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BIOMECHANICS

Biomechanical Stability of Lateral Interbody Implants and Supplemental Fixation in a Cadaveric Degenerative Spondylolisthesis Model

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Study Design. *In vitro* cadaveric biomechanical study of lateral interbody cages and supplemental fixation in a degenerative spondylolisthesis (DS) model.

Objective. To investigate changes in shear and flexion-extension stability of lateral interbody fusion constructs.

Summary of Background Data. Instability associated with DS may increase postoperative treatment complications. Several groups have investigated DS in cadaveric spines. Extreme lateral interbody fusion (XLIF) cages with supplemental fixation have not previously been examined using a DS model.

Methods. Seven human cadaveric L4–L5 motion segments were evaluated using flexion-extension moments to ±7.5 N·m and anterior-posterior (A-P) shear loading of 150 N with a static axial compressive load of 300 N. Conditions were: (1) intact segment, (2) DS simulation with facet resection and lateral discectomy, (3) standalone XLIF cage, (4) XLIF cage with (1) lateral plate, (2) lateral plate and unilateral pedicle screws contralateral to the plate (PS), (3) unilateral PS, (4) bilateral PS, (5) spinous process plate, and (6) lateral plate and spinous process plate. Flexion-extension range of motion (ROM) data were compared between conditions and with results from a previous study without DS simulation. A-P shear displacements were compared between conditions.

Results. Flexion-extension ROM after DS destabilization increased significantly by 181% of intact ROM. With the XLIF cage alone, ROM decreased to 77% of intact. All conditions were less stable than corresponding conditions with intact posterior elements except those including the spinous process plate. Under shear loading, A-P displacement with the XLIF cage alone increased by 2.2 times intact. Bilateral PS provided the largest reduction of A-P displacement, whereas the spinous process plate alone provided the least.

Conclusion. This is the first *in vitro* shear load testing of XLIF cages with supplemental fixation in a cadaveric DS model. The variability in sagittal plane construct stability, including significantly increased flexion-extension ROM found with most fixation conditions including bilateral PS may explain some clinical treatment complications in DS with residual instability.

Key words: degenerative spondylolisthesis, XLIF, extreme lateral, stability, range of motion (ROM), lumbar interbody fusion, shear loading, shear displacement.

Level of Evidence: N/A

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Degenerative spondylolisthesis (DS) is defined by disc and facet degeneration that allows displacement of one vertebral body with respect to another. It is predominantly found in older females at the L4–L5 level, and is often associated with more sagittally oriented facets joints. The facet orientation limits resistance to normal shear and when combined with hormonal factors, buckling of the ligamentum flavum, disc degeneration, facet joint osteoarthritis, ligament laxity, ineffective muscular stabilization, high pelvic incidence, and high sacral slope leads to forward vertebral subluxation and lateral recess stenosis of the passing nerve roots.[1–4]

Powerful shear forces in spondylolisthesis affect spinal stability. The shear forces generated in the human lumbar spine *in vivo* have been estimated to be in the range of 400 to 800 N but the musculature plays a large part in resisting shear, resulting in the motion segment being subject to shear loads of approximately 200 N.[5–8] In physiological motion of the intact motion segment, the disc provides the strength and stiffness for the joint, whereas the facets guide the motion. The lumbar facets play an important role in resisting shear and axial rotation and to a lesser extent flexion-extension and lateral bending.

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The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication.

This manuscript includes unlabeled/investigational uses of the products/devices listed below and the status of these is disclosed in the manuscript: the CoRoent XL interbody cage is only FDA-cleared for use with supplemental fixation. It is not indicated for standalone use.

Material support was provided by NuVasive Inc.

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Stenosis associated with spondylolisthesis is typically treated with laminectomy, which may further increase instability by removing posterior stabilizing elements such as the ligamentum flavum, inter- and supraspinous ligaments, and part or all of the facet joints and facet capsules, leading to unsatisfactory results. Additional stabilization of the laminectomy with fusion and supplemental fixation has become the established treatment of choice. Successful outcomes depend on fusion healing that requires sufficient stability to facilitate bone growth and prevent fibrous tissue formation. The best opportunity for healing may be the anterior interbody fusion with better loading of the graft and the largest surface area for fusion. The mechanical stiffness environment of the implant construct favorably influences the healing response of the fusion. Continued motion across the operative segment is detrimental to obtaining a successful spinal fusion and may lead to treatment complications.

