomechanics of the constructs discussed in this project. In the end, we recognize that in clinical settings, the segments below ASD level may be solidly fused and the constructs discussed in this study may behave differently under such conditions.

Conclusion

We compared the ROM in flexion, extension, and lateral bending at time zero after LLIF with the traditional posterior bilateral pedicle screw rod fixation. Our results are in agreement with other reports that LLIF effectively reduces ROM, though extension of posterior instrumentation provides more substantial stability in all planes of ROM. Supplementation of lateral interbody fusion with a plate or SSR provides further stability as compared with stand-alone LLIF. Further clinical correlations are necessary to determine the benefits of augmentation of LLIF with a plate or SSR in vivo and evaluate the clinical effects and outcomes.

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