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Contribution of Round vs. Rectangular Expandable Cage Endcaps to Spinal Stability in a Cadaveric Corpectomy Model

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Abstract

Background

Expandable cages are gaining popularity in anterior reconstruction of the thoracolumbar spine following corpectomy as they can provide adjustable distraction and deformity correction. Rectangular, rather than circular, endcaps provide increased resistance to subsidence by spanning the apophyseal ring; however their impact on construct stability is not known. The objective of this study was to investigate the contribution of expandable corpectomy cage endcap shape (round vs. rectangular) and fixation method (anterior plate vs. posterior pedicle screws) to the stability of an L1 sub-total corpectomy construct.

Methods

Eight fresh-frozen cadaveric specimens (T11-L3) were subjected to multi-directional flexibility testing to 6 N·m with a custom spine simulator. Test conditions were: intact, L1 sub-total corpectomy defect, expandable cage (round endcap) alone, expandable cage (round endcap) with anterior plate, expandable cage (round endcap) with bilateral pedicle screws, expandable cage (rectangular endcap) alone, expandable cage (rectangular endcap) with anterior plate, expandable cage (rectangular endcap) with bilateral pedicle screws. Range-of-motion across T12-L2 was measured with an optoelectronic system.

Results

The expandable cage alone with either endcap provided significant stability to the corpectomy defect, reducing motion to intact levels in flexion-extension with both endcap types, and in lateral bending with rectangular endcaps. Round endcaps allowed greater motion than intact in lateral bending, and axial rotation ROM was greater than intact for both endcaps. Supplemental fixation provided the most rigid constructs, although there were no significant differences between instrumentation or endcap types.

Conclusions

These results suggest anterior-only fixation may be adequate when using an expandable cage in a sub-total corpectomy application and choice of endcap type may be driven by other factors such as subsidence resistance.

Introduction

There is an increasing interest in less invasive, direct lateral approaches to the thoracolumbar spine to treat pathology including trauma, tumors, and infection. The potential benefits of this approach include decreased perioperative morbidity and pain, expedited ambulation, and earlier discharge from the hospital.[1-8]

Vertebral body involvement by trauma, tumors, and infections often necessitate corpectomy and canal decompression followed by spinal reconstruction and stabilization. Expandable corpectomy cages are gaining popularity in reconstructive procedures of the thoracolumbar spine, as newer cage designs allow for the adjustment of cage height *in situ* to provide controlled distraction and deformity correction.

There are several surgical techniques currently used to treat instability of the thoracolumbar spine including anterior-alone fixation, posterior fixation, or combined anterior-posterior fixation. However, the effects of these various spinal fusion constructs on spinal stiffness have not been clearly defined, and the

strengths and weaknesses of each technique are still controversial.[9] Biomechanical analysis of these surgical techniques is needed to enable selection of the appropriate surgical method for restoration of spinal stability and successful spinal fusion.

While the ability to restore anterior column support with an expandable cage is appealing, the optimum cage design and endcap footprint have not been determined. Smaller, cylindrical footprint designs have been associated with subsidence and loss of deformity correction.[10] Larger, rectangular endcaps have been shown to increase resistance to subsidence by traversing the width of the vertebral body to rest on the apophyseal ring (Figure 1).[11,12] The apophyseal ring has been shown to possess the strongest and most dense vertebral body endplate bone.[13] In addition to reducing the likelihood of subsidence, rectangular endcaps for an interbody expandable device have been proposed to provide a more stable construct for anterior column support. This proposal is based on previous demonstration that larger footprint intervertebral implants and those that span the apophyseal ring resulted in greater stability, potentially due to the implant shape helping to block motion.[14]

Sasso et al.[15] demonstrated successful treatment with decompression and fusion of three-column thoracolumbar fractures in 95% of patients using anterior-only reconstruction. While the use of anterior-only fixation is attractive and minimizes the increased risk and surgical time of a second stage procedure, the biomechanical implications of this method have not been fully demonstrated. This study investigates the contribution of the endcap shape (round vs. rectangular) and fixation method (anterior plate vs. posterior pedicle screws) to the stability of an L1 corpectomy reconstruction in a cadaveric model.