Because of its ability to provide indirect decompression without disrupting the posterior elements, segmental stability, and lordosis restoration, the transpsoas lateral interbody fusion (extreme lateral interbody fusion [XLIF], lateral lumbar interbody fusion [LLIF], direct lateral interbody fusion [DLIF]) technique has been proposed as a treatment for DS.[9–16] The biomechanics of this type of interbody approach with various supplemental fixation are quite well understood in normal cadaveric spines.[17–23] However, most previous biomechanical studies have not taken the spondylolisthesis pathology into account. There are limited cadaveric biomechanical studies investigating DS with shear loading,[24–28] and there has also been little emphasis on shear loading with interbody implants.[29] Our objective was to evaluate anterior-posterior (A-P) shear displacement and flexion-extension range of motion (ROM) in a spondylolisthesis model with a laterally inserted interbody cage with various supplemental fixation techniques.

MATERIALS AND METHODS

Specimen Preparation

Seven human cadaveric lumbar L4–L5 motion segments were dissected from donor spines (average age, 53.1 yr; range, 43–66 yr) and cleaned of muscle and adipose tissue, leaving the intervertebral discs, ligaments, and facet capsules intact. A-P and lateral radiographs confirmed that specimens were free of deformity or degeneration. Bone density was assessed by dual-energy x-ray absorptiometry, with average bone mineral density of 0.92 ± 0.11 g/cm^2 (range, 0.81–1.14 g/cm^2). The caudal and cephalad ends of each specimen were mounted in polyurethane resin (Smooth-Cast 300; Smooth-On Inc., Easton, PA), positioned with the disc space horizontal.

Each specimen was initially instrumented with 2 lateral plate bolts (XLP; NuVasive Inc., San Diego, CA) and 4 pedicle screws (PSs) (SpheRx DBR II; NuVasive Inc.) with the aid of fluoroscopy. Lateral plate bolts were inserted along the coronal plane, and parallel and adjacent to the L4 inferior and L5 superior endplates. Care was taken to avoid facet impingement with the PSs. Motion tracking marker arrays, consisting of 4 noncollinear infrared LEDs, were attached to the L4 and L5 vertebral bodies.

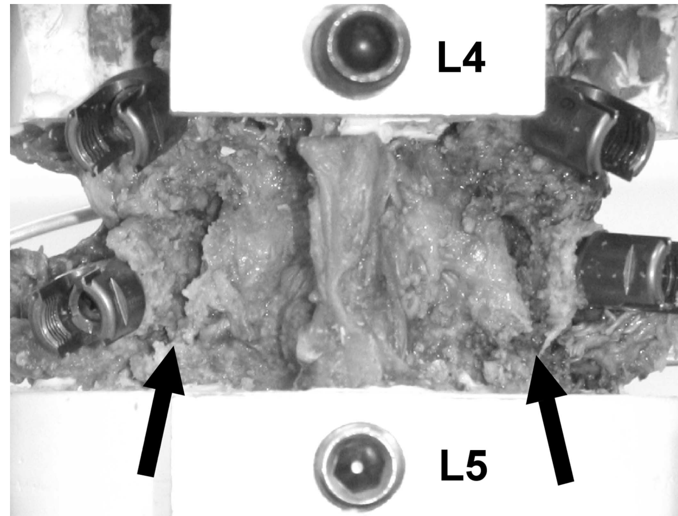

Figure 1. Posterior view of a simulated L4–L5 spondylolisthesis model specimen with bilateral facet resection using 4-mm burr (indicated by arrows), lateral annulotomy, and discectomy. Pedicle screws shown *in situ* without connecting rods.

Spondylolisthesis Simulation

In previous studies, DS has been simulated by resection of the facet joints, followed by various soft-tissue dissection including annulotomy, nucleotomy, longitudinal ligament, or ligamentum flavum.[24,27,28] In this study, spondylolisthesis was simulated at L4–L5 (Figure 1). We first created a lateral discectomy using a knife, pituitary rongeur, and curettes, preserving the anterior longitudinal ligament, the posterior longitudinal ligament, and the anterior and posterior annulus. Then, using a 4-mm burr, similar to the way of Melnyk *et al*,[27] the inferior facets were cut parallel to the joint surfaces through the anterolateral aspect of the L4 inferior articular process and the posteromedial aspect of the L5 superior articular process. On the basis of initial pilot testing, this resulted in an average A-P displacement corresponding to a Meyerding grade I spondylolisthesis (0%–25% slip; Figure 2A).

