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Biomechanics of lateral lumbar interbody fusion constructs with lateral and posterior plate fixation

Laboratory investigation

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Object. Lumbar interbody fusion is indicated in the treatment of degenerative conditions. Laterally inserted interbody cages significantly decrease range of motion (ROM) compared with other cages. Supplemental fixation options such as lateral plates or spinous process plates have been shown to provide stability and to reduce morbidity. The authors of the current study investigate the in vitro stability of the interbody cage with a combination of lateral and spinous process plate fixation and compare this method to the established bilateral pedicle screw fixation technique.

Methods. Ten L1–5 specimens were evaluated using multidirectional nondestructive moments (± 7.5 N·m), with a custom 6 degrees-of-freedom spine simulator. Intervertebral motions (ROM) were measured optoelectronically. Each spine was evaluated under the following conditions at the L3–4 level: intact; interbody cage alone (stand-alone); cage supplemented with lateral plate; cage supplemented with ipsilateral pedicle screws; cage supplemented with bilateral pedicle screws; cage supplemented with spinous process plate; and cage supplemented with a combination of lateral plate and spinous process plate. Intervertebral rotations were calculated, and ROM data were normalized to the intact ROM data.

Results. The stand-alone laterally inserted interbody cage significantly reduced ROM with respect to the intact state in flexion-extension (31.6% intact ROM, $p < 0.001$), lateral bending (32.5%, $p < 0.001$), and axial rotation (69.4%, $p = 0.002$). Compared with the stand-alone condition, addition of a lateral plate to the interbody cage did not significantly alter the ROM in flexion-extension ($p = 0.904$); however, it was significantly decreased in lateral bending and axial rotation ($p < 0.001$). The cage supplemented with a lateral plate was not statistically different from bilateral pedicle screws in lateral bending ($p = 0.579$). Supplemental fixation using a spinous process plate was not significantly different from bilateral pedicle screws in flexion-extension ($p = 0.476$). The combination of lateral plate and spinous process plate was not statistically different from the cage supplemented with bilateral pedicle screws in all the loading modes ($p \geq 0.365$).

Conclusions. A combination of lateral and spinous process plate fixation to supplement a laterally inserted interbody cage helps achieve rigidity in all motion planes similar to that achieved with bilateral pedicle screws.
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Key Words • **lumbar interbody fusion** • **XLIF** • **stability** • **fixation** • **range of motion**

Lumbar interbody fusion is indicated in the treatment of lumbar stenosis, spondylolisthesis, trauma, and discogenic pain of the lumbar spine. Successful outcomes depend on fusion. The best opportunity for fusion may be anterior interbody fusion owing to improved loading of the graft and the largest surface area for fusion compared with other techniques.[22,25,32] Several operative approaches are commonly used to access the anterior column for fusion, including posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF), anterior lumbar interbody fusion (ALIF), and more recently, lateral transpsoas approach (or the extreme-lateral interbody fusion [XLIF]). The interbody cage is often supplemented by internal fixation. The mechanical stiffness environment of the implanted construct influences the healing response of the fusion.

Studies have shown that laterally inserted interbody cages significantly decrease range of motion (ROM) compared with PLIF, TLIF, or ALIF cages.[4,16,24,26] The cage

Abbreviations used in this paper: ALIF = anterior lumbar interbody fusion; BMD = bone mineral density; PLIF = posterior lumbar interbody fusion; ROM = range of motion; TLIF = transforaminal lumbar interbody fusion; XLIF = extreme-lateral interbody fusion.

stability may decrease the rigidity requirements of the supplemental fixation. Supplemental fixation is typically employed to maximize stability to allow bony fusion to occur. The choice of fixation method is driven by many factors, including instability, bone quality, hypoplastic pedicles, activity level of the patient, and previous surgeries. Bilateral pedicle screw constructs, applied through open or percutaneous techniques, provide multiplanar stability[4,14,30] and have the longest clinical history of supplementing interbody fusion. However, bilateral pedicle screw fixation requires an additional posterior procedure that not only requires patient repositioning but may also result in morbidity and further complications,[1,6,9–12,15,17–19,21,29,35] which may reduce the clinical and practical advantages of a minimally invasive lateral procedure.