Materials And Methods

Specimen Preparation
Eight fresh-frozen male cadaveric specimens (average age: 45.5, range: 29-62 yrs) were dissected, retaining the ligaments and intervertebral discs. Bone mineral density was measured by standard lumbar anterior-posterior (A-P) dual-energy x-ray absorp-

tiometry (average: 0.887 g/cm^2, range: 0.764-1.045 g/cm^2). The specimens were potted in polyurethane resin (Smooth-Cast® 300; Smooth-On, Inc. Macungie, PA) at T11 and L3. Prior to mounting on the testing system, 2 lateral bolts (6.5 x 45 or 50 mm) for the 2 bolt/2 screw anterior plate (Traverse®; NuVasive, Inc., San Diego, CA) were placed at T12 and L2 according to the prescribed surgical technique. In addition, 5.5 × 40 or 45 mm polyaxial pedicle screws (Armada®; NuVasive, Inc.) were placed bilaterally, without connecting rods, at T12 and L2 taking care to avoid damage to the facet capsules. Infrared LED marker arrays were placed at T12 and L2 for motion capture purposes.

Experimental Protocol
Each specimen was tested on a custom 6 degrees-of-freedom spine test system (Figure 2) described previously,[16] using three cycles each of unconstrained 6.0 N·m moments in flexion-extension, left-right lateral bending, and left-right axial rotation. No axial load was applied. Test parameters were based on the quasi-static load testing performed by Hitchon et al.[17]
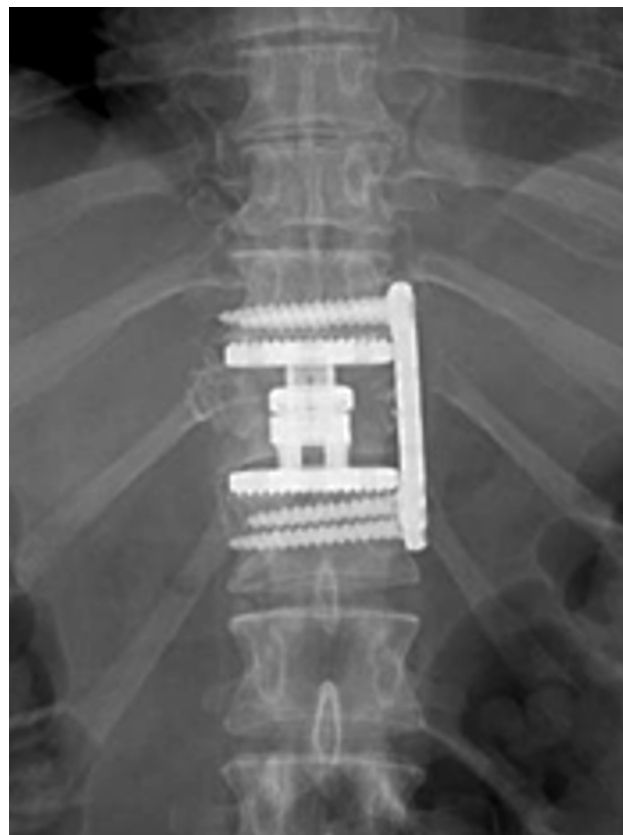

Fig. 1. A-P radiograph showing expandable corpectomy cage with rectangular endcaps spanning the ring apophysis.

After testing the intact spine (A), the following conditions were evaluated: (B) L1 sub-total corpectomy defect, (C) expandable cage (round endcaps) alone, (D) expandable cage (round endcaps) with anterior plate, (E) expandable cage (round endcaps) with bilateral pedicles screws, (F) expandable cage (rectangular endcaps) alone, (G) expandable cage (rectangular endcaps) with anterior plate, and (H) expandable cage (rectangular endcaps) with bilateral pedicle screws (Figure 3). Sequence randomization was used with the order of testing of round and rectangular endcaps. The testing sequence was (A–H) for 4 of the specimens, and (A, B, F–H, C–E) for the other 4.

The L1 sub-total corpectomy defect was approximately 26 mm in A-P width and spanned the lateral width of the T12 and L2 endcaps. The T12-L1 and L1-L2 discs and cartilaginous endcaps within the 26 mm space were excised while the anterior and posterior longitudinal ligaments were preserved.