Interbody Cage Insertion

The laterally inserted XLIF cage (CoRoent XL; NuVasive Inc.) is 18-mm wide in the A-P direction and made from polyetheretherketone. Interbody sizing was based on individual specimen anatomy to determine height and lateral length, and was performed by a surgeon experienced with lateral approach surgery taking care not to damage the endplates. Implant height was in the range from 8 to 12 mm. The taller implants are likely larger than clinical use because specimens were not degenerated. Implant length was in the range from 50 to 55 mm.

Testing Equipment

Each test condition was subjected to pure moment flexibility testing followed by A-P shear loading. All testing was performed on a custom 6-*df* spine testing system described in the previous text (Figure 3A).[30] The system was modified

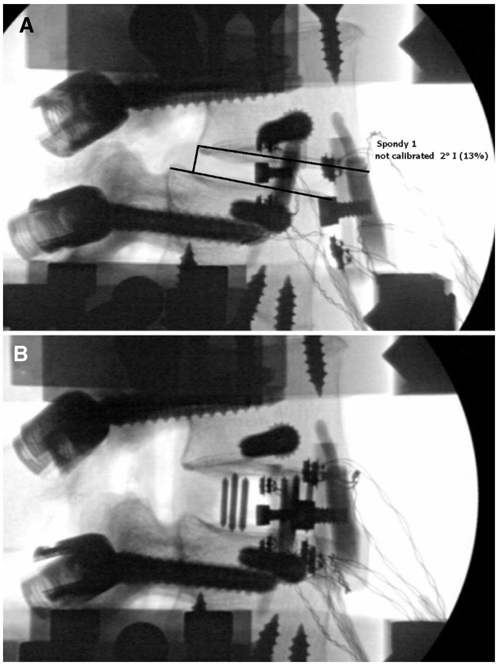

Figure 2. **A**, Creation of grade I (13% in this example) spondylolisthesis. **B**, Reduction of spondylolisthesis after insertion of the lateral cage. Disc space partially obscured by motion tracking markers. Lateral fluoroscopic images taken during initial pilot testing where zero axial load was applied during application of the A-P shear load to maximize A-P translation. A-P indicates anterior-posterior.

to include shear loading that is applied to the specimen by attaching cables to the caudal end of the specimen and applying a prescribed tension to the cables. Cable tension is controlled by a motor connected *via* load cells to the platform (Figure 3B). An infrared marker array was attached to the mobile platform.

Testing Parameters

Flexibility testing consisted of 3 cycles of unconstrained flexion-extension moments to ±7.5 N·m, with the final cycle used in data analysis. During testing, the lateral bending and axial rotation axes were commanded to zero N·m using active torque control with feedback from the 6-*df* load cell. The axial load was maintained at zero N. Testing parameters are consistent with the literature.[31,32] Motion segment kinematics were obtained using an optoelectronic motion system (Optotrak Certus; Northern Digital Inc., Waterloo, Ontario, Canada).

For shear testing, a static cranial-caudal compressive load (300 N) was initially applied *via* a pneumatic actuator. A posterior shear load was applied to the L5 vertebra using the motorized cable system while L4 was fixed. A shear load of 150 N, which is in the range of typical shear loads,[6–8] was applied. The specimen was unloaded and a smaller shear load of 25 N was applied in the reverse direction. Intervertebral A-P shear displacement was measured using the Optotrak system.

Testing Protocol

Each spine was evaluated with flexibility testing followed by shear testing under the following conditions (Figure 4):