Fixation options for lateral interbody fusion such as lateral plates and spinous process plates have been shown to provide stability[3,4,7,8,14,16] and to reduce morbidity.[20,27,28,33,37] Lateral plates have the advantage of being applied through the same surgical corridor as the interbody cage. Spinous process plates may be placed with the patient in the same lateral decubitus position used for the interbody procedure, avoiding the need for repositioning. Clinically, both of these supplemental fixation options potentially shorten operative times, decrease blood loss, and reduce fluoroscopic exposure compared with bilateral pedicle screw fixation. From a biomechanical standpoint, lateral plates have been shown to add stiffness in lateral bending and axial rotation but little in flexion-extension.[3,4,16] Spinous process plates as an adjunct to XLIF interbody cages have not been investigated. Studies have shown that spinous process plates, when supplementing ALIF or TLIF interbody cages, are most effective in reducing flexion-extension motion but are less so in lateral bending and axial rotation.[7,8,14,31,34]

Considering the relative stability provided by spinous process plates and lateral plates in different planes, a combination of these plates may provide multiplanar stability similar to that of bilateral pedicle screws. This fixation combination may also provide clinical benefits due to the reduced morbidity associated with the minimally invasive surgical approaches compared with pedicle screws.

The current study investigates the stability of this combination of lateral and spinous process plates for supplemental fixation of XLIF in an in vitro cadaveric model, and results are compared to those of established bilateral pedicle screw fixation.

Methods

Specimen Selection and Preparation

Ten lumbar specimens (L1–5) were dissected from fresh-frozen cadaveric specimens (average age 53.2 years, range 25–72 years; 9 males, 1 female). Anteroposterior and lateral radiographs were obtained to confirm that the specimens were free of deformity, excessive degeneration, and prior instrumentation. Suitable bone mineral density (BMD) was confirmed in all specimens using standard anteroposterior dual-energy x-ray absorptiometry (Discovery C, Hologic Inc.); the average BMD was 0.851 g/cm^2 (range 0.695–1.043 g/cm^2). The specimens were cleaned of musculature and adipose tissue, taking care to retain all ligamentous structures.

In preparation for biomechanical testing, the rostral (L-1) and caudal (L-5) ends of each specimen were rigidly potted using wood screws and polymethylmethacrylate with the L3–4 level positioned in the horizontal plane. Bilateral pedicle screws (6.5 × 40–45 mm; SpheRx DBR II, NuVasive, Inc.) and lateral plate bolts (5.5 × 50–55 mm; XLP, NuVasive, Inc.) sized to fit the individual specimen anatomy were implanted at the L-3 and L-4 vertebrae, initially without connecting rods or lateral plates. This was not thought to influence biomechanical outcomes, as the screws were placed taking care to avoid facet impingement and the lateral bolts were not in contact with any motion-inhibiting structures. Marker arrays consisting of 4 noncollinear infrared light–emitting diodes were attached to each vertebral body for tracking of 3D specimen angular motions during testing by an optoelectronic motion capture system (Optotrak Certus, Northern Digital, Inc.). Intervertebral rotations were calculated using rigid body kinematics.

Flexibility Testing

Prior to biomechanical testing, all specimens were thawed overnight. Specimens were subjected to nondestructive multidirectional testing using a Labview-controlled (National Instruments Corp.) custom-built 6 degrees-of-freedom spine testing system described previously.[5] Forces and moments were continuously measured by a 6 degrees-of-freedom load cell mounted at the cranial end of the specimen. The specimens were loaded with unconstrained pure moments of ± 7.5 N·m in the sagittal plane (flexion-extension), coronal plane (left-right lateral bending), and transverse plane (left-right axial rotation). No compressive preload was applied.[23,36] Three cycles of pure-moment flexion-extension, lateral bending, and axial rotation were performed, with data evaluation from the third cycle.

Study Protocol

The specimens were tested under the following conditions (Fig. 1): 1) intact; 2) lateral interbody cage alone (stand-alone); 3) cage supplemented with lateral plate; 4) cage supplemented with ipsilateral pedicle screws; 5) cage supplemented with bilateral pedicle screws; 6) cage supplemented with spinous process plate; and 7) cage supplemented with a combination of lateral plate and spinous process plate.

All specimens were first tested intact and baseline kinematics data were recorded. A subtotal discectomy was then performed at the L3–4 level; this consisted of resection of the ipsilateral and contralateral anulus, nucleotomy, and removal of the cartilaginous endplates, while taking care to preserve the bony endplates. Each specimen was then implanted with an 18-mm-anteroposterior-width interbody cage (CoRoent XL, NuVasive). Cages were sized by surgeons experienced with lateral approach surgery. The lateral width was selected to span the ring apophysis, and height was determined subjectively to provide adequate distraction and tensioning of the ligaments.