The modular expandable cage (X-CORE®, NuVasive, Inc.) is available with round or rectangular endcaps in flat or lordotic configurations. The largest diameter round endcaps (26 mm) were tested in conditions (C–E), while the smallest A-P width rectangular endcaps (18 mm) were used in conditions (F–H), with lateral length (40 or 50 mm) selected to span the width of the vertebral body. The endcaps were secured to the expandable core of appropriate height
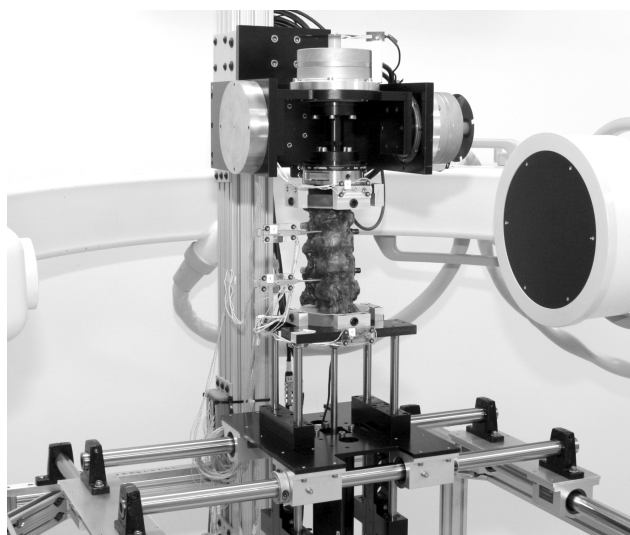
(28–40 mm or 35–52 mm). The expandable cages were deployed using a digital torque meter to ensure uniform distraction forces. The largest diameter round endcaps and smallest A-P width rectangular endcaps were selected in order to not bias the data towards the rectangular endcaps.

The anterior plate conditions (D and G) consisted of a 2 bolt/2 screw titanium alloy compression plate applied over the expandable cage. An appropriately sized plate was positioned over the previously placed bolts and lock nuts were tightened to the manufacturer-specified torque. The two 5.5 mm diameter anterior screws (lengths 35–45 mm) were subsequently driven through the plate to lag it down to the bone. For the bilateral pedicle screw fixation conditions (E and H), the anterior screws and plate were removed, leaving the 2 bolts in place, and the T11 and L2 pedicle screws were connected with bilateral 5.5 mm diameter titanium alloy rods.

Fig. 2. Experimental test setup showing T11-L3 intact spine mounted on multiaxial spine test system. Infrared LED marker arrays attached at T12 and L2.
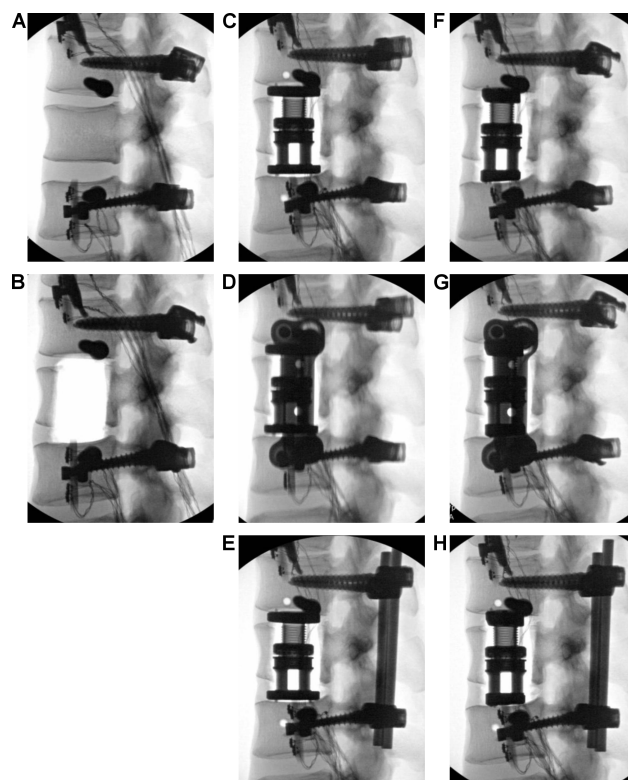

Fig. 3. Lateral fluoroscopic images showing test conditions: (A) intact, (B) sub-total corpectomy, (C) expandable cage with round endcaps, (D) round endcaps with lateral plate, (E) round endcaps with bilateral pedicle screws, (F) expandable cage with rectangular endcaps, (G) rectangular endcaps with lateral plate, and (H) rectangular endcaps with bilateral pedicle screws. Intact spine shows implantation of bilateral pedicle screws and lateral plate bolts prior to testing.