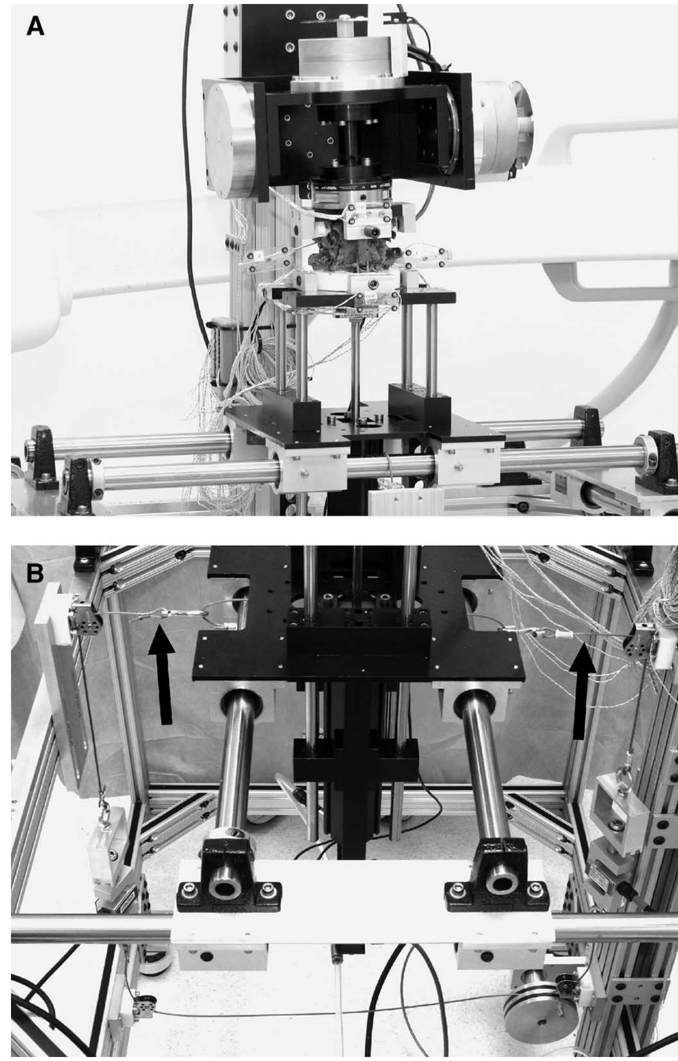

Figure 3. **A**, Custom 6-*df* spine testing apparatus with servomotors for flexion-extension, lateral bending, and axial rotation. The L4–L5 spine segment is in position with infrared LED markers on each vertebral body. **B**, Cable system for applying shear loading for specimens. Cables attached to specimen platform indicated by arrows. LED indicates light emitting diode.

(1) Intact.
(2) Simulated spondylolisthesis destabilization.
(3) Standalone laterally inserted XLIF cage.
(4) XLIF cage with various supplemental fixations such as:
    (a) lateral plate supplemental fixation,
    (b) lateral plate + unilateral PSs contralateral to the lateral plate,
    (c) unilateral PSs,
    (d) bilateral PSs,
    (e) spinous process plate, and
    (f) lateral plate + spinous process plate.

The order of construct assembly was the same for all specimens. Conditions that included the spinous process plate Conditions 4(e) and 4(f) were tested last in all cases because they required removal of the inter- and supraspinous ligaments that could have affected the kinematics of other conditions.

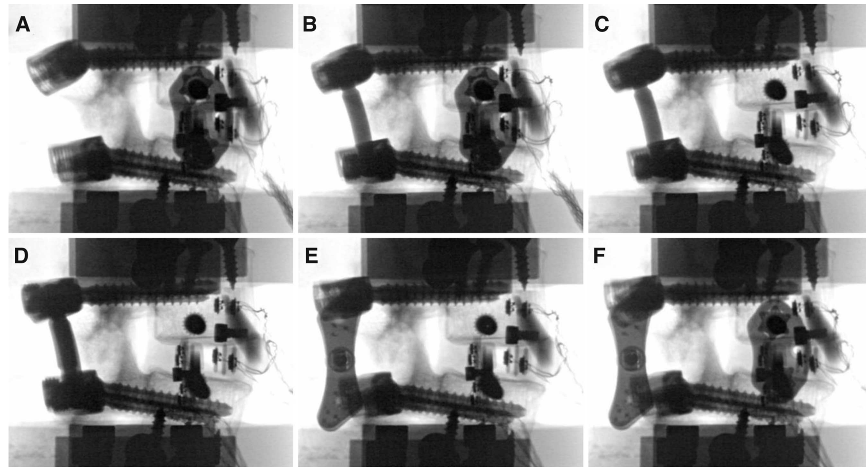

Figure 4. Representative lateral fluoroscopy images of the fixation test constructs: lateral plate (**A**), lateral plate + unilateral pedicle screws (**B**), unilateral pedicle screws (**C**), bilateral pedicle screws (**D**), spinous process plate (**E**), and lateral plate + spinous process plate (**F**).

