

Systematic Review/Meta-Analysis

Expandable interbody cages for lumbar spinal fusion: a systematic review

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Abstract

BACKGROUND CONTEXT: Since the early 2000s, various expandable spinal fusion cages have been developed to facilitate less invasive procedures, however, expandable cages have often been evaluated as a homogeneous group, neglecting differences in shape, size, material, expandability and lordotic adjustability. This systematic review aimed to comprehensively survey the literature on expandable spinal fusion cages, discuss their differentiating factors, and identify gaps in the literature regarding these devices.

PURPOSE: To demonstrate the range of design features included in expandable interbody devices and identify which of these features are associated with improved surgical outcomes.

STUDY DESIGN: Systematic review.

METHODS: The study followed the Preferred Reporting Items for Systematic Reviews and Meta Analysis (PRISMA) guidelines. An electronic search of MEDLINE and Embase using the search terms “lumbar” AND “fusion” AND (“expandable cage” OR “expandable interbody”) including only English language articles that contained sufficient detail to correlate a specific expandable cage design to patient outcomes. Relevant elements, including device design parameters, patient population information, details of the intervention, comparison data, outcome variables, and the timeframe were extracted. Statistical analysis was conducted to correlate patient outcomes with different device features.

RESULTS: While 387 different articles were initially identified, 49 met all the criteria for inclusion. Design differences contributed to disparate outcomes, with rectangular titanium cages featuring medial lateral and vertical expansion and continuous lordotic adjustability being correlated with significantly improved patient reported outcomes. The surgical approach and location were also found to be correlated with patient outcomes, indicating that confounding factors are present.

CONCLUSIONS: We recommend that expandable cage technologies not be considered a homogeneous group, as long term outcomes likely are dependent upon specific design characteristics. Categorizing devices based on design features such as material composition, shape, vertical expandability, horizontal expandability, and restoration of segmental lordosis may allow for more rapid identification of device characteristics associated with better outcomes. © 2025 Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Keywords:

Cage; Expandable; Interbody; Lumbar; Review; Spinal fusion; Surgical fixation devices; Treatment outcome

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Introduction

Since the US FDA approved the first spinal fusion cage for human use in the 1990's, numerous additional interbody devices have been developed coming in various shapes, sizes, and materials, featuring a range of different functionalities [1–3]. Recently, with many surgeons transitioning to less invasive techniques, a new class of interbody devices has emerged. These new expandable interbody devices are inserted in a smaller, nonexpanded configuration and then are deployed to an expanded configuration once inside the disc space [1,4,5]. These new expandable interbody devices are ideally suited for minimally invasive procedures as they can be inserted through a small operating window, then subsequently expanded to restore intervertebral spacing and segmental lordosis. This process requires less nerve root retraction, reduces the risk of endplate violation due to device impaction, and potentially lowers the risk of subsidence depending on the expanded device size [6–8].

Clinical studies on expandable lumbar fusion cages generally aim to determine the clinical efficacy of a specific device, compare the efficacy of expandable devices to static devices, describe unique surgical techniques benefiting from the smaller insertion profile of expandable devices compared to traditional static cages, or compare the clinical and radiographic results of 2 expandable cages with different functionalities. Four systematic reviews and meta-analyses published within the last 5 years focused on whether static or expandable cages result in superior outcomes, but they reached conflicting conclusions [6,9–11]. Three of the 4 agreed that expandable cages resulted in significantly higher disc height than static cages [6,10,11] while the fourth study found the opposite [9]. Similarly, one review found that expandable cages resulted in significantly less subsidence [6], while the others found no significant differences between the 2 categories of cages [9–11]. These contradictions also extend to changes in segmental lordosis and patient-reported outcomes. Though there are many possible explanations for these conflicting results, we propose that a more nuanced approach that separates cages by design features is needed to better understand this problem and ultimately develop devices that lead to optimal outcomes.

To our knowledge, no systematic review to date has comprehensively compared the various features of expandable interbody fusion cages, including material composition, unexpanded insertion dimensions, biplanar versus uniplanar expansion, and lordotic correction capabilities. The present work aims to address this gap by systematically examining the literature on expandable lumbar interbody cages, highlighting the range of design features currently in use. Furthermore, it seeks to determine whether the existing literature can identify which design features of expandable lumbar interbody fusion cages are associated with improved outcomes. Finally, the review provides recommendations regarding a reporting paradigm for future studies that includes specific features of the expandable interbody

devices, enhancing our understanding of these devices and their impact on surgical outcomes.

Methods

Search strategy and selection process

This literature review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA 2020) guidelines [12]. Records were identified via an electronic search of MEDLINE and Embase using the search terms “lumbar” AND “fusion” AND (“expandable cage” OR “expandable interbody”) on March 1, 2024. Only English-language articles were included, and no additional filters were used. Results were imported into EndNote software (EndNote X9, Clarivate PLC, London, UK), where duplicates were identified and removed. Two authors (D.O. and A.E.B.) independently screened each article based on the title and abstract. Conflicts between the authors were resolved via discussion between the authors until a consensus was reached.

In the abstract review phase, an article was excluded if the title or abstract failed to indicate any usage of an expandable interbody cage for a lumbar fusion procedure in a clinical setting. After reviewing the abstracts, the full text of each article was screened for inclusion. A study was excluded if: it did not provide sufficient details about the expandable cage used, it only reported data from patients implanted with a static device, the paper was a commentary on the topic, it was a case report, or if the data being reported was also reported in a later study with a longer follow-up time (Fig. 1).