Data Analysis

The T12-L2 angular rotations were recorded using an Optotrak Certus® motion capturing system (Northern Digital, Inc., Waterloo, Ontario, Canada). Data from the third loading cycle in each motion direction was analyzed. Range of motion (ROM) was defined as the total angular displacement in the motion cycle, for example from flexion at 6.0 N·m to extension at –6.0 N·m. ROM across the corpectomy construct (T12 to L2) from each group was compared with repeated-measures ANOVA followed by Holm-Sidak comparisons. Statistical significance was defined as $p < 0.05$.

Results

T12-L2 range-of-motion (Figure 4A-C) was significantly increased following the corpectomy procedure, with the greatest increase in motion seen in axial rotation (flexion-extension: 2.2 times, lateral bending: 3.3 times, axial rotation: 11.7 times, $p < 0.001$; Table 1). In all motion planes tested, the expandable cage alone (round or rectangular endcaps) significantly reduced motion with respect to the corpectomy defect condition ($p < 0.001$). Both expandable cage endcap designs without supplemental fixation demonstrated similar motion to the intact spine in flexion-extension (round: $p = 0.639$, rectangular: $p = 0.589$). In lateral bending, the rectangular endcap cage was not significantly different from intact ($p = 0.999$), while the round endcap cage alone allowed more motion than intact ($p < 0.001$). Both endcap design cages without fixation allowed greater motion than intact in axial rotation ($p < 0.001$).

Addition of supplemental fixation to the round endcap expandable cage increased rigidity and all statistical comparisons to this were significant ($p < 0.001$) with the exception of the cage with anterior plate in flexion-extension ($p = 0.054$). Similarly for the rectangular endcap cage, addition of fixation significantly increased rigidity in all directions for both the anterior plate and pedicle screws ($p \leq 0.050$). For both endcap designs, pedicle screw fixation provided greater stability in flexion-extension compared with the anterior plate (round: $p = 0.526$, rectangular: $p = 0.632$), while anterior plating was more rigid than pedicle screws in axial rotation (round: $p = 0.751$, rec-

tangular: $p = 0.910$); however none of these differences reached statistical significance. Furthermore, average axial rotation ROM did not reach below intact for either the anterior plate or pedicle screws. The two fixation methods were comparable in lateral bending (round: $p = 1.000$, rectangular: $p = 1.000$).

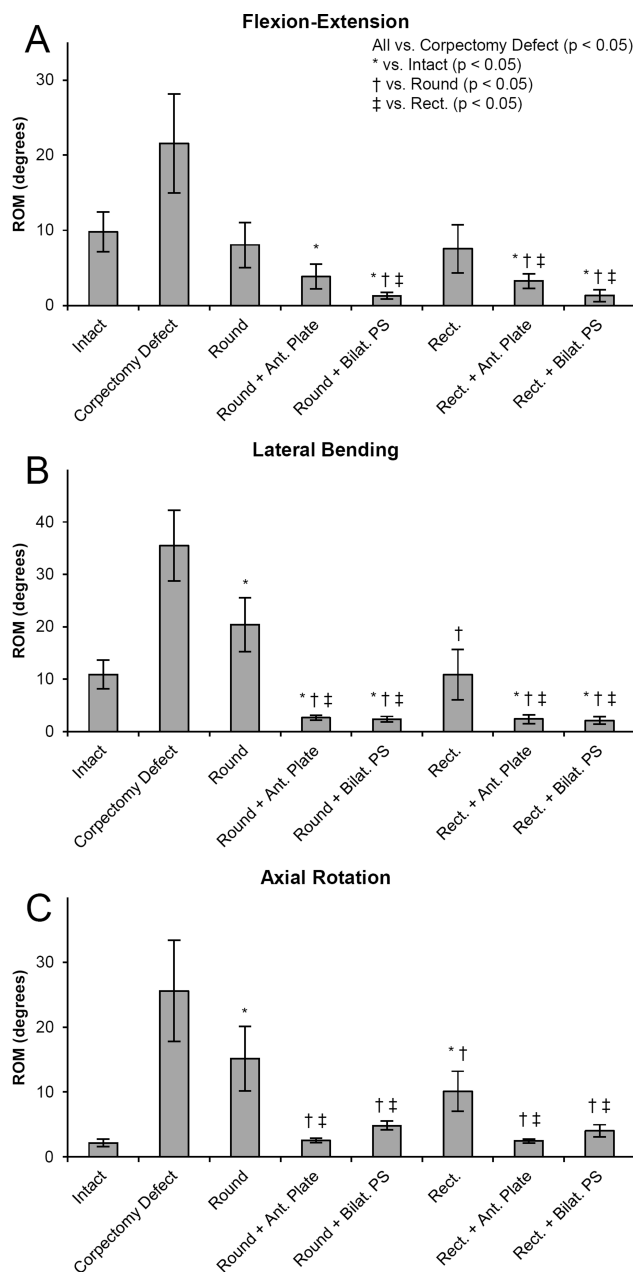Comparing the two endcap designs directly without supplemental fixation, there was no significant differ-