Data Analysis

Flexion-extension L4–L5 ROM was determined for each specimen from the third loading cycle. For each experimental condition, ROM was normalized to the intact ROM. A-P shear displacement was calculated from the single cycle of A-P shear loading between 0 N and 150 N. A-P shear displacement was not normalized to intact because values were small relative to the accuracy of the optoelectronic motion system (quoted as 0.1 mm by the manufacturer) and dividing results by the intact condition shear displacements could compound error on those results. The means and standard deviations for the flexion-extension ROM and the A-P shear displacement were calculated for each test condition. For both flexion-extension ROM and A-P displacement, pair-wise comparisons were made between all conditions except the destabilized condition (condition, 2) using repeated-measures analysis of variance and the Holm-Sidak test, with a level of significance of $P < 0.05$. The spondylolisthesis defect condition was excluded from the ROM analysis because it was significantly higher than the other groups and would have reduced the ability to detect statistical differences. Similarly, A-P shear displacement in this condition was excluded because under axial load, the disc collapses and the burred surfaces of the facetectomy impinge, restricting motion under shear loading. In subsequent conditions, the lateral inserted cage elevates the disc space and increases foraminal height unlocking the facet impingement and reducing the spondylolisthesis, but A-P displacement is not restricted.

The current spondylolisthesis model flexion-extension normalized ROM data were also compared with previously reported lateral cage-specific biomechanical testing results in the intact specimen obtained at the same testing facility.[18,19] Statistical comparisons were made within each test conditions using 2-tailed *t* tests (non-normalized data were compared for the intact condition).

RESULTS

Intact flexion-extension ROM was 8.8° (standard deviation, 3.5°) (Table 1). After destabilization from the simulated spondylolisthesis, ROM increased significantly to 181% of intact. With the XLIF cage alone, ROM decreased to 77% of intact in flexion-extension (Figure 5). Introducing the lateral cage after destabilization was also noted to reduce the spondylolisthesis (Figure 2B). The most rigid constructs were those incorporating spinous process plate fixation, however there were no significant differences between fixation with bilateral PSs, spinous process plates, or a combination of spinous process and lateral plates ($P \geq 0.361$; Table 2). All conditions tested were less stable than corresponding conditions with intact posterior elements (Figure 5). The differences in ROM varied by 1.0 to 2.4 times, which were statistically significant in all cases except the spinous process plate ($P = 0.967$; Table 1) and the spinous process plate plus lateral plate conditions ($P = 0.818$).

Under shear loading, A-P displacement with the XLIF cage alone increased by approximately 2.2 times compared with the intact spine ($P = 0.002$; Figure 6). Compared with the cage alone condition, addition of supplemental fixation significantly reduced the amount of shear displacement in all cases except the spinous process plate ($P = 0.932$; Table 2), which provided the least resistance to shear. Bilateral PSs provided the largest reduction of A-P displacement however; this was not significantly different from the intact condition ($P = 0.553$).

DISCUSSION

There have been several comparable biomechanical models described for DS. Crawford *et al*[24] created a model for spondylolisthesis by removing the facet joints, complete discectomy and stripping the anterior and posterior longitudinal ligaments to loosen them. Both disc and facet destabilization procedures were necessary to create model a grade I spondylolisthesis. In their series, ROM and shear testing without compressive load showed significant increases as each phase of the destabilization process proceeded. Using this model, Cagli *et al*[29] found that cages were suboptimal standalone, and PSs with threaded interbody cages were the most stable. Melnyk *et al*[27]created a model of DS under combined loading of shear and axial compression. The same authors tested posterior dynamic fixation only without interbody implants.[25,26]

TABLE 1. Flexion-Extension ROM and A-P Shear Displacement Results

Test Condition	Flexion-Extension ROM: Spondylolisthesis Defect ROM, º	Flexion-Extension ROM: No Defect ROM, º	Flexion-Extension ROM: *P* (Defect *vs.* No Defect ROM)	A-P Shear Displacement, mm
Intact	8.8 (3.5)	6.4 (1.7)	0.081	0.33 (0.23)
Destabilized	15.2 (4.4)	n/a	n/a	0.58 (0.39)
Cage alone	6.6 (2.4)	2.0 (0.9)	**<0.001**	0.74 (0.22)
Lateral plate	6.6 (2.1)	2.1 (0.9)	**<0.001**	0.42 (0.11)
Lateral plate + Unilateral PS	3.4 (1.4)	1.3 (0.7)	**0.002**	0.24 (0.07)
Unilateral PS	4.8 (1.9)	1.4 (0.7)	**<0.001**	0.30 (0.28)
Bilateral PS	2.1 (0.8)	0.8 (0.3)	**0.002**	0.16 (0.17)
Spinous process plate	1.5 (0.6)	1.1 (0.6)	0.967	0.63 (0.21)
Spinous process + lateral plates	1.3 (0.3)	1.0 (0.5)	0.818	0.36 (0.17)

P values from mean and standard deviation flexion-extension ROM values for this study (spondylolisthesis defect) and existing (no defect[18,19]) data.