Data analysis

Four authors independently gathered data from each report with 2 authors (A.J. and T.P.) gathering data regarding expandable interbody device parameters including outer shape, material makeup, compressed dimensions both medial-lateral and vertical, expanded dimension both medial-lateral and vertical, and the lordotic angulation options. The device specifics were extracted directly from the study, where possible, with unstated parameters gathered from the manufacturers' websites when possible. Most devices had multiple size and angle options all of which were gathered when possible. For analysis, when comparing the compressed widths and heights, the mean of the size options was used. These authors also gathered radiographic and clinical outcome data including visual analog scale (VAS) scores for both the back and leg, Oswestry disability index (ODI) scores, intraoperative blood loss (IBL), length of stay (LOS) in the hospital, study location, reported subsidence, and reported fusion rates. Two different authors (D. O. and R.A.) gathered study information including the study population, the interventions used, what the study was comparing to, the outcome variables and results, the latest follow-up time of each study and whether the authors received

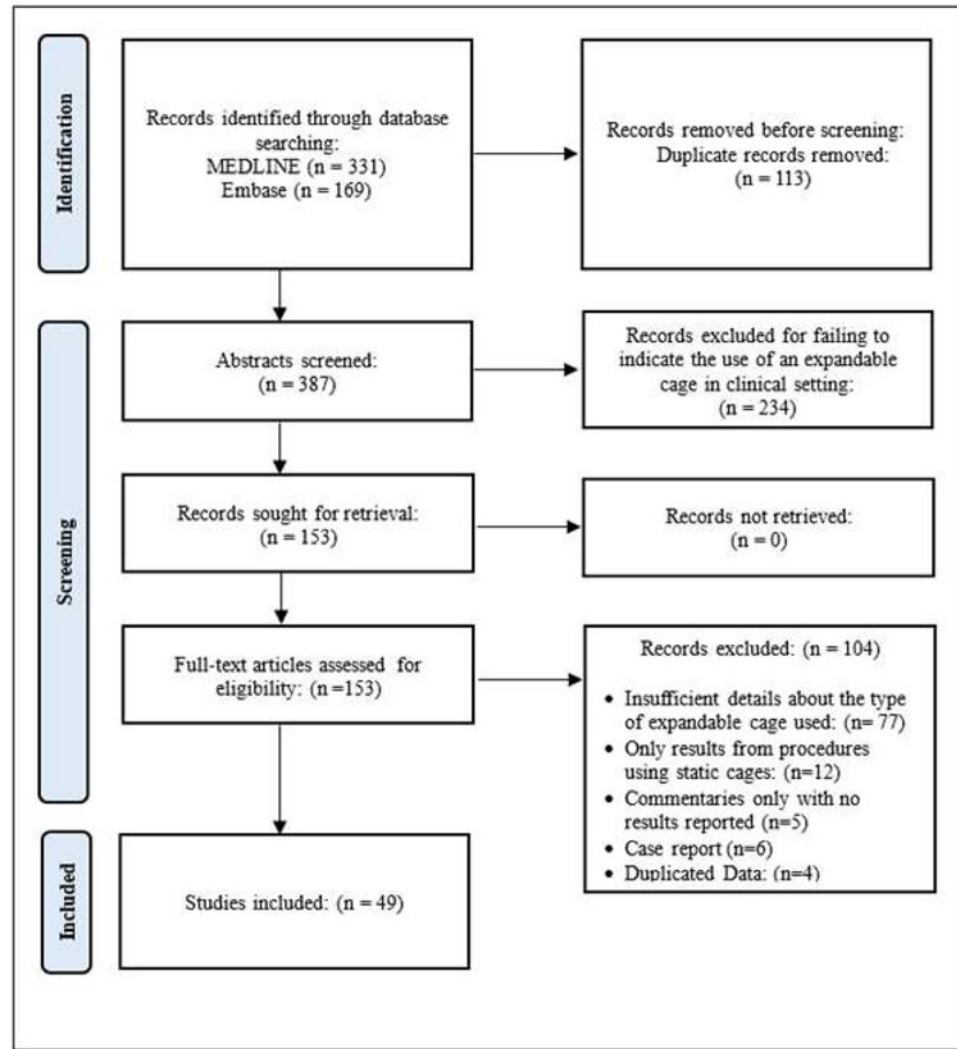


Fig. 1. PRISMA flow diagram.

funding for or were affiliated with the device manufacturer in question either as consultants or employees. These data are summarized in a PICOTS table (Table 1).

Analyses were conducted to compare the gathered cage parameters to the radiographic and clinical results gathered from each study. Separate analyses were done to evaluate these outcomes in relation to the various cage parameters mentioned earlier.

Studies typically reported outcomes as a mean followed by the standard deviation or variance. To compile this data, the weighted mean was found using the following method:

weighted mean

$$= \frac{\sum((\text{of patients}) * (\text{reported mean}))}{\sum(\text{of patients})} \quad (1)$$

The # of patients represent the number reported at final follow up in the cohort of patients who received the expandable cage in question. Either standard deviation or variance was reported in the included studies. To compile these, all

were converted to variance then multiplied by the # of patients as follows:

weighted variance

$$= \frac{\sum((\text{of patients}) * (\text{reported variance}))}{\sum(\text{of patients})} \quad (2)$$

$$PRO_{\text{change}} = (\text{preoperative score})$$

$$- (\text{follow up score}) \quad (3)$$

This variance was then converted to standard deviation. In the case of patient-reported outcomes (PROs), VAS back, VAS leg, and ODI, studies typically reported the preoperative value and the follow-up value each with a variance or standard deviation. To compile this information concisely, we took the difference between the values as shown in equation 3. PRO outcomes from multiple studies could then be compiled by taking the weighted mean of the