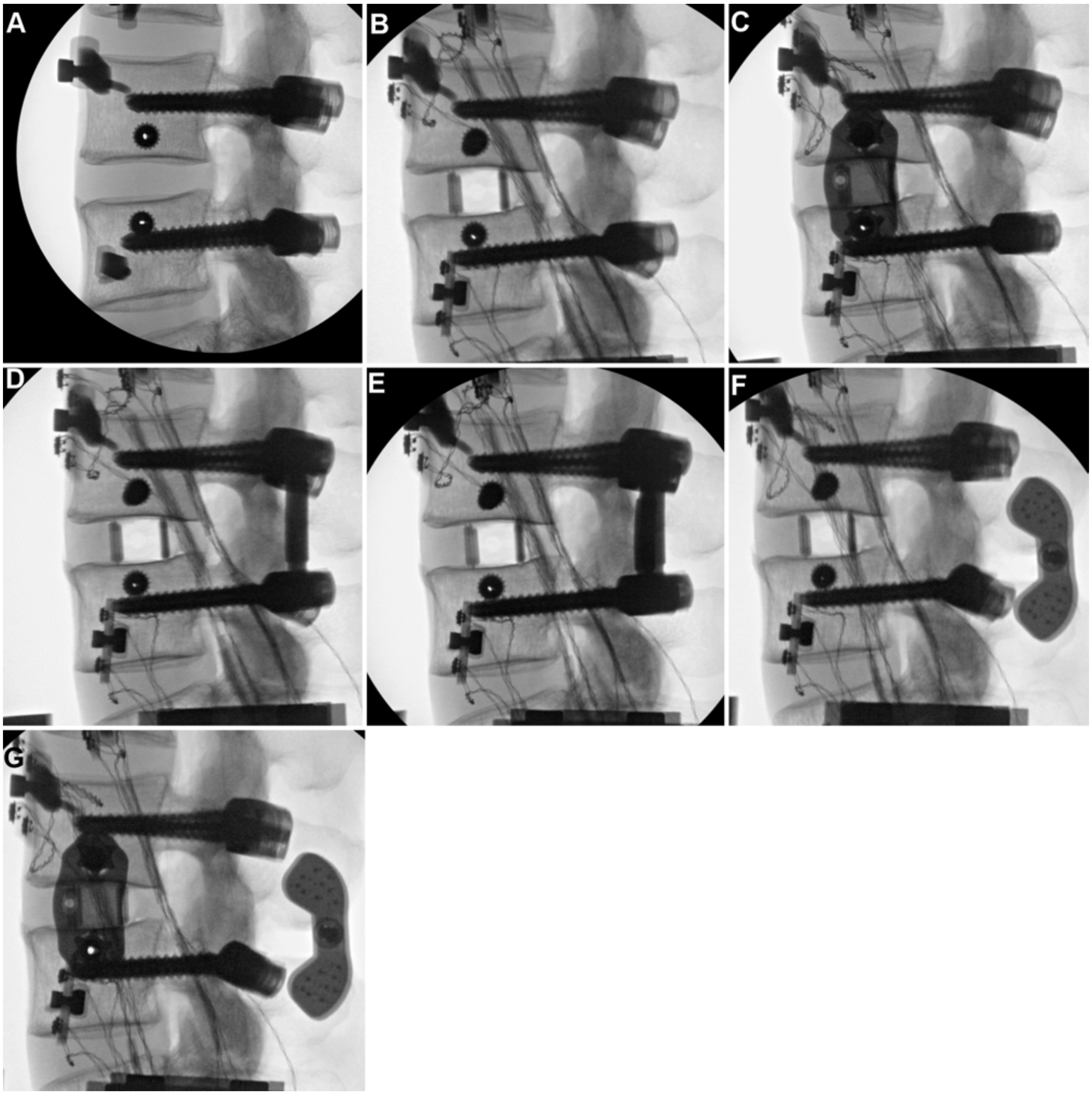

Fig. 1. Representative lateral fluoroscopy images of the test constructs: intact spine **(A)**, stand-alone cage **(B)**, cage with lateral plate **(C)**, cage with ipsilateral pedicle screws **(D)**, cage with bilateral pedicle screws **(E)**, cage with spinous process plate **(F)**, and cage with spinous process plate plus lateral plate **(G)**.

After the stand-alone condition was tested, the lateral plate was applied and testing was repeated. To test the ipsilateral and bilateral pedicle screw conditions, the lateral plate was removed, leaving the bolts in place, and the ipsilateral and then contralateral 5.5-mm-diameter titanium rods were secured. The rods were then removed, and resection of the interspinous and supraspinous ligaments was performed. A 45-mm spinous process plate (Affix, NuVasive) was then applied, and testing was completed with and without the lateral plate. The order of testing of the pedicle screws (ipsilateral/bilateral) and lateral plates was randomized to limit sequence bias. Since the spinous process plate conditions required resection of the supraspinous and interspinous ligaments, these conditions were always instrumented last. Additionally, the order of the last two conditions with spinous process plate fixation was alternated among specimens.