Fig. 4. Mean T12-L2 range of motion for all test conditions in: (A) flexion-extension, (B) lateral bending and (C) axial rotation. Error bars represent ± 1 standard deviations. ROM denotes range of motion, Round – expandable cage with round endcaps, Rect. – expandable cage with rectangular endcaps, Ant. Plate – anterior plate, Bilat. PS – bilateral pedicle screws.

ence between the round or rectangular endcaps under flexion-extension (p = 0.924), however in lateral bending the rectangular endcaps provided 1.9 times more stability than the round (p < 0.001) and in axial rotation the rectangular endcaps increased stability by 1.5 times (p = 0.026). When fixation was added, there were no statistically significant differences between the fixation or endcap types (p ≥ 0.497).

Discussion

The importance of anterior column support in thoracolumbar corpectomy reconstruction has previously been demonstrated. Addition of anterior support to

Table 1. Statistical comparisons (p-values) of test conditions in each plane of motion.

Testing Conditions	Flexion-Extension	Lateral Bending	Axial Rotation
Intact vs.			
Corpectomy	< 0.001	< 0.001	< 0.001
Round	0.639	< 0.001	< 0.001
Round + Ant. Plate	0.002	< 0.001	0.992
Round + Bilat. PS	< 0.001	< 0.001	0.643
Rect.	0.589	0.999	< 0.001
Rect. + Ant. Plate	< 0.001	< 0.001	0.980
Rect. + Bilat. PS	< 0.001	< 0.001	0.867
Corpectomy vs.			
Round	< 0.001	< 0.001	< 0.001
Round + Ant. Plate	< 0.001	< 0.001	< 0.001
Round + Bilat. PS	< 0.001	< 0.001	< 0.001
Rect.	< 0.001	< 0.001	< 0.001
Rect. + Ant. Plate	< 0.001	< 0.001	< 0.001
Rect. + Bilat. PS	< 0.001	< 0.001	< 0.001
Round vs.			
Round + Ant. Plate	0.054	< 0.001	< 0.001
Round + Bilat. PS	< 0.001	< 0.001	< 0.001
Rect.	0.924	< 0.001	0.026
Rect. + Ant. Plate	0.020	< 0.001	< 0.001
Rect. + Bilat. PS	< 0.001	< 0.001	< 0.001
Round + Ant. Plate vs.			
Round + Bilat. PS	0.526	1.000	0.751
Rect.	0.121	< 0.001	< 0.001
Rect. + Ant. Plate	0.967	1.000	0.939
Rect. + Bilat. PS	0.497	1.000	0.900
Round + Bilat. PS vs.			
Rect.	0.001	< 0.001	0.018
Rect. + Ant. Plate	0.687	0.986	0.739
Rect. + Bilat. PS	0.987	0.998	0.975
Rect. vs.			
Rect. + Ant. Plate	0.050	< 0.001	< 0.001
Rect. + Bilat. PS	0.001	< 0.001	0.004
Rect. + Ant. Plate vs. Rect. + Bilat. PS	0.632	1.000	0.910

Round denotes expandable cage with round endcaps, Rect. – expandable cage with rectangular endcaps, Ant. Plate – anterior plate, Bilat. PS – bilateral pedicle screws

anterior, posterior or circumferential fixation devices significantly increases compression and lateral bending stiffness, and to a lesser extent, flexion-extension.[18-22] The results of the current study also support the use of combined anterior column support and additional supplemental fixation for reconstruction following corpectomy. The expandable cages alone, with round or rectangular endcaps, were noted to provide substantial stability to the corpectomy defect, although not beyond that of the intact spine.

