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BIOMECHANICS

Can A Novel Rectangular Footplate Provide Higher Resistance to Subsidence Than Circular Footplates?

An Ex Vivo *Biomechanical Study*

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Study Design. *Ex vivo* biomechanical evaluation using cadaveric vertebral bodies.

Objective. To compare the subsidence characteristics of a novel rectangular footplate design with a conventional circular footplate design.

Summary of Background Data. Cage subsidence is a postoperative complication after reconstruction of corpectomy defects in the thoracolumbar spine and depends on factors, such as bone quality, adjunctive fixation, and the relationship between the footplate on the cage and the vertebral body endplate.

Methods. Twenty-four cadaveric vertebrae (T12–L5) were disarticulated, potted in a commercial resin, loaded with either a circular or a rectangular footplate, and tested in a servo hydraulic testing machine. Twelve vertebral bodies were loaded with a circular footplate, and after subsidence the same vertebral bodies were loaded with a rectangular footplate. The second set of 12 vertebral bodies was loaded with a rectangular footplate only. Force-displacement curves were developed for the 3 groups, and the ultimate load to failure and stiffness values were calculated.

Results. The ultimate load to failure with the circular footplate was 1310 N (SD, 482). The ultimate load to failure with a rectangular footplate with a central defect and without a central defect was 1636 N (SD, 513) and 2481 N (SD, 1191), respectively. The stiffness of the constructs with circular footplate was 473 N/mm (SD, 205). The stiffness of the constructs with a rectangular footplate with a central defect and without a central defect was 754 N/mm (SD, 217) and 1054 N/mm (SD, 329), respectively.

Conclusion. A rectangular footplate design is more resistant to subsidence than a circular footplate design in an *ex vivo* biomechanical model. The new design had higher load to failure even in the presence of a central defect. These findings suggest that rectangular footplates may provide better subsidence resistance when used to reconstruct defects after thoracolumbar corpectomy.

Key words: thoracolumbar corpectomy, subsidence, expandable, endplate. **Spine 2012;37:E1177–E1181**

Despite modifications in the design of vertebral cages, such as expandable cores, modular footplates, sizing of the footplate, and sagittal alignment options, cage subsidence and catastrophic adjacent level fractures can occur after reconstruction of the anterior and middle vertebral columns.[1–5] Previous design modifications increased the surface area of the footplate to distribute the forces across the endplate. The strength of the endplate is not distributed evenly and the periphery has been shown to be stronger than the center. [6] Therefore, the ideal interbody implant should rest on the periphery of the endplate. To address this, a novel expandable cage with a rectangular footplate has been designed to span the ring apophysis, which is structurally stronger than the center of the endplate.[5] Whether this novel design has improved the subsidence characteristics compared with conventional circular designs has not been previously studied. The purpose of this study was to compare the resistance to subsidence between a cage with a conventional circular footplate and that with a novel rectangular footplate, using a human cadaver model.

MATERIALS AND METHODS

Twenty-four fresh-frozen human cadaver vertebral bodies from T12 to L5 were procured from 4 adult donors (2 women and 2 men). Each specimen was radiographically examined using planar radiographs (BV Pulsera; Philips, Andover, MA) to rule out any previous fractures, cysts, or other spine pathology. In addition, dual-energy x-ray absorptiometry

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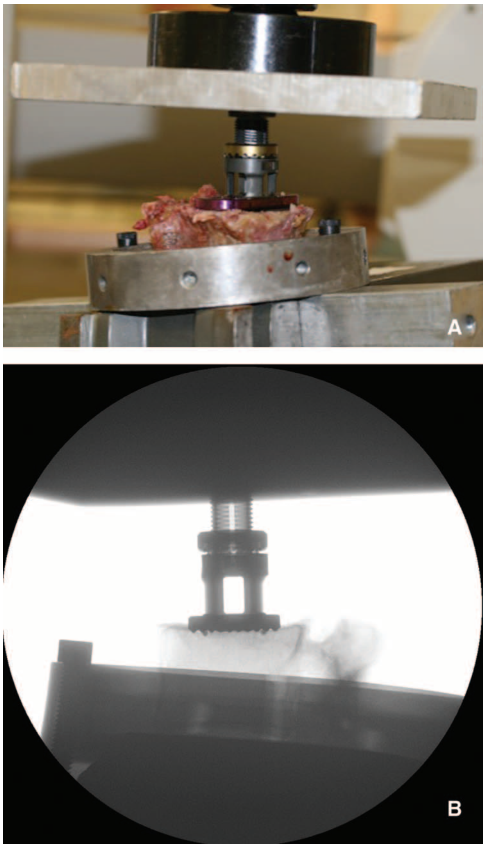

Figure 1. The position of the vertebral body and the footplate was adjusted so that the footplate had a perfect fit on the endplate without any edge loading (**A**) and confirmed with fluoroscopy views (**B**).