Statistical Analysis

Index level (L3–4) ROM for each condition was normalized to the intact condition and the means and standard deviations were calculated. Pairwise comparisons of ROM were made between test conditions within each loading direction by using repeated-measures ANOVA and the Holm-Sidak test, with a level of significance of $p < 0.05$. Comparisons were initially performed with all conditions included and additionally with the intact data excluded from the analysis.

Results

In all 3 directions of loading, ROM at the index level was significantly decreased from the intact condition for the stand-alone interbody condition and the cage with supplemental fixation conditions ($p \leq 0.002$). The interbody cage alone significantly reduced ROM in flexion-extension (31.6% of the intact ROM, $p < 0.001$) and lateral bending (32.5%, $p < 0.001$). In axial rotation, the reduction in motion was not as great, with stand-alone ROM of 69.4% ($p = 0.002$), but the initial intact ROM (2.6°) was small and more than half that of the intact ROMs in the other 2 directions (flexion-extension 6.4°; lateral bending 8.4°). The ROMs normalized to the intact state in the 3 planes of motion for each test condition are presented in Fig. 2 and p values are presented in Table 1.

Compared with the stand-alone condition, the addition of a lateral plate to the interbody cage did not significantly alter flexion-extension ROM ($p = 0.904$); however, it significantly decreased the ROM in lateral bending ($p < 0.001$) and axial rotation ($p < 0.001$). The cage and lateral plate ROM was not statistically different from the bilateral pedicle screw ROM in lateral bending ($p = 0.579$). Ipsilateral pedicle screws decreased the ROM with respect to the stand-alone condition in all loading modes ($p \leq 0.002$) and was not significantly different from the lateral plate ROM in lateral bending ($p = 0.216$) and axial rotation ($p = 0.763$). Supplemental bilateral pedicle screw fixation provided the most rigid construct in all the loading modes; the ROM was significantly reduced compared to use of a cage alone ($p < 0.001$).

The ROM for spinous process plate fixation was significantly reduced in flexion-extension compared to the stand-alone cage condition ($p < 0.001$), but it was not significantly different in lateral bending ($p = 0.707$) or axial rotation ($p = 0.813$). Compared with the lateral plate, the spinous process plate was significantly more rigid in flexion-extension ($p < 0.001$) but significantly less rigid in lateral bending and axial rotation ($p < 0.001$). The ROM for the spinous process plate was not significantly different from that of the bilateral pedicle screws in flexion-extension ($p = 0.476$). However, similar to the lateral plate, bilateral pedicle screws provided significantly more stability in lateral bending and axial rotation ($p < 0.001$). The combination of a lateral plate and a spinous process plate created the second-most rigid construct in all the loading directions and was the only test condition not statistically different from bilateral pedicle screws in all loading modes ($p = 0.565$, flexion-extension; $p = 0.568$, lateral bending; and $p = 0.365$, axial rotation).

Discussion

The current study shows that supplemental lateral plate fixation in the setting of a laterally inserted interbody cage provides stability in lateral bending and axial rotation comparable to that of bilateral pedicle screws; however flexion-extension was not improved. These findings are in agreement with those of previous biomechanical studies.[3,4,16] Conversely, the spinous process plate imparted stability comparable to that of bilateral pedicle screws in flexion-extension while offering little improvement in lateral bending and axial rotation. This finding also corroborated findings in the literature for spinous process plates when used in conjunction with other interbody approaches (ALIF[8,14,34] and TLIF[7,31]). Furthermore, we also found that a combination of lateral and spinous process plates created stability similar to that of bilateral pedicle screws in all loading directions, whereas the individual plates alone were not able to do so. Biomechanical studies using a combination approach for supplemental fixation in ALIF constructs (spinous process plate + ALIF interbody with integrated screws[14] or with anterior plate[8]) and TLIF constructs (spinous process plate + TLIF interbody + unilateral pedicle screws[7,31]) have also shown multiplanar stability comparable to bilateral pedicle screws.