Table 1
PICOTS table summarizing all the studies included in this review

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
Wang et al [64]	Prospective review with 42 patients	MIS TLIF using ERAS protocol with rhBMP 2 in anterior disc space, insertion of OptiMesh® mesh expandable cage packed with allograft matrix. Supplemental pedicle screw and rod fixation	Enhanced Recovery After Surgery Protocols to traditional protocols	EBL, LOS, Complications	ERAS protocol, with modification, will likely reduce postoperative recovery times, complications and acute care costs	2 y
[†] Koleun et al [56]	Retrospective review with 100 patients,	Awake endoscopic MIS TLIF with rhBMP 2 in anterior disc space, insertion of OptiMesh® mesh expandable cage packed with allograft matrix. Supplemental pedicle screw and rod fixation	Enhanced Recovery After Surgery Protocols to traditional protocols	EBL, Operative Time, LOS, ODI, Complications	This procedure can provide a safe and efficacious option for lumbar fusion with less morbidity than open surgery	1 y
Alimi et al [25]	Retrospective review with 49 patients	TLIF with StaXx® XD expandable cage. Unspecified bone graft and fillers used. Unspecified Supplemental pedicle screw and rod fixation fixation used.	Comparison of Polyether ether ketone (PEEK) expandable cage to previously published conventional cages	VAS B, VAS buttock, VAS L, ODI, disc height, foraminal height, spondylolisthesis, local disc angle, lumbar lordosis, disc height	PEEK spacers can effectively and durably restore disc and foraminal height and improve the outcome without significant subsidence	19 mo
*Coe et al [28]	32 patients	TLIF or PLIF with Luna® 3D biplanar expandable cage. Concavity of device filled with unspecified bone graft. Supplemental pedicle screw and rod fixation	Comparison of PEEK biplanar expandable cage to previously published data	MCID, ODI, disc height, local disc angle, foraminal height, regional lumbar lordosis	Luna 3D Cage provides a smaller footprint and immediate vertebral height restoration, anatomic alignment, and excellent early clinical results	3 mo
Jansen et al [30]	Retrospective review with 30 Patients	MIS TLIF procedures with Luna® 360 biplanar expandable cage. Concavity of device filled with autograft bone graft. Supplemental pedicle screw and rod fixation	Comparison of PEEK biplanar expandable cage to previously published data	VAS, ODI, SF 36 PCS, complications	MIS TLIF with Luna 360 Cage is safe and effective for patients with DDD with low complication rates and improved pain, functional impairment and quality of life	1 y
*Kucharzyk et al [32]	Retrospective review with 50 patients	TLIF with the Luna® 360 biplanar expandable cage. Concavity of device filled with unspecified bone graft. Supplemental pedicle screw and rod fixation	Comparison of PEEK biplanar expandable cage to previously published data	ODI, SF 36 PCS, MCID, disc height, foraminal height, segmental lordosis, subsidence, implant migration, pseudoarthrosis.	Multidimensional, expandable inter body implant allows surgeons to re establish sagittal balance and provide a larger surface area for fusion compared to traditional minimally invasive devices	2 y
[†] Woodward et al [39]	Retrospective review with 120 patients	MIS TLIF with the Luna® 360 biplanar expandable cage. Autologous bone packed and rhBMP 2 into device. Supplemental pedicle screw and rod fixation	Comparison of PEEK biplanar expandable cage to previously published data	ODI, numeric pain rating scale (NRS), disc height, intervertebral foraminal height, spondylolisthesis, segmental lordosis, lumbar lordosis, fusion.	Luna 360 through MIS corridor represents a safe and efficacious alternative to a static TLIF in adults with degenerative lumbar pathology	1 y

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
[†] Woodward et al [40]	69 patients	Single center cohort study of MIS TLIF procedures with Luna [®] 360 biplanar expandable cage. Autologous bone packed and rhBMP 2 into device. Supplemental pedicle screw and rod fixation.	Comparison of PEEK biplanar expandable cage to previously published data	NRS, ODI, SF 12, VR 12, disc height, neuroforaminal height, spondylolisthesis, segmental lordosis, and fusion rate.	Use of Luna 360 is safe and able to produce durable radiographic and clinical improvements for those undergoing MIS TLIFs.	2 y
[*] Kim et al [31]	Prospective study with 50 patients	MIS TLIF procedures with the Caliber [™] expandable cage. Autologous bone packed into disc space and device. Supplemental pedicle screw and rod fixation.	Comparison of an expandable cage compared to both titanium and PEEK to traditional devices	surgery time, EBL, fluoroscopy time, LOS, VAS, ODI, neurologic deficits, implant migration, subsidence, cage breakage, disc height, neuroforaminal height, fusion rate, device migration, subsidence, and Cobb angle.	Expandable cages after MIS TLIF resulted in improved disc height restoration, high fusion rates and no evidence of device related complications	2 y
[†] Cheng et al [27]	Retrospective review with 7 patients	PLIF procedures with 2 Flarehawk [®] biplanar expandable cages placed bilaterally. Bone graft not stated. Supplemental pedicle screw and rod fixation.	Comparison of a biplanar expandable PEEK cage to previously published data	Fusion rate, device deformation	Bidirectionally expandable multilateral cages can successfully achieve interbody fusion.	1 y
[†] Tan et al [37]	Retrospective review with 13 patients	MIS TLIF procedures using the Flarehawk [®] biplanar expandable cage. Allograft bone packed into device and disc space. Supplemental pedicle screw and rod fixation.	Comparison of a biplanar expandable PEEK cage to previously published data	Disc height, foraminal height, segmental lordosis, Meyerding grade, spondylolisthesis reduction, end plate violation, cage subsidence, VAS, EQ 5D, and surgical complications	Biplanar expandable cage is safe and efficacious in treating lumbar spondylolisthesis using the MIS TLIF approach.	6 mo
[†] Folman et al [29]	Prospective study with 87 patients	PLIF procedures with 2 B Twin [™] titanium expandable cages placed bilaterally. Autologous bone packed into disc space. Pedicle screw and rod fixation when needed.	Use of a circular titanium biplanar expandable cage to traditional static cages	VAS, ODI, surgical complications, fusion rate	B twin cage has as good clinical outcome as preceding cages but with far fewer surgical complications	2 y
Korovessis et al [57]	Prospective study with 150 patients with 1 level procedure	PLIF procedures with monosegmental circumferential instrumented fusion vs single B Twin [™] cage placed diagonally in the disc space with supplemental pedicle screw and rod fixation. Autologous bone and DBM packed into disc space for cage procedures. Autograft and calcium phosphate bone graft substitute used for posterior fusion with pedicle screws and rods.	Use of a circular titanium biplanar expandable cage with supplemental fixation to traditional PLIF procedures	SF 36, ODI, VAS, disc height, segmental disc wedging, and fusion rate	Cage fusion offered better sagittal radiological restoration but with no medium term clinical impact. The expandable cage was associated with fewer surgical complications.	3 y
[†] Attia [26]	Retrospective review with 72 patients	PLIF procedures with 2 LIFE [®] titanium expandable cages placed bilaterally. Autologous bone graft packed into device. Supplemental fixation not stated	Use of a circular titanium cage with anterior expandability to traditional cages.	Surgical complications, fusion rate, and segmental lordosis	This PLIF technique resulted 92% patient satisfaction but 6% [5] “bad” results.	1–5 y