2-tailed t tests between spondylolisthesis defect and no defect flexion-extension ROM data for each test condition (no comparisons between conditions, data normalized to intact prior to comparisons, statistically significant values [P < 0.05] shown in bold-type text), and mean and standard deviation.

A-P shear displacement values for this study.

ROM indicates range of motion; A-P, anterior-posterior; n/a, not applicable.

We were able to create a spondylolisthesis model with reproducible results. Our results show that flexion-extension ROM drastically increased with the spondylolisthesis defect to 181% of intact. Introduction of the lateral cage reduced ROM significantly ($P < 0.001$) to less than intact, which was in contrast to the finding by Cagli *et al*,[29] where ROM remained greater than intact after insertion of anterior threaded interbody devices. Lack of anterior longitudinal ligament retention was one reason cited by the authors. The lateral interbody fusion technique retains this ligament that is tensioned along with the posterior longitudinal ligament and remaining annulus with cage insertion, providing rigidity to the segment. Endplate preservation is therefore important to achieving initial stability. In this study, all supplemental fixation methods evaluated, except the lateral plate, further reduced ROM significantly with respect to the cage alone ($P < 0.001$). Comparing current ROM results with previous data[18,19] with posterior elements intact (Figure 5) revealed significant increases in flexion-extension ROM with each type of fixation in the spondylolisthesis model, with the exception of the spinous process plate conditions. For other conditions, there was 1.9 to 2.4 times more motion than with posterior elements intact. Lower ROM in the previous studies indicates that intact facet joints, in combination with the retained longitudinal ligaments and annulus, contribute to stability. Lateral interbody fusion may allow for preservation of the posterior structural elements through ligamentotaxic spondylolisthesis reduction and indirect decompression of the neural elements,[9,10,15] providing a more biomechanically stable environment for facilitating fusion in patients. However, patients further along the degenerative cascade may not be adequately addressed by indirect decompression alone due to osteophyte formation.[15]

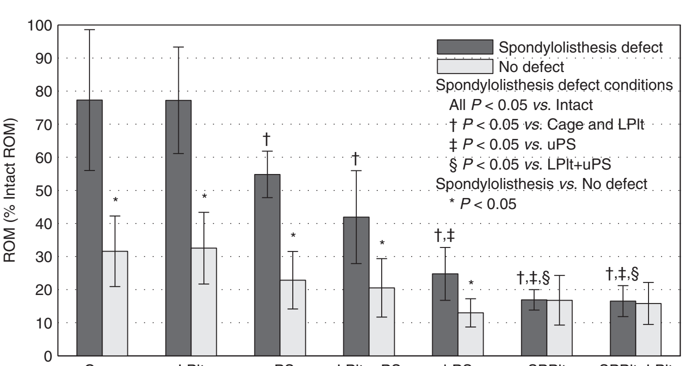

Figure 5. Mean flexion-extension ROM as a percent of intact spine comparing current data (spondylolisthesis defect) with existing data (no defect[18,19]). Error bars represent ±1 standard deviation. Cage denotes cage alone condition; LPlt, lateral plate; uPS, unilateral pedicle screws; LPlt + uPS, lateral plate + unilateral pedicle screws; bPS, bilateral pedicle screws; SPPlt, spinous process plate; SPPlt + LPlt, spinous process plate + lateral plate. ROM indicates range of motion.

Under combined shear and compressive load, the anterior shear displacement with an anterior cage alone increased by 2.2 times over the intact spine ($P = 0.002$). Lateral plate plus unilateral PSs and bilateral PSs were the only conditions to reduce shear displacement below intact. Bilateral PSs were the most rigid fixation in this direction. All fixation methods except the spinous process plate alone significantly reduced shear displacement with respect to the cage alone ($P < 0.029$). Interestingly, the lateral plate did not improve flexion-extension ROM over the cage alone ($P = 0.987$), however it provided a significant reduction in A-P translation ($P = 0.029$). Similarly, the lateral plate provided a significant reduction in translation when added to the spinous process plate ($P = 0.001$). Also, of note was that the spinous process plate provided the greatest