The combination of lateral and spinous process plate fixation adds an alternative surgical method that can be performed from a lateral operating position with minimal blood loss and can offer potentially reduced operative and fluoroscopic exposure time. The combination technique may be useful in patients with hypoplastic pedicles, in those with damaged or overgrown pedicles due to previous surgery, or in patients with adjacent-segment degeneration in whom extension of the posterior instrumentation is required. However, in patients with higher activity levels, in individuals who are obese in whom high loads are expected, or in patients in whom the bone is weakened by osteoporosis, the implant-bone interface strength may be insufficient, resulting in spinous process fractures, especially in patients with osteoporotic bone.[2,13] Similarly, in patients with endplate fractures, lateral plate fixation may not provide sufficient strength and may increase the chances of cage migration and subsidence. In such cases, bilateral pedicle screw fixation may provide better implant-bone interface strength because of multiple fixation points and better load distribution.

Limitations exist with this in vitro cadaveric study. The results extend only to the immediate postoperative state, without taking into account the biological healing process and long-term effects of fatigue and settling on the strength of the implants and the implant-bone interfaces. Multiple fixation options were tested on the same specimen with the spinous process plate being always the last configuration to be tested because of the resection of the supraspinous and interspinous ligaments. Specimens had variable BMDs; however they were screened using dual-energy x-ray absorptiometry to exclude osteoporotic specimens. Although applied loads were considered nondestructive, multiple test conditions applied to the same specimen might have influenced the results of later test conditions due to viscoelastic changes to soft tissue—for example, loss of longitudinal ligament and anular tension around the interbody cage or loosening of the implant-bone interfaces. This could have resulted in decreased stiffness of constructs tested later in the sequence, and longer-term cyclic testing may have provided different