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
*Neely et al [61]	Retrospective review with 470 patients	PLIF procedures with 2 VariLift® devices placed bilaterally. Device filled with autograft bone. Supplemental fixation not stated	Use of a circular titanium cage with anterior expandability without posterior fixation to traditional PLIF procedures	EBL, fusion, progression towards fusion, subsidence, migration, postoperative motor deficits, and composite back pain scores	The VariLift L device produced high fusion rates, a low incidence of reoperation and effective symptom relief for a large group of patients. 94% fusion rate at 1 year. 3% [16] developed ASD.	5 y
Wang et al [63]	Retrospective review with 32 patients	Full endoscopic TLIF procedures with Luna® flexible expandable cylindrical fusion cages. Disc space filled with autograft and allograft bone and rhBMP 2. Supplemental pedicle screw and rod fixation	Full endoscopic TLIF procedures with a circular expandable cage compared to traditional TLIF procedures	Nerve decompression, VAS B, VAS L, ODI scores, sensory and muscle strength, the McNab score, and fusion	FE LIF is a safe and effective technique for lumbar interbody fusion surgery with an anterior expandable cylindrical fusion cage. No nonunions.	1 y
Kim et al [54]	57 patients	PLIF procedures with 2 Tyche® expandable fusion cages placed. Device filled with autograft bone. Supplemental fixation not stated.	Use of a circular titanium cage with anterior expandability without posterior fixation to traditional PLIF procedures	VAS B, VAS L, ODI score, fusion rate, intervertebral disc height, dynamic stability, segmental lordosis, and total lumbar lordosis	No special complications over follow up periods, and results demonstrate functional stability and clinical success	2 y
Massie et al [33]	Retrospective review with 44 patients	MIS TLIF procedures on patients with spondylolisthesis using the ALTERA™ titanium expandable cage. Disc space and device filled with unspecified graft material. Supplemental pedicle screw and rod fixation	Use of a crescent shaped titanium expandable cage placed in the anterior disc space to traditional MIS TLIF cages	VAS B, VAS L, segmental and lumbar lordosis, evidence of disc height, endplate violations	Globus Altera Cage provides a significant restoration of segmental height and segmental lordosis, with associated improvements in sagittal balance parameters and acceptable levels of fusion and significant reductions in pain and disability.	2 y
Steinhaus et al [36]	Retrospective review with 63 patients	MIS TLIF procedures with the ALTERA™ titanium expandable cage on patients with degenerative spondylolisthesis. Autograft bone used but location unspecified. Supplemental pedicle screw and rod fixation	Use of a crescent shaped titanium expandable cage placed in the anterior disc space to traditional MIS TLIF cages	ODI, VAS B, VAS L, fusion rate, SF 12, PROMIS Physical Function (PF), intraoperative reduction and loss of reduction	Significant loss of reduction rate but overall few differences in patient reported outcomes with similar rates of fusion and reoperation	1 y
Tassemieir et al [68]	Retrospective review with 61 patients	TLIF procedures with either an unspecified banana shaped or unspecified straight expandable titanium cage. Bone graft and Supplemental fixation not stated	Results from a banana shaped titanium expandable cage placed in the anterior disc space to a straight expandable titanium cage	Disc height, segmental lordosis angle, lumbar lordotic angle, and subsidence	Significantly superior to the straight cage in terms of restoring DH and showed less rates of subsidence and a better segmental correction. The straight cage was superior in restoring the overall lordosis but without statistical significance.	Not stated
Park and Heo [34]	Retrospective review with 10 patients	TLIF procedures with the Dual X® biplanar expandable cage. Autologous bone packed into disc space. Allograft bone and DBM packed into device. Supplemental fixation not stated	Use of a biplanar expandable cage to traditional cages	surgery time, EBL, complications, VAS B, VAS L, ODI, disc height, segmental lordosis, and lumbar lordosis	Use of this biplanar expandable cage may be favorable at 6 months follow up with no evidence of significant subsidence	6 mo