TABLE 2. *P* Values From Statistical Comparisons Among Test Conditions

Test Conditions	Flexion-Extension	A-P Shear Displacement
Intact *vs.*		
Cage alone	**<0.001**	**0.002**
Lateral plate	**<0.001**	0.960
Lateral plate + unilateral PS	**<0.001**	0.950
Unilateral PS	**<0.001**	0.953
Bilateral PS	**<0.001**	0.559
Spinous process plate	**<0.001**	**0.043**
Spinous process + lateral plates	**<0.001**	0.928
Cage alone *vs.*		
Lateral plate	0.987	**0.029**
Lateral plate + unilateral PS	**<0.001**	**<0.001**
Unilateral PS	**<0.001**	**0.007**
Bilateral PS	**<0.001**	**<0.001**
Spinous process plate	**<0.001**	0.932
Spinous process + lateral plates	**<0.001**	**0.005**
Lateral plate *vs.*		
Lateral plate + unilateral PS	**<0.001**	0.560
Unilateral PS	**<0.001**	0.977
Bilateral PS	**<0.001**	0.114
Spinous process plate	**<0.001**	0.331
Spinous process + lateral plates	**<0.001**	0.976
Lateral plate + unilateral PS *vs.*		
Unilateral PS	0.083	0.860
Bilateral PS	0.012	0.924
Spinous process plate	**<0.001**	**0.004**
Spinous process + lateral plates	**<0.001**	0.897
Unilateral PS *vs.*		
Bilateral PS	**<0.001**	0.314
Spinous process plate	**<0.001**	0.123
Spinous process + lateral plates	**<0.001**	0.899
Bilateral PS *vs.*		
Spinous process plate	0.361	**<0.001**
Spinous process + lateral plates	0.402	0.358
Spinous process plate *vs.*		
Spinous process + lateral plates	0.997	**0.100**

Statistically significant values (P < 0.05) are shown in bold-type text.
Destabilized condition is excluded from the analysis.
A-P indicates anterior-posterior.

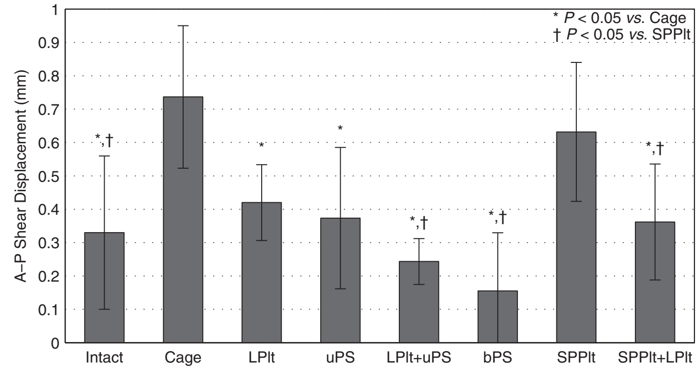

Figure 6. Mean anterior-posterior shear displacement. Error bars represent ±1 standard deviation. Intact denotes intact condition; cage, cage alone condition; LPlt, lateral plate; uPS, unilateral pedicle screws; LPlt + uPS, lateral plate + unilateral pedicle screws; bPS, bilateral pedicle screws; SPPlt, spinous process plate; SPPlt + LPlt, spinous process plate + lateral plate.

reduction in flexion-extension ROM, yet the least reduction in A-P shear. The lateral and spinous process plates when not applied in combination demonstrated a lack of correlation between rotational stability and translational stability.

This study and previous studies[24,27,28] simulating DS showed significant increases in ROM (hypermobility) that potentially overestimates clinical instability. Radiographical studies demonstrate that some patients with DS in fact display normal ROM or hypomobility.[33–37] This may be due to restabilization as described in the study by Kirkaldy-Willis and Farfan,[38] where degeneration progresses from normal to dysfunctional to unstable and then the segment restabilizes. Alternatively, hypomobility may be attributed to pain and muscle spasms.[37,39,40] In the DS biomechanical studies, the facet joint is violated to allow anterior subluxation of L4 with respect to L5 as seen clinically. Because the facet joint is an important stabilizing structure, this has the effect of increasing ROM, producing results not unlike studies investigating the iatrogenic instability associated with direct posterior decompression including facetectomy,[41,42] or in studies investigating isthmic spondylolisthesis.[43–45] These ROM results may not be applicable to a DS surgical technique that relies on indirect decompression, such as a lateral-approach interbody fusion, although if additional posterior decompression is required, the test results suggest greater instability may be present. Because of uncertainty about the clinical implications of the ROM data caused by disrupting the facets, we limited our analysis to the sagittal plane. A number of studies investigating intraoperative and *in vitro* spinal instability were also limited to this plane.[28,46–48]