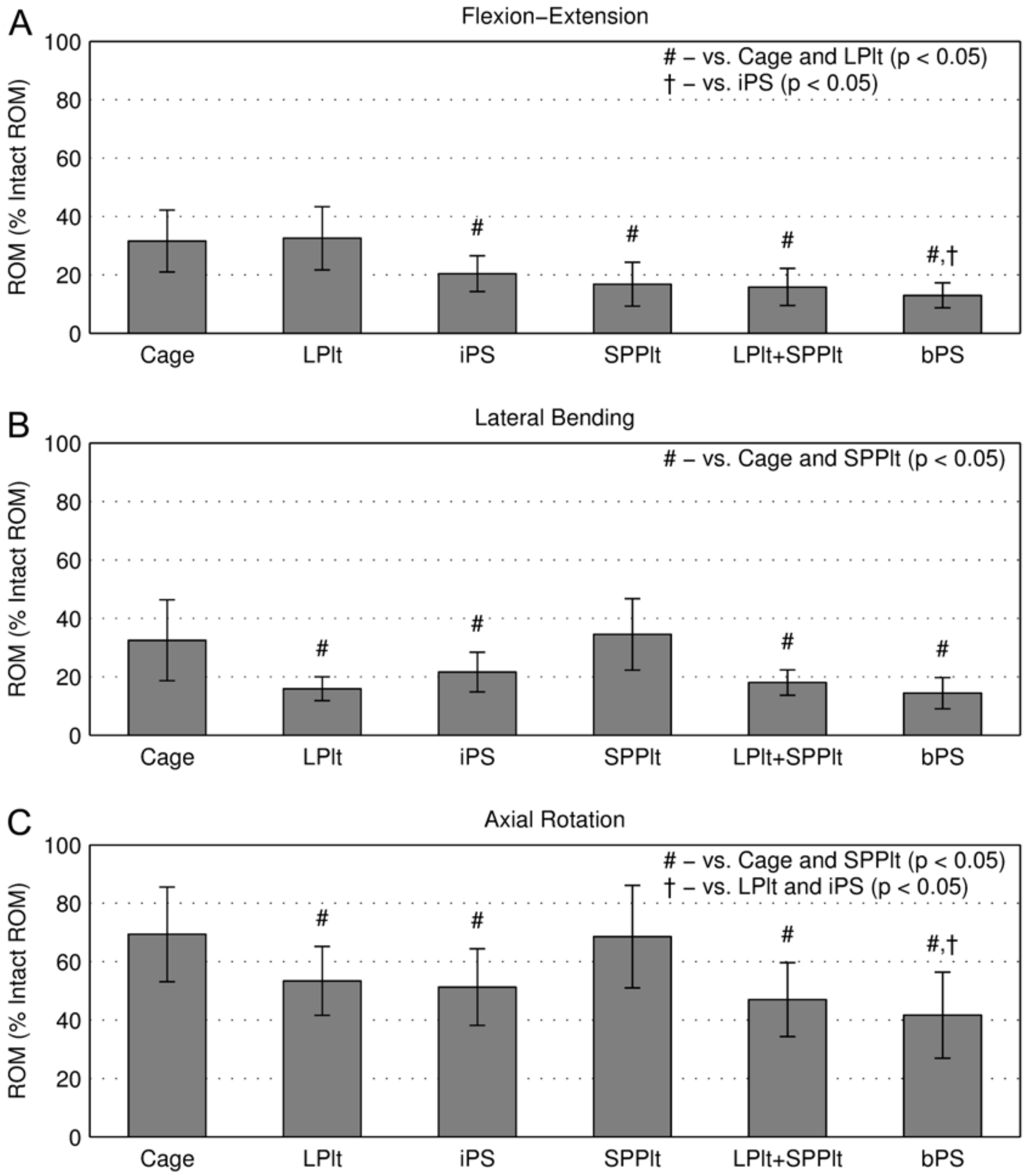

Fig. 2. Mean ROM normalized to intact ROM at L3–4 in flexion-extension **(A)**, lateral bending **(B)**, and axial rotation **(C)**. *Error bars* indicate ± 1 SD. bPS = bilateral pedicle screws; iPS = ipsilateral pedicle screws; LPlt = lateral plate; SPPlt = spinous process plate.

results. Additionally, on completion of the testing we did not detect loosening of the pedicle screws and lateral plate bolts. This study compares supplementary fixation techniques with laterally inserted interbody cages, and hence the findings should be interpreted with the understanding that they apply only to this particular interbody technique. Additionally, the interbody cage was inserted into healthy excised spine specimens with good bone quality and no existing pathology. The surgical procedure may therefore not be fully representative of the actual clinical situation. Further clinical studies examining the various fixation options are needed to fully elucidate the differences between them.

The results obtained in this biomechanical study suggest that a combination of lateral and spinous process plate fixation provides stability similar to that of bilateral pedicle screws. Each of these techniques has intrinsic advantages, but there is no fixed guideline on the use of one technique over the other. The surgeon should take into consideration the biomechanical and patient-specific factors in selecting the appropriate supplemental fixation technique for a laterally inserted interbody cage.

Conclusions

A combined anterior-posterior fixation of lateral plate and a spinous process plate to supplement a laterally inserted interbody cage provides rigidity in all mo-

TABLE 1: Summary of p values determined from statistical comparisons between each test condition in each plane of motion*

Comparison	Flexion-Extension	Lateral Bending	Axial Rotation
intact vs all operative conditions	**<0.001**	**<0.001**	**0.002**
XLIF/supplemental fixation conditions			
stand-alone vs ipsilat screw	**<0.001**	**0.002**	**<0.001**
stand-alone vs bilat screw	**<0.001**	**<0.001**	**<0.001**
stand-alone vs lat plate	0.904	**<0.001**	**<0.001**
stand-alone vs SPPlt	**<0.001**	0.707	0.813
stand-alone vs lat plate + SPPlt	**<0.001**	**<0.001**	**<0.001**
ipsilat screw vs bilat screw	0.025	0.070	0.029
ipsilat screw vs lat plate	**<0.001**	0.216	0.763
ipsilat screw vs SPPlt	0.460	**<0.001**	**<0.001**
ipsilat screw vs lat plate + SPPlt	0.335	0.643	0.480
bilat screw vs lat plate	**<0.001**	0.579	**0.005**
bilat screw vs SPPlt	0.476	**<0.001**	**<0.001**
bilat screw vs lat plate + SPPlt	0.565	0.568	0.365
lat plate vs SPPlt	**<0.001**	**<0.001**	**<0.001**
lat plate vs lat plate + SPPlt	**<0.001**	0.827	0.246
SPP vs lat plate + SPPlt	0.695	**<0.001**	**<0.001**

* Boldface type indicates statistical significance as determined by repeated-measures ANOVA and Holm-Sidak test. SPPlt = spinous process plate.

tion planes, similar to that provided by bilateral pedicle screws, which is not available when using the individual plates alone. This combination may offer an alternative to bilateral pedicle screw fixation, with the afforded advantages of less invasiveness and single-position surgery.

Disclosure

Support for this study was provided by NuVasive, Inc. NuVasive, Inc., assisted with study design, materials, collection, management, analysis, and interpretation of the data, as well as preparation and review of the manuscript.

Mr. Parikh owns stock in and is an employee of NuVasive, Inc. Dr. Ryu is a consultant to NuVasive, Inc. Dr. Turner owns stock in and is an employee of NuVasive, Inc.

Author contributions to the study and manuscript preparation include the following. Conception and design: Fogel, Turner. Acquisition of data: Fogel, Parikh, Turner. Analysis and interpretation of data: all authors. Drafting the article: Fogel, Parikh, Turner. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Fogel. Statistical analysis: Turner. Administrative/technical/material support: Turner. Study supervision: Fogel, Turner.