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
Kim et al [55]	Retrospective review with 69 patients	PLIF procedures with 2 VariAn™ cages placed. Bilaterally. Bone graft and Supplemental fixation not stated	Use of a rectangular titanium cage with anterior expandability without posterior fixation to traditional PLIF procedures	Segmental angle and translation, short and whole LL, pelvic incidence, pelvic tilt, sacral slope (SS), sagittal vertical axis, thoracic kyphosis, subsidence, pseudarthrosis, retropulsion, cage breakage, proximal junctional kyphosis, and screw malposition	Stand alone expandable cage fusion can restore local lordosis; however, global sagittal balance was not restored.	5 y
Chen et al [20]	Retrospective review with 62 patients	MIS TLIF procedures with a VariAn™ rectangular titanium expandable cage. Device filled with autograft bone. Supplemental pedicle screw and rod fixation	Efficacy of an expandable titanium cage compared to nonexpandable cage	surgey time, EBL, LOS, VAS B, VAS L, ODI, Japanese Orthopaedic Association Score, disc height, foraminal height, lumbar lordosis, sacral lordosis, VAS B, VAS L, ODI, and postoperative Macnab outcomes	No significant difference in short term clinical outcomes but use of expandable cages in MIS TLIF can provide significant restoration of disc height, and neural foraminal height. Results are like conventional surgery with fast patient recovery and early postoperative hospital discharge	1 y
[†] Morgenstern and Morgenstern [60]	16 patients	perLIF with either the Opticage, Rise, or Concorce Lift expandable cages and an interspinous spacer. Device and disc space filled with DBM. Supplemental fixation not stated	PercLIF with an expandable cage and interspinous spacer to traditional TLIF procedures			
[†] Wang et al [66]	Retrospective review with 16 patients	PercLIF via Kambin's triangle using unsupplemented expandable titanium cage for patients with spondylolisthesis	Fusion using a percutaneous approach with an expandable cage to traditional TLIF procedures	ODI, spondylolisthesis, anterior disc height, and posterior disc height, fusion, demographic information, preoperative and postoperative radiographic factors, perioperative data and complications	PercLIF effective with expandable titanium cage through Kambin's triangle without endoscope and with significant improvements of spondylolisthesis, disc height, and ODI scores.	1 y
Lara Reyna and Margolis. [58]	Retrospective review with 4 patients	MIS TLIF with Rise IntraLIF™ expandable titanium cage. DBM in disc space. Supplemental pedicle screw and rod fixation with facet fusion with allograft bone.	Addition of facet fusion to MIS TLIF with an expandable titanium cage to traditional TLIF	LOS, surgical complications, patient reported pain reduction	Endoscopic facet fusion appears safe though larger study needed.	8 mo
*Kucharzyk et al [24]	Retrospective review with 100 patients	TLIF procedure with either a static PEEK cage or the ProLift® titanium expandable cage. Autologous and allogenic bone graft packed into device. Supplemental pedicle screw and rod fixation fixation not stated	Patient outcomes with an expandable interbody spacer compared to a static spacer	VAS B, VAS L, ODI, disc height, foraminal height, segmental lordosis, fusion rate, rate of revision	Patients with expandable cages had improved radiographic and clinical results compared to static cohort.	2 y
[†] Wang et al [66]	Retrospective review with 16 patients	perLIF via Kambin's triangle using the Elite® expandable titanium cage. Allograft cortical fibers packed into device. Supplemental pedicle screw and rod fixation pedicle screw and rod fixation.	Results using a full percutaneous TLIF approach with an expandable titanium cage without an endoscope	surgey time, EBL, LOS, ODI, spondylolisthesis, disc height, lumbar lordosis, fusion rate, and complications	The perLIF with an expandable cage is an effective without the need for an endoscope and improved spondylolisthesis, disc height, and ODI scores.	1 y

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
*Huo et al [23]	Prospective study with 98 patients	LLIF with either the Rise™ L expandable cage or TI Modulus® XLIF static titanium interbody cage. Allograft bone packed into disc space. Allograft bone and rhBMP 2 packed into devices. Supplemental pedicle screw and rod fixation not stated	Clinical and radiographic outcomes with an expandable titanium cage compared to a static titanium cage	PROMs, ODI, VAS B, VAS L, SF 36 MCS, SF 36 PCS, subsidence, segmental lordosis, disc height, fusion	Expandable cages result in improved fusion rates (83 vs 94%) with reduced subsidence risks and increased PROs at 12 months post operatively.	1 y
*Frisch et al [21]	56 patients, 49 (88%) with 1 level procedure, 7 (12%) 2 level	LLIF using either a PEEK static cage or the Caliber™ L expandable cage. Autologous bone packed into devices and disc space. Supplemental pedicle screw and rod fixation pedicle screw and rod fixation.	Clinical and radiographic outcomes with an expandable titanium and PEEK cage compared to a static PEEK cage	surgery time, EBL, LOS, VAS, ODI, disc height, fusion, subsidence, migration	LLIF expandable cages had similar clinical and radiographical outcomes to static cages and led to lower subsidence rates but surgery time was nearly twice as long due to unilateral vs bilateral supplemental fixation.	2 y
†Malham et al [59]	Prospective observational study with 33 patients, 8 (24%) with 1 level procedure, 15 (46%) 2 level and 8 (24%) 3 level, and 2 (6%) 4 level	LLIF with the Elsa™ expandable cage in patients exhibiting ASD from previous fusion. Device filled with rhBMP 2 or DBM. Disc space filled with hydroxyapatite bone substitute. Supplemental fixation not used.	Use of an expandable laterally placed titanium cage with integrated fixation in a standalone fashion compared to traditional fusion techniques	ODI, Segmental lordosis, disc height, fusion, retraction time, blood loss, complications, cost	Significant improvements in ODI, VAS B, VAS L, SF 36 PCS, SF 36 MCS, disc height, and lumbar lordosis compared to preop. 94% fusion rate. Lower cost than cages with supplemental fixation. Use of this expandable cage with integrated fixation provides a robust alternative to traditional ASD lumbar surgery and should be considered a safe, effective, and lower cost alternative	1 y
Hiyama et al [22]	Retrospective review of 67 patients, 38 (67%) with 1 level procedure, 26 (30%) 2 level and 3 (3%) 3 level	Lateral single position lumbar interbody fusion using either the Rise™ L expandable cage or a static lateral cage. DBM packed into devices. Supplemental pedicle screw and rod fixation not stated	Results of this single position LLIF with both a static and an expandable cage. Devices compared	surgery time, EBL, LOS Disc Height, segmental lordosis, foraminal area, and complications	No significant in disc height, segmental lordosis, foraminal area, or dural sac expansion between devices	2 wk
Ledesma et al [67]	Retrospective review with 93 patients	MIS TLIF procedures with either the Flarehawk® biplanar expandable cage, or the Caliber™ uniplanar expandable cage performed with uniplanar and biplanar PEEK cages. Autologous bone packed into devices and disc space. Supplemental pedicle screw and rod fixation	Radiographic and clinical outcomes using both a uniplanar and biplanar expandable cage each being made from titanium and PEEK. Devices compared.	VAS B, VAS L, ODI, disc height, segmental lordosis, subsidence, complication rates, readmission rates, revision surgical procedures and fusion rates	Both devices resulted in significant improvements in disc height and segmental lordosis. No difference ODI, VAS B, VAS L, cage subsidence and fusion rates (85 vs 94%) between devices. Both uniplanar and biplanar expandable PEEK cages are safe options at 1 year postop with no significant differences in clinical, radiographic, and postoperative complication rates.	1 y