Treatment solutions for DS have been effective.[10,49–59] Weinstein *et al*[49] concluded from the Spine Patient Outcomes Research Trial study that patients with DS and spinal stenosis treated surgically showed substantially greater improvement in pain relief and function than patients treated nonsurgically for 4 years. A review by Martin *et al*[50] suggests that a fusion is more likely to have a satisfactory result than with decompression alone. There is moderate evidence that adding instrumentation enhances the fusion rate.[50–56] Depending on the treatment method, patients with spondylolisthesis treated with surgery with preoperative instability factors including motion on flexion-extension radiograph,[4,55,57,58] tall disc height, and sagittal facet angle,[59] previous laminectomy and facetectomy,[4,60] or localized kyphosis or scoliosis,[4,61] may be more prone to complications such as increased slip,[51,56,62] progressive kyphosis,[51,55,62] higher rate of pseudarthrosis,[51,58] extrusion of inserted cages,[63–65] failure of interspinous process devices,[66,67] and higher incidence of PS failure.[55,56,60] Although the rate of these complications is low, poor outcomes and a higher rate of revision surgery are more likely to occur in these patients. Postoperative stability afforded by rigid supplemental fixation seems important to obtaining good clinical results, and conversely, residual instability may be associated with less successful results. In this study, the rotational and translational instability created by the simulated DS was variable across the supplemental fixation devices, which may lend some explanation for complications in spondylolisthesis, decompression, and fusion with residual instability. The laterally inserted interbody cage with bilateral PS supplemental fixation provided the best combination of both flexion-extension and A-P shear stability. The increased displacements in some other conditions suggest the supplemental fixation may not always be sufficient in spondylolisthesis to enhance the fusion environment. Therefore, the biomechanical behavior and requirements of the supplemental fixation devices should be understood.

This study has limitations that are shared with most other cadaveric biomechanics studies. The sample size was limited to 7, with specimens of variable bone density and preexisting intervertebral motion. Simplified loading was applied to be repeatable between specimens and independent of specimen size. Sequence dependence was another limitation. The 7.5-N·m pure moments are considered to be nondestructive, however less is known about the A-P shear loading. It is possible that sequential shear tests may have led to diminished shear displacement however, the ROM testing before each shear test may have acted to precondition each condition similarly. We chose a load that was less than prior studies and applied a small reverse load to limit sequence dependence. Another limitation is that the no defect/existing ROM to which the spondylolisthesis defect ROM was compared was obtained from the L3–L4 level in L1–L5 specimens. A different level (L4–L5) was used in this study because it is the predominant level where DS presents. In addition, intact adjacent levels were not available because a direct mechanical connection between the test system and the L4 and L5 vertebrae is needed to apply and measure shear loads and displacements. It is likely that these differences are accounted for by normalizing the ROM data to intact, because both effects should be constant for all test conditions. This can be assessed by comparing the non-normalized intact ROM data where a statistically significant difference was not detected between the spondylolisthesis defect and no defect groups ($P = 0.081$; Table 2), which suggests variation between specimens may be more meaningful than differences due to choice of spinal level or presence of adjacent intact levels.

CONCLUSION

This is the first *in vitro* shear load testing of lateral-approach interbody fusion cages with supplemental fixation in a human cadaveric DS model. The variability in sagittal plane construct stability, including significantly increased flexion-extension ROM found with most supplemental fixation devices including bilateral PSs over a spine without the spondylolisthesis defect, may explain some clinical treatment complications in spondylolisthesis, decompression, and fusion with residual instability. Consideration should be given to including shear loading in biomechanical studies to understand behavior in spondylolisthesis applications.

➢ Key Points

- ❑ This cadaveric study investigated the instability associated with DS.
- ❑ There was significant increased instability in flexion-extension ROM found with all types of supplemental fixation with the exception of conditions including the spinous process plate.
- ❑ A-P shear displacement was only reduced below intact with bilateral PS and a combination of lateral plate and unilateral PS.
- ❑ The increased instability with many fixation options may explain clinical treatment complications in spondylolisthesis.

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