References

1. Amato V, Giannachi L, Irace C, Corona C: Accuracy of pedicle screw placement in the lumbosacral spine using conventional technique: computed tomography postoperative assessment in 102 consecutive patients. Clinical article. **J Neurosurg Spine 12:**306–313, 2010
2. Barbagallo GM, Olindo G, Corbino L, Albanese V: Analysis of complications in patients treated with the X-Stop Interspinous Process Decompression System: proposal for a novel anatomic scoring system for patient selection and review of the literature. **Neurosurgery 65:**111–120, 2009
3. Bess RS, Cornwall GB, Vance RE, Bachus KN, Brodke DS: Biomechanics of lateral arthrodesis, in Goodrich JA, Volcan IJ (eds): **Extreme Lateral Interbody Fusion (XLIF).** St. Louis: Quality Medical Publishing, 2008, pp 31–40
4. Cappuccino A, Cornwall GB, Turner AW, Fogel GR, Duong HT, Kim KD, et al: Biomechanical analysis and review of lateral lumbar fusion constructs. **Spine (Phila Pa 1976) 35 (26 Suppl):**S361–S367, 2010
5. Dooley ZA, Turner AW, Cornwall GB: Multiaxial spine testing apparatus: system characterization by evaluation of analog and cadaveric lumbar spines. **Int J Exp Comput Biomechan 2:**189–203, 2013
6. Johnson RG, Murphy M, Miller M: Fusions and transfusions. An analysis of blood loss and autologous replacement during lumbar fusions. **Spine (Phila Pa 1976) 14:**358–362, 1989
7. Kaibara T, Karahalios DG, Porter RW, Kakarla UK, Reyes PM, Choi SK, et al: Biomechanics of a lumbar interspinous anchor with transforaminal lumbar interbody fixation. **World Neurosurg 73:**572–577, 2010
8. Karahalios DG, Kaibara T, Porter RW, Kakarla UK, Reyes PM, Baaj AA, et al: Biomechanics of a lumbar interspinous anchor with anterior lumbar interbody fusion. Laboratory investigation. **J Neurosurg Spine 12:**372–380, 2010
9. Kawaguchi Y, Matsui H, Tsuji H: Back muscle injury after posterior lumbar spine surgery. A histologic and enzymatic analysis. **Spine (Phila Pa 1976) 21:**941–944, 1996
10. Kawaguchi Y, Matsui H, Tsuji H: Back muscle injury after posterior lumbar spine surgery. Part 1: Histologic and histochemical analyses in rats. **Spine (Phila Pa 1976) 19:**2590–2597, 1994
11. Kawaguchi Y, Matsui H, Tsuji H: Back muscle injury after posterior lumbar spine surgery. Part 2: Histologic and histochemical analyses in humans. **Spine (Phila Pa 1976) 19:**2598–2602, 1994
12. Kawaguchi Y, Yabuki S, Styf J, Olmarker K, Rydevik B, Matsui H, et al: Back muscle injury after posterior lumbar spine surgery. Topographic evaluation of intramuscular pressure and blood flow in the porcine back muscle during surgery. **Spine (Phila Pa 1976) 21:**2683–2688, 1996