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
Sim et al [35]	Retrospective review with 23 patients, 7 (30%) with 1 level procedure, 12 (52%) 2 level and 4 (18%) 3 level	TLIF procedures with an unstated biplanar expandable titanium and PEEK cage. Autologous and allogenic bone graft packed into device and disc space. Supplemental pedicle screw and rod fixation pedicle screw and rod fixation	Radiographic and clinical outcomes using a bidirectional expanding PEEK and titanium cage compared to traditional cages	VAS B, VAS L, ODI, PROMs, NSS, disc height, foraminal height, segmental lordosis, lumbar lordosis, subsidence, cage migration and revision surgery	Significant improvements in ODI, VAS B, VAS L, NSS, disc height, foraminal height, segmental lordosis, lumbar lordosis. No cage related complications. TLIF performed with biplanar expandable cages led to significantly improved patient reported outcomes and radiographic parameters at 1 year and is safe for Asians.	1 y
*Tabarestani et al [62]	Retrospective review with 49 patients	PercLIF via Kambin's triangle using the Elite® expandable cage without the use of an endoscope or a facetectomy. Allograft bone packed into device and disc space. Supplemental pedicle screw and rod fixation pedicle screw and rod fixation	Long term results using the percLIF procedure compared to either endoscopic or open TLIF procedures	VAS, ODI, spondylolisthesis, lumbar lordosis, sacral slope, pelvic tilt, disc height, pelvic incidence, fusion rates, and annual rate of surgically significant adjacent segment disease	Significant improvements in ODI, VAS B, VAS L, spondylolisthesis, disc height, lumbar lordosis, pelvic tilt, pelvic slope, and PI LL. 94% (17/18) and 88% (7/8) fusion rate by CT at 1 and 2 years postop respectively. 2.7% annual rate of ASD at 2.7 years. percLIF via Kambin's triangle is a safe and successful procedure with long term improvements in both clinical and radiographic outcomes	2 y
†Weinstein et al [38]	Prospective study with 28 patients	TLIF with an FLX fit15® articulating expandable titanium cage. Allograft bone packed into device and disc space. Supplemental pedicle screw and rod fixation pedicle screw and rod fixation with rhBMP 2	Radiographic and clinical results using an articulating expandable titanium cage compared to traditional cages. Radiographic fusion assessment	ODI, VAS B, VAS L, pelvic incidence and tilt, lumbar and segmental lordosis, disc height	Significant improvements in ODI, VAS B, VAS L, segmental lordosis, L1 S1 lordosis, disc height. No nonunions. No device complications. FLXfit15 cage design represents an effective and safe option to increase cage size and allow significant segmental lordosis correction.	2 y
†Khechen et al [41]	Retrospective study of 60 patients with one level procedure	MIS TLIF with T PAL® static with expandable articulating titanium coated PEEK cage vs ALTERA™ articulating static PEEK cage. Bone graft and Supplemental pedicle screw and rod fixation fixation not stated	Pre and postprocedure clinical scores and radiographic measurements. Radiographic fusion assessment. Devices compared	EBL, LOS, PROs, MCID, lumbar lordosis, segmental lordosis, disc height, and foraminal height	Expandable device produced greater improvement in disc and foraminal height than static device. No difference in PROs, lumbar or segmental lordosis. No complications or fusion rate reported.	7 mo