(DXA) (DPX; Lunar, Madison, WI) was performed to determine the bone mineral density. All specimens were stored at −20°C, thawed to room temperature prior to testing, and kept moist with saline during storing, thawing, and testing procedures.

Testing was carried out using circular (26-mm diameter) and rectangular (22 × 60 mm) footplates with expandable titanium cages (X-Core; NuVasive, Inc., San Diego, CA). The vertebral bodies were assigned into 2 test groups: (1) T12, L2, and L4 and (2) L1, L3, and L5. The footplates were randomized so that each footplate would be tested on the same number of vertebral levels.

The intervertebral discs were removed and the vertebral bodies were potted in a quickset 2-part epoxy resin (Smooth-cast; Smoothon, Easton, PA), such that the resin did not encase more than 30% of the vertebral body. The specimens were tested using a servohydraulic-testing machine (858 MiniBionix; MTS, Eden Prairie, MN), with the superior endplate parallel to the actuator head (Figure 1A, B). Then either the circular or rectangular cage was placed on the specimen by a spine fellowship trained orthopedic surgeon such that the footplate would perfectly fit the endplate without edge loading. The cage was compressed at 5 mm/min until 10 mm of displacement (subsidence) was reached. X-ray films were obtained during loading to evaluate subsidence.

Immediately after testing the circular footplate, the rectangular footplate was compressed on the same endplate spanning the circular defect in the center. This created 3 test groups: group A with the circular footplate over an intact endplate (Figure 2A), group B with the rectangular footplate spanning a central circular defect (Figure 2B), and group C with the rectangular footplate over an intact vertebral endplate (Figure 2C).

The force and displacement were recorded during loading, and the ultimate load to failure was determined as the first peak for the force-displacement curve as described by Auerbach *et al*.[7] The stiffness was calculated in the linear portion of the curve (initial stiffness) and in 5 equally spaced 1-mm displacement intervals after the ultimate load. The average load of these 1-mm intervals was also calculated to describe response of the vertebra after the ultimate load event.

The force data were tested for a normal distribution, using the D'Agnostino-Pearson omnibus normality test. The comparison groups were found to be normally distributed; therefore, parametric statistics were used to compare the treatment groups. Comparison of the circular cage group to the rectangular cage with a defect group was done using a paired *t* test, whereas the comparison of the rectangular cage with the 2 other groups was done using a 1-way analysis of variance, with the Dunnett post-test for multiple comparisons. P values less than 0.05 were considered statistically significant. The statistical analysis was performed with GraphPad Prism software (Version 5; GraphPad Software, La Jolla, CA).

RESULTS

The mean age at the time of death was 68.8 years (range, 51–88 yr). The DXA scores were 3.2, −0.5, −2.1, and −3.6. Because equal number of vertebral bodies from each specimen was used in each study group, the groups were equal with regard to DXA scores and age of the specimens (Table 1).

The ultimate load with the circular footplate was (1310 N; SD, 482 N) less than the rectangular cage without a central defect (2481 N; SD, 1190 N), $P = 0.003$) but not different than the rectangular cage with a central defect (1636 N; SD, 513 N), $P = 0.066$; Figure 3). The rectangular cage without a central defect also had a higher ultimate load than the rectangular cage with a central defect ($P = 0.027$).

The rectangular cage without a central defect had stiffness in the initial linear region of the load displacement curve of 1054 N/mm (SD, 329), which was higher than both the rectangular cage with a central defect (754 N/mm (SD, 217), $P = 0.011$) and the circular cage (473 N/mm (SD, 205), $P < 0.0001$). The circular cage was also less stiff than the rectangular cage with a central defect ($P = 0.0005$; Figure 3).