In the absence of supplemental fixation, we noted significant differences (p ≤ 0.023) between the endcap types in lateral bending and axial rotation, with the rectangular endcap providing greatest stability. In flexion-extension, the results were similar between endcap types. The authors are not aware of previous studies investigating kinematics of different corpectomy cage types without supplemental fixation. However, studies have shown that the type of anterior support (strut, mesh, expandable cage), in the presence of supplemental fixation generally does not have a significant effect on the stability of the corpectomy reconstruction.[19,23-25] Similar findings were observed in the current study, where there were no statistically significant differences between the round and rectangular endcap expandable cages with either anterior or posterior fixation. It is apparent that the rigidity of the supplemental fixation is the dominant factor influencing construct ROM, making it difficult to detect differences between the endcap types.

The fixation requirements for corpectomy reconstruction are not clearly defined, however some form of supplemental internal stabilization is always recommended. Some authors have advocated the use of anterior-only fixation in certain conditions, including up to three-column thoracolumbar injuries, as demonstrated with promising results in clinical studies.[15,26-28] Conversely, Hitchon et al.[29] recommend combined anterior-posterior fixation for three-column injuries. Anterior-only fixation has the advantage of being performed through the same surgical approach as the anterior column support; alleviating the need for a second posterior surgery and minimizing potential risks. Biomechanical stability of anterior fixation devices, in the form of anterolateral

plate or dual-rod constructs, has been investigated in multiple studies, however results are mixed with respect to stability offered by different anterior devices and comparisons with posterior instrumentation.

Comparing between anterior fixation devices, most studies generally indicate rigidity similar to or exceeding the intact spine. Results are variable likely based on degree of destabilization, type of instrumentation, and differences in test methods. In the current study, we found that with supplemental anterior fixation, there was a significant reduction in flexion-extension and lateral bending ROM, while axial rotation ROM was not reduced relative to the intact specimen. Hitchon et al.[30] evaluated an anterior plate with constrained screws to supplement an L1 sub-total corpectomy. The instrumentation reduced flexion-extension and lateral bending significantly with respect to intact. Axial rotation motion was greater than intact, but there was no significant difference. They recommended a device that includes four bicortical, constrained screws to maximize rigidity, similar to the findings of Disch et al.[31] Postoperative bracing was suggested to restrict axial rotation since the results showed higher ROM than intact in that plane. Disch et al.[31] discovered that an angular stable plate system provided superior stability over a polyaxial system after fatigue loading in spine with expandable cage and L1 total corpectomy. The angular-stable plate was more rigid than the polyaxial in lateral bending; and both allowed less motion than intact. However, neither plate system achieved intact stability in axial rotation. In addition, both plates were less rigid than intact in flexion-extension. Chang et al.[32] found improved stability with respect to intact in all directions except extension, but detected no significant differences between stability of 5.5 mm diameter and 6.35 mm diameter dual-rod constructs in a total T11 corpectomy. Reddy et al.[33] showed a single-rod construct stabilizing a sub-total L1 corpectomy with stackable carbon fiber-reinforced cage was significantly less rigid than intact, however addition of a second rod and a dual cross-connectors provided stability that approximated the intact spine. In a bisegmental L1 sub-total corpectomy model, Schreiber et al.[34] noted that anterior plating only increased frontal and sagittal plane stiffness significantly over intact. Axial rotation ROM was increased, al-

though not significantly. Additional posterior fixation was recommended for stabilization for questionable bone quality.