13. Kondrashov DG, Hannibal M, Hsu KY, Zucherman JF: Interspinous process decompression with the X-STOP device for lumbar spinal stenosis: a 4-year follow-up study. **J Spinal Disord Tech 19:**323–327, 2006
14. Kornblum MB, Turner AW, Cornwall GB, Zatushevsky MA, Phillips FM: Biomechanical evaluation of stand-alone lumbar polyether-ether-ketone interbody cage with integrated screws. **Spine J 13:**77–84, 2013
15. Lau D, Terman SW, Patel R, La Marca F, Park P: Incidence of and risk factors for superior facet violation in minimally invasive versus open pedicle screw placement during transforaminal lumbar interbody fusion: a comparative analysis. Clinical article. **J Neurosurg Spine 18:**356–361, 2013
16. Laws CJ, Coughlin DG, Lotz JC, Serhan HA, Hu SS: Direct lateral approach to lumbar fusion is a biomechanically equivalent alternative to the anterior approach: an in vitro study. **Spine (Phila Pa 1976) 37:**819–825, 2012
17. Lieberman IH, Hardenbrook MA, Wang JC, Guyer RD: Assessment of pedicle screw placement accuracy, procedure time, and radiation exposure using a miniature robotic guidance system. **J Spinal Disord Tech 25:**241–248, 2012
18. Lonstein JE, Denis F, Perra JH, Pinto MR, Smith MD, Winter RB: Complications associated with pedicle screws. **J Bone Joint Surg Am 81:**1519–1528, 1999
19. Lotfinia I, Sayahmelli S, Gavami M: Postoperative computed tomography assessment of pedicle screw placement accuracy. **Turk Neurosurg 20:**500–507, 2010
20. Noel SH, Keene JS, Rice WL: Improved postoperative course after spinous process segmental instrumentation of thoracolumbar fractures. **Spine (Phila Pa 1976) 16:**132–136, 1991
21. Okuyama K, Abe E, Suzuki T, Tamura Y, Chiba M, Sato K: Influence of bone mineral density on pedicle screw fixation: a study of pedicle screw fixation augmenting posterior lumbar interbody fusion in elderly patients. **Spine J 1:**402–407, 2001
22. Oxland TR, Lund T: Biomechanics of stand-alone cages and cages in combination with posterior fixation: a literature review. **Eur Spine J 9 (Suppl 1):**S95–S101, 2000
23. Panjabi MM: Biomechanical evaluation of spinal fixation devices: I. A conceptual framework. **Spine (Phila Pa 1976) 13:** 1129–1134, 1988
24. Perez-Orribo L, Kalb S, Reyes PM, Chang SW, Crawford NR: Biomechanics of lumbar cortical screw-rod fixation versus pedicle screw-rod fixation with and without interbody support. **Spine (Phila Pa 1976) 38:**635–641, 2013
25. Phillips FM, Cunningham B, Carandang G, Ghanayem AJ, Voronov L, Havey RM, et al: Effect of supplemental translaminar facet screw fixation on the stability of stand-alone anterior lumbar interbody fusion cages under physiologic compressive preloads. **Spine (Phila Pa 1976) 29:**1731–1736, 2004
26. Pimenta L, Turner AW, Dooley ZA, Parikh RD, Peterson MD: Biomechanics of lateral interbody spacers: going wider for going stiffer. **ScientificWorldJournal 2012:**381814, 2012
27. Pradhan BB, Turner AW, Zatushevsky MA, Cornwall GB, Rajaee SS, Bae HW: Biomechanical analysis in a human cadaveric model of spinous process fixation with an interlaminar allograft spacer for lumbar spinal stenosis. Laboratory investigation. **J Neurosurg Spine 16:**585–593, 2012
28. Rodgers WB, Gerber EJ, Rodgers JA: Lumbar fusion in octogenarians: the promise of minimally invasive surgery. **Spine (Phila Pa 1976) 35 (26 Suppl):**S355–S360, 2010
29. Shah RR, Mohammed S, Saifuddin A, Taylor BA: Radiologic evaluation of adjacent superior segment facet joint violation following transpedicular instrumentation of the lumbar spine. **Spine (Phila Pa 1976) 28:**272–275, 2003
30. Slucky AV, Brodke DS, Bachus KN, Droge JA, Braun JT: Less invasive posterior fixation method following transforaminal lumbar interbody fusion: a biomechanical analysis. **Spine J 6:** 78–85, 2006
31. Techy F, Mageswaran P, Colbrunn RW, Bonner TF, McLain RF: Properties of an interspinous fixation device (ISD) in lumbar fusion constructs: a biomechanical study. **Spine J 13:**572–579, 2013
32. Tsantrizos A, Andreou A, Aebi M, Steffen T: Biomechanical stability of five stand-alone anterior lumbar interbody fusion constructs. **Eur Spine J 9:**14–22, 2000
33. Wang JC, Haid RW Jr, Miller JS, Robinson JC: Comparison of CD HORIZON SPIRE spinous process plate stabilization and pedicle screw fixation after anterior lumbar interbody fusion. **J Neurosurg Spine 4:**132–136, 2006
34. Wang JC, Spenciner D, Robinson JC: SPIRE spinous process stabilization plate: biomechanical evaluation of a novel technology. **J Neurosurg Spine 4:**160–164, 2006
35. Wang MY, Anderson DG, Poelstra KA, Ludwig SC: Minimally invasive posterior fixation. **Neurosurgery 63 (3 Suppl):** 197–203, 2008
36. Wilke HJ, Wenger K, Claes L: Testing criteria for spinal implants: recommendations for the standardization of in vitro stability testing of spinal implants. **Eur Spine J 7:**148–154, 1998
37. Youssef JA, McAfee PC, Patty CA, Raley E, DeBauche S, Shucosky E, et al: Minimally invasive surgery: lateral approach interbody fusion: results and review. **Spine (Phila Pa 1976) 35 (26 Suppl):**S302–S311, 2010

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