A similar trend was observed in the average force over the 1-mm displacement increments after the ultimate load occurred (Figure 4). The average force for every 1-mm displacement was 1154 N (SD, 344) in the circular footplate group and was significantly lower than the rectangular footplate with defect (1395 N; SD, 452) and without defect groups (2089 N; SD, 848). It was statistically significantly greater when comparing either rectangular cage group with the circular cage. The

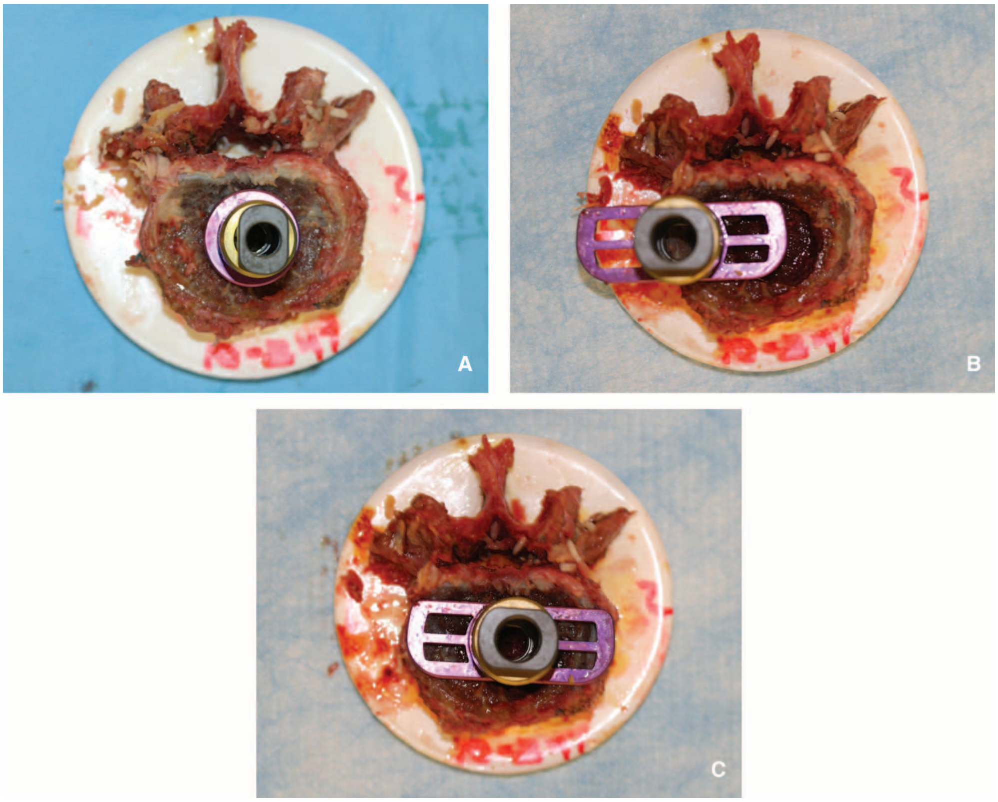

Figure 2. The test groups were group **A** with the circular footplate over an intact endplate, group **B** with the rectangular footplate spanning a central circular defect, and group **C** with the rectangular footplate over an intact vertebral endplate.

average force typically decreased between 0 and 3 mm of displacement after the ultimate load and slightly increased between 3 and 5 mm of displacement.

The stiffness, or slope of the force displacement curve, along the same 1-mm increments after the ultimate load showed different trends for all 3 groups. In the circular footplate group, the force-displacement curves (stiffness) tended to be steeply decreasing after the ultimate load except at the 3- to 4-mm interval in which the curve was relatively horizontal. The rectangular cage without a defect showed the least variation in the slope of the force displacement curve after the ultimate load, whereas the circular cage showed the highest variation; however, these 2 groups were significantly different only at the 4- to 5-mm interval (Figure 5). In comparing the rectangular cage with a defect *versus* the circular cage, there was a significant difference in the slope of the curves at 1- to 2-mm, 3- to 4-mm, and 4- to 5-mm intervals. There was no significant difference between the rectangular cage with and without the central defect in stiffness over any of the 5 intervals examined.

DISCUSSION

Expandable cages are frequently used in the reconstruction of defects after thoracolumbar corpectomy; however, subsidence remains a problem. Subsidence of expandable cages depends on several variables, including bone quality, fit on the endplate, size and shape of the footplate, and adjunctive fixation. The majority of the current cage designs use a circular footplate resting on the central portion of the endplate. Recently, a novel rectangular footplate design that loads the ring apophysis was introduced. This study showed that the novel rectangular footplate design had a higher ultimate load as well as higher stiffness values than a circular footplate design. The new design was also at least equal to the circular footplate, even in the presence of an endplate defect. These results suggest the rectangular footplate design may provide higher resistance to subsidence than circular footplates in reconstruction of thoracolumbar corpectomy defects.

The subsidence of the cages is a function of footplate-vertebral endplate interaction. In the reconstruction of a

TABLE 1. Demographic Information and BMD of the Specimens

	Age (yr)	DXA	Sex	Levels (# of Specimen)					
				T12	L1	L2	L3	L4	L5
Circular	68.8	−0.75	2M/2F	2	2	2	2	2	2
Rectangular with defect	68.8	−0.75	2M/2F	2	2	2	2	2	2
Rectangular without defect	68.8	−0.75	2M/2F	2	2	2	2	2	2

DXA indicates dual-energy x-ray absorptiometry; BMD, bone mineral density.