Comparing anterior fixation systems with posterior pedicle-based systems, Shono et al.[35] and Schultheiss et al.[36] both showed higher stability of the anterior dual-rod device over posterior intrapedicular fixation. Knop et al.[24] showed similar stability in axial rotation and lateral bending between dual-rod and posterior pedicle screw fixation systems; however in neither case was axial rotation ROM less than intact. Flexion-extension ROM was reduced for the posterior system. Ulmar et al.[37] measured similar lateral bending stability between a fixed-angle screw anterior plate system and posterior pedicle screws. In flexion-extension and axial rotation, the posterior fixation was more rigid than the anterior plate. In axial rotation, both the plate and pedicle screw systems allowed greater ROM than intact, which was only improved by combining anterior and posterior fixation, which was recommended for rotationally unstable fractures. Bence et al.[38] created a partial corpectomy with posterior ligament disruption at L1, which was reconstructed with iliac crest strut graft. They found both anterolateral plating and posterior fixation provided increased flexion-extension and lateral bending stability compared with the intact spine. The posterior system provided greater stability, but not statistically significantly so. Neither system provided axial rotation stability levels that reached intact. They recommended consideration of a combined anterior-posterior stabilization procedure for ligamentous disruptions of the posterior column in combination with vertebral fractures in the thoracolumbar junction. Bishop et al.[39] also concluded that combined anterior-posterior fixation should be considered in cases in which anterior column reconstruction alone may be insufficient. Although not directly investigated in this study, many studies have also shown the increased stability of combined anterior-posterior (circumferential) fixation over anterior-only fixation.[20,37,38,40-42]

The results of this study suggest that supplemental fixation is needed with both expandable cage endcap designs, and that anterior plating yielded similar stability to bilateral pedicle screw instrumentation in all

motion planes. The lack of clear difference between the endcap designs in the presence of supplemental fixation in this study suggests that the primary benefit of the large surface area, wide rectangular endcaps might be in resisting subsidence. In vitro studies investigating static[12] and dynamic[11] subsidence have demonstrated superior behavior with the rectangular endcaps over round endcaps. Further differences between the endcap designs with respect to potential range of motion endcaps afforded by the rectangular stability may be elucidated with cyclic testing. Similar stability between the anterior expandable cage with anterior plate instrumentation and bilateral pedicle screw fixation displayed in this study suggests anterior-only fixation may be sufficient, potentially obviating the need for a second stage posterior procedure with associated additional complications. However, long-term in vivo clinical studies will be needed to further evaluate the clinical success of this treatment method.

Limitations with the current study are similar to other cadaveric biomechanical studies. The sample size was limited to eight specimens. A larger number of specimens may have allowed smaller statistical differences between test conditions to be detected. Testing the corpectomy defect may have introduced variability to the specimens that could influence subsequent test results. The small standard deviations for the conditions with fixation (anterior plate of posterior pedicle screws) suggest that the rigidity of the fixation was more dominant than the underlying specimen flexibility; however the cage alone conditions may have been influenced. The order of testing may have also had an effect on the test results. For this reason, the order of testing the round and rectangular endcap conditions was altered between specimens to distribute this variability between the two endcap types. Specimens were tested without a follower load or axial load. This may underestimate the stability afforded by the different constructs; however trends are expected to be similar. In the clinical situation, all constructs may be more stable due to compressive loading caused by body weight and the surrounding musculature. Strengths of the study include testing non-osteoporotic human specimens to minimize variation related to implant-bone interface strength and using pure-moments to apply

repeatable loading.

Conclusions

An anterior expandable cage alone with either round or rectangular endcaps provided significant stability as compared to corpectomy. In lateral bending and axial rotation, the rectangular endcaps provided significantly more stability than the round endcaps, however in flexion-extension the motion was similar between endcap types. The clinical implications of this warrants further investigation. Fixation with the anterior plate or bilateral pedicle screws provided the most rigid constructs although there were no significant differences in stability between the anterior plate and bilateral pedicle screw fixation methods with either endcap design. This finding suggests it may be appropriate to use an expandable cage in a sub-total corpectomy application using anterior-only supplemental fixation, without need for posterior or circumferential fixation. Choice of endcap type may be driven by other factors such as ability to resist subsidence.

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Disclosures

Dr. Eastlack is a consultant to, has direct stock ownership in and has provided expert testimony on behalf of NuVasive, Inc.; Dr. Mundis is a consultant to and received royalties from NuVasive. Dr. Mundis is also a board member of SOLAS. Drs. Cornwall and Turner are employees of and have direct stock ownership in NuVasive. Dr. Moazzaz has no disclosures relevant to this manuscript.

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