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
*Russo et al [42]	Retrospective study of 48 patients with one level procedure	MIS TLIF with ALTERA™ expandable banana shaped titanium articulating spacer vs unspecified radiolucent static spacer made from polymer. Expandable spacer filled with autograft. Static spacer filled with bone marrow aspirate, DBM and bioactive amniotic suspension. Supplemental pedicle screw and rod fixation MIS PLIF with 2 expandable B Twin® spacers in both groups. Allograft bone graft in 35 cases and iliac crest autograft in 27. Supplemental pedicle screw and rod fixation not stated.	Pre and postprocedure radiographic measurements. Radiographic fusion assessment. Devices compared	Lumbar lordosis, posterior disc height, and foraminal height	Expandable device produced greater improvement in disc and foraminal height and lumbar lordosis than static device. No complications or fusion rate reported.	9 mo
†Gepstein et al [43]	Prospective study of 62 MIS PLIF patients with a previously reported group of 87 patients with open approach. All one level procedures.	MIS PLIF with one expandable titanium B Twin™ spacer. Iliac crest autograft in 4 cases and allograft in 8. Supplemental pedicle screw and rod fixation not stated.	Pre and postprocedure clinical scores and radiographic measurements. Radiographic fusion assessment	EBL, surgery time, VAS, ODI, radiographic disc height, union	Increased disc height in both groups. 2 y Decreased pain and disability scores compared to preoperatively in both groups. No nonunions. Statistical comparison of surgical approaches not performed	2 y
†Xiao et al [44]	Retrospective review of 12 patients with one level procedure	MIS PLIF with one expandable titanium B Twin™ spacer. Disc space packed with bone allograft or autograft with DBM. Supplemental pedicle screw and rod fixation not stated	Pre and postprocedure clinical scores and radiographic measurements. Radiographic fusion assessment	EBL, surgery time, VAS, ODI, disc height, radiographic union, complications	Increased disc space height and improved VAS, ODI for all but one patient who had a nonunion requiring implant removal	2 y
Lee et al [45]	Retrospective review of 18 patients with one level procedure	MIS PLIF with 2 expandable titanium B Twin™ spacers. Disc space packed with bone allograft or autograft with DBM. Supplemental pedicle screw and rod fixation not stated	Pre and postprocedure clinical scores and radiographic measurements. Radiographic fusion assessment	VAS B, VAS L, ODI, disc height, radiographic union, complications	Increased disc height and improved VAS B, VAS L, and ODI scores. One patient had a nonunion. Another required revision surgery with anterior lumbar interbody fusion and pedicle screw fixation due to implant migration one month postsurgery	46 mo
†Wang et al [46]	Retrospective review of 10 patients with one level procedure	MIS TLIF with OptiMesh® cage packed with allograft matrix. rhBMP 2 in anterior disc space. Supplemental pedicle screw and rod fixation	Pre and postprocedure clinical scores. Radiographic fusion assessment	ODI, SF 36 PCS, SF 36 MCS, EQ 5D	Clinically and statistically significant differences in ODI and EQ 5D after procedure. No complications or nonunions	1 y
†Yao et al [53]	Retrospective review of 43 patients with one level procedure	MIS PLIF with 2 expandable titanium B Twin™ spinal spacers and autologous bone graft. Supplemental pedicle screw and rod fixation not stated	Pre and postprocedure clinical scores and radiographic measurements. Radiographic fusion assessment	EBL, surgery time, LOS, VAS B, VAS L, disc height, radiographic union, complications, Chinese Orthopedic Assoc. outcome score	Increased disc height and improved VAS B, VAS L scores. Good Chinese Orthopedic Assoc. outcomes. One nonunion with cage migration requiring revision	18 mo

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
*Coric et al [47]	Retrospective review of 45 patients with radiographic fol low up and 58 patients with clini cal scores. 65% 1 level procedure and 35% 2 level	MIS TLIF or PLIF surgery with a FlareHawk® bidirectional expandable interbody fusion device with PEEK shell and titanium shim. Autologous and/or allogenic bone graft packed into device and disc space. Supplemental pedicle screw and rod fixation	Pre and postprocedure clinical scores and radiographic measure ments. Radiographic fusion assessment	EBL, surgery time, LOS, VAS B, VAS L, disc height, radiographic union, complications	Improved VAS B, VAS L and ODI scores. 97% radiographic fusion. 1 case of device migration. Another case with nonunion requiring addi tional surgery	4.5 mo clini cal score fol low up, 1 y radiographic follow up
†Li et al [49]	Retrospective review of 47 patients with expandable inter body spacer without adjust able lordosis and 66 with expandable spacer adjustable lordosis. 79% one level procedure, 21% 2 level	MIS LLIF with RISE AL® expandable titanium interbody spacer with or without RISE™ L adjustable lordosis. Device and disc space filled with autograft bone. Supplemental pedicle screw and rod fixation fixation used	Pre and postprocedure clinical scores and radiographic measure ments. Radiographic fusion assessment. Devices compared	VAS B, VAS L, ODI, disc height, segmental lordosis, neuroforaminal height, PI LL, lumbar lordosis and radiographic fusion	Improved VAS B, VAS L, ODI, disc height, segmental lordosis, neuroforaminal height, pelvic incidence lumbar lordosis, lumbar lordosis. 100% radiographic fusion. No sig nificant differences between devices	2 y
†Li et al [50]	Retrospective review of 24 patients. 79% 1 level procedure and 21% 2 level	MIS LLIF with RISE™ L expandable titanium interbody spacer with adjustable lordosis. Device filled with autograft bone. Supplemental pedicle screw and rod fixation	Pre and postprocedure clinical scores and radiographic measure ments. Radiographic fusion assessment	VAS B, ODI, disc height, segmental lordosis, neuroforaminal height, lumbar lordosis and radiographic fusion	Improved VAS B, ODI, lumbar lordosis, posterior disc height, neuroforaminal height and segmental lordosis. 100% radiographic fusion	2 y
*Russo et al [52]	Retrospective review of 46 patients. 50% 1 level procedure and 50% 2 level	MIS TLIF with AL.TERA™ expandable titanium lumbar interbody fusion device. Bone graft and Supplemental pedicle screw and rod fixation fixation not stated	Pre and postprocedure clinical scores and radiographic measure ments. Radiographic fusion assessment	EBL, surgery time, fluro time, VAS B, VAS L, disc height, neuroforaminal height, lumbar lordosis and radiographic fusion	Improved VAS B, VAS L, disc height, lumbar lordosis. 89% radiographic fusion	6 mo
*McMordie et al [51]	Retrospective review of 50 patients. 64% 1 level procedure and 36% 2 level	MIS TLIFs with Elevate® lordotic expandable interbody device. Disc space filled with allograft bone and device filled with allograft bone and rhBMP 2. Supplemental pedicle screw and rod fixation	Pre and postprocedure clinical scores and radiographic measure ments. Radiographic fusion assessment	VAS, ODI, lumbar lordosis, segmental lordosis, disc height, foraminal height, PI LL and radiographic fusion	Improved ODI, VAS, segmental lordosis, disc height, and foraminal height. Postoperative lumbar lordosis inversely correlated with preoperative lordosis in patients with an initial PI LL mismatch. Preoperative lumbar lordosis predicted of postoperative lumbar lordotic change in patients with sagittal imbalance. One nonunion	6 wk

Table 1 (Continued)

Reference	Population	Intervention	Comparison	Outcome variables	Stated findings	Time
[†] Li et al [48]	Retrospective review of 63 patients 77% 1-level procedure and 23% 2-level	MIS LLIF with expandable Trans-continental [®] or Rise TM -L, nonexpandable titanium interbody spacer Device filled with autograft bone Supplemental pedicle screw and rod fixation	Pre- and postprocedure clinical scores and radiographic measurements Radiographic fusion assessment Devices compared	VAS-B, VAS-L, ODI, disc height, segmental lordosis, neuroforaminal height, lumbar lordosis, PL-LL and radiographic fusion	Improved VAL-B, VAL-L, ODI, disc height, neuroforaminal height compared to baseline for both cages Improved VAL-B, VAL-L, ODI, disc height and lower subsidence rate for expandable cage 100% radiographic fusion	2 y

* One or more authors received funding from the manufacturer of the device used for the research

[†] One or more authors are consultants or employees for the manufacturer of the device used in the research

[‡] The study did not provide any conflict of interest or acknowledgments information

ASD, adjacent segment disease; DBM, demineralized bone matrix; EBL, estimated blood loss, EQ-5D, EQ-5D, EuroQol 5-dimension survey; FE-LIF, full endoscopic lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; LOS, length of stay/MICD, minimal clinically important difference; MIS-LLIF, minimally invasive lateral lumbar interbody fusion; MIS-PLIF, minimally invasive posterior lumbar interbody fusion; MIS-TLIF, minimally invasive transforaminal lumbar interbody fusion; NPRS, numeric pain rating scale/NPRS Back, numeric pain rating scale leg; NPRS Leg, numeric pain rating scale leg; NSS, North American Spine Society neurogenic symptom score; ODI, Oswestry disability index; PE-TLIF, percutaneous endoscopic transforaminal lumbar interbody fusion; PEEK, polyetheretherketone; PercLIF, percutaneous lumbar interbody fusion; PLIF, posterior interbody fusion; PROs, patient-reported outcomes measurement information system physical function; PL-LL, pelvic incidence to lumbar lordosis; rhBMP-2, recombinant human bone morphogenetic protein-2; SF-12 PCS, SF-12 PCS, SF-12 health survey physical component summary; SF-36 PCS, SF-36 PCS, SF-36 health survey physical component summary; SF-36 MCS, SF-36 MCS, SF-36 health survey mental component summary; SF-36 PCS, SF-36 PCS, SF-36 health survey physical component summary; TLIF, transforaminal lumbar interbody fusion VAS-B, visual analog pain scale-back; VAS-L, visual analog pain scale-leg; VR-12, veterans RAND 12 item health survey

difference between the preoperative and follow-up scores as shown in equation 1 but with *PRO_{change}* in place of *reported mean*. However, the standard deviation for these PROs was more challenging to compile. More information would be required to find the exact variance in the change in any given PRO from preoperative values to follow-up values, but a conservative

$$PRO_{variance} = \sqrt{(preoperative\ variance)^2 + (followup\ variance)^2} \tag{4}$$

estimate was found using the following equation:

This conservative estimate of the variance in the change of any given PRO could then be used to find a weighted mean as described in equation 2. If a study provided the mean without reporting variance or standard deviation, the data was not included in the synthesis.

Because all but one of our datasets were large, we could apply the central limit theorem in assuming normality of the data. Therefore, to test for statistical significance, the first step was to perform an analysis of variance (ANOVA). If the null hypothesis was rejected, then post hoc comparisons of each category were performed using Tukey’s least significant difference method [13–15]. The results were compared with nonparametric methods, including Dunn’s test with Bonferroni correction assuming the data were skewed with a shape factor of 1, to ensure the robustness of the findings. All analyses were performed using the R statistical software package.

Results

A total of 387 articles were identified after duplicates were removed. Of these, 234 were excluded based on abstracts and titles. All 153 remaining articles were retrieved, and the full text was examined. Among these, 104 were excluded based on the predefined exclusion criteria mentioned earlier, leaving 49 articles included in this review. Multiple reports provided only 1 or 2 cage details, which were insufficient for device categorization, leading to their exclusion [16–19]. The PRISMA flow diagram is summarized in Fig. 1.

The articles were mainly prospective or retrospective studies aiming to compare an expandable cage to a static cage or to explore the use of a specific expandable device [20–53]. Thirteen studies focused on a unique lumbar interbody fusion approach using an expandable cage [54–66]. Additionally, 2 studies directly compared outcomes using 2 different expandable cages [67,68]. For each study, details on the population, intervention, comparison, outcome variables, and stated findings (PICOTS) were extracted and summarized in Table 1, while Fig. 2 displays images of all the various expandable cages used.

Comparison of design features

The design features compared include material composition, shape, insertion size, biplanar expandability, and lordotic correction. Surgical approaches and study location



Fig. 2. Expandable spinal fusion cages discussed in this study with the device name and manufacturer listed below each image.

were also compared to understand potential confounding factors better.

The materials used in the various expandable cages included titanium, PEEK, a combination of titanium and PEEK, and a knitted polyethylene terephthalate sac filled with bone graft postinsertion. Titanium was the most prevalent, used exclusively in 15 of the 22 devices. Of primary interest is the comparison of patient-reported outcomes, specifically changes in VAS back, VAS leg, and ODI score changes from before surgery to the latest follow-up. Subsidence and fusion rates are also included, as previous research has hypothesized that material may impact these parameters [69]. Interestingly, expandable devices exclusively made of titanium led to significantly greater improvements across VAS back, VAS leg, and ODI scores compared to cages made solely of PEEK and those

constructed from both PEEK and titanium. Table 2 summarizes these findings. Note that total number of patients across all studies is reported in each category, however, not all studies reported each outcome, so the number of subjects included in the analysis of each outcome is noted.

Four distinct shapes were identified across all the devices found in the literature, with the