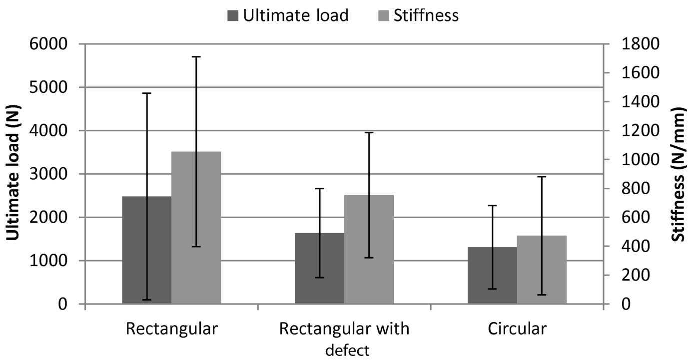

Figure 3. The ultimate load and stiffness results for the 3 test groups. Error bars represent the 95% confidence intervals of the mean.

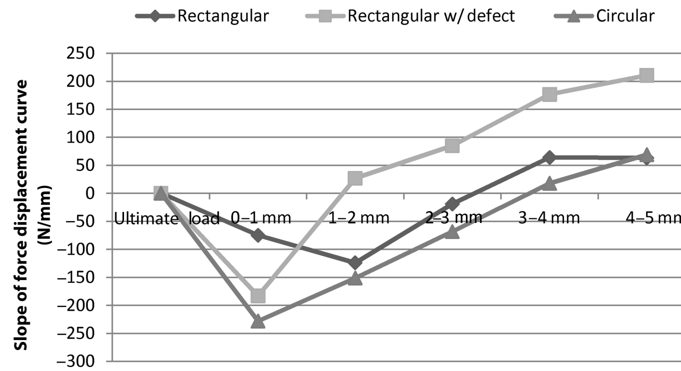

Figure 5. Slope of the force displacement curve after the ultimate load shown in 1-mm increments, with all curves normalized to the values at the ultimate load. There were no statistically significant differences between any group at any displacement.

corpectomy defect, the goal is to implant the largest footplate suitable. The higher contact area results in a lower force per unit area, which in turn should lead to lower subsidence rate. Reinhold *et al*[9] recently confirmed that bigger endplate surface areas are associated with higher resistance to subsidence. Although an increase in the surface area with a larger footplate will decrease the force per unit area, circular cages are placed on the central portion of the endplate and not on the ring apophysis. Bailey *et al*[6] showed that the endplate was stronger at the periphery than at the center. Steffen *et al*[8] reported similar results and suggested that the ideal interbody implant should rest on the periphery of the endplate. The rationale of the rectangular design was to engage with the ring apophysis and provide a stronger biomechanical support. This study confirmed that rectangular footplates, which engage the ring apophysis, have a higher ultimate load to failure than circular footplates. Reinhold *et al*[9] reported the ultimate load of the X-Tenz (1470 N), Obelisc (1310 N), Synex I (1690 N), and Synex II (1790 N) cages, using a similar testing protocol. In this study, all were equal or lower than the ultimate load of the rectangular footplate with or without central defect. This suggests that the rectangular footplate design may offer potential advantages over the circular footplate design as well as other nonrectangular designs.

Interestingly, the ultimate load was higher for rectangular footplates with a central defect than for the circular foot-

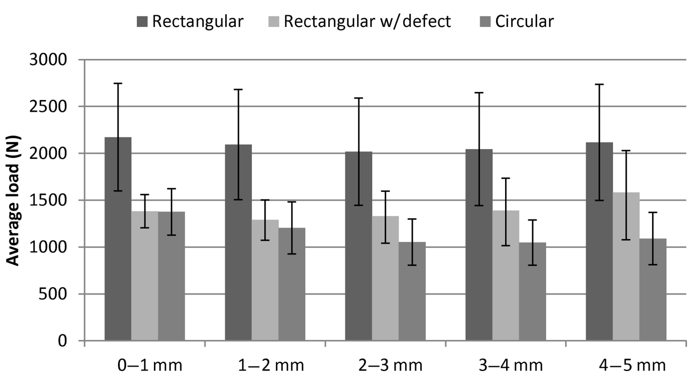

Figure 4. Mean load values for 1-mm intervals after the ultimate load. Error bars represent the 95% confidence interval around the mean.

plate on an intact endplate. This further suggests that the ring apophysis is the key anatomic structure that resists subsidence more than the central portion of the endplate and could have important clinical implications. For example, defects in the central portion of the endplate can occur when preparing the endplate for implantation of an interbody cage or they are created when a primary vertebral body replacement fails. This study suggests that rectangular cages may be safely employed in these situations in which the structural integrity of the center of the endplate has been compromised.

After the ultimate load to failure, the average force required for further displacement was lower in all 3 groups, explained by the failure of the endplate. Compared with the force required for the initial load to failure, the circular footplates had more variability and required less force to result in further subsidence, whereas rectangular designs had less variability and required more load to result in further subsidence when compared with the circular footplate. This suggests that the type of bone under the endplate influences the amount of subsidence. For example, the circular endplates crush and compact the trabecular bone in the central portion of the vertebral body whereas the rectangular footplates span the vertebra and compress on the stronger cortical apophysis in addition to the centralized trabecular bone. Thus, a higher variability after the ultimate load to failure was observed in the circular cages traversing trabecular bone after endplate failure. In addition, higher loads compared with the circular cage were required for further subsidence after endplate failure in the rectangular cage. This suggests that rectangular footplates may be advantageous when compared with circular footplates even after an initial subsidence occurs.

There are several limitations to this study. First, a motion segment with adjunctive instrumentation was not used, which prevented the direct correlation of stiffness in the clinical setting; however, the goal of this study was to investigate the subsidence characteristics of the footplate designs. Second, cyclic testing was not performed and should be considered in future studies. Strength of this study was that using the same vertebral level for both the circular and rectangular cages, a repeatable defect model could be created. This allowed for the direct comparison of the circular footplate with a worst-case scenario, using the rectangular footplate. In addition, the response of the vertebral body after the ultimate load occurred was also quantified, which, to our knowledge, had yet to be presented in the literature.

In summary, this study demonstrated that a rectangular footplate design was more resistant to subsidence than a circular footplate design in an *ex vivo* biomechanical model. These findings suggest that rectangular footplates may help reduce subsidence-related complications after thoracolumbar corpectomy. Future *ex vivo* biomechanical studies with cyclic loading protocols should be performed to further characterize the mechanical response and subsidence in the 2 designs.

➢ Key Points

- ❑ An *ex vivo* biomechanical cadaveric model was used to load endplates with circular and/or rectangular footplates.
- ❑ A novel rectangular footplate design is more resistant to subsidence than circular footplate design.
- ❑ The advantage of the rectangular footplate design compared with circular design is maintained even in the presence of a central endplate defect.
- ❑ Rectangular footplates may provide better subsidence resistance when used to reconstruct defects after thoracolumbar corpectomy.

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References

1. Chou D, Lu DC, Weinstein P, et al. Adjacent-level vertebral body fractures after expandable cage reconstruction. *J Neurosurg Spine* 2008;8:584–8.
2. Arts MP, Peul WC. Vertebral body replacement systems with expandable cages in the treatment of various spinal pathologies: a prospectively followed case series of 60 patients. *Neurosurgery* 2008;63:537–44.
3. Aryan HE, Lu DC, Acosta FL Jr, et al. Corpectomy followed by the placement of instrumentation with titanium cages and recombinant human bone morphogenetic protein-2 for vertebral osteomyelitis. *J Neurosurg Spine* 2007;6:23–30.
4. Uchida K, Kobayashi S, Nakajima H, et al. Anterior expandable strut cage replacement for osteoporotic thoracolumbar vertebral collapse. *J Neurosurg Spine* 2006 ;4:454–62.
5. Smith WD, Dakwar E, Le TV, et al. Minimally invasive surgery for traumatic spinal pathologies: a mini-open, lateral approach in the thoracic and lumbar spine. *Spine (Phila Pa 1976)* 2010;35: S338–46.
6. Bailey CS, Sjovold SG, Dvorak MF, et al. The strength profile of the thoracolumbar endplate reflects the sagittal contours of the spine. *Spine(Phila Pa 1976)* 2011;36:124–8.
7. Auerbach JD, Ballester CM, Hammond F, et al. The effect of implant size and device keel on vertebral compression properties in lumbar total disc replacement. *Spine J* 2010;10:333–40.
8. Steffen T, Tsantrizos A, Fruth I, et al. Cages: designs and concepts. *Eur Spine J* 2000;9:S89–94.
9. Reinhold M, Schmoelz W, Canto F, et al. A new distractable implant for vertebral body replacement: biomechanical testing of four implants for the thoracolumbar spine. *Arch Orthop Trauma Surg* 2009;129:1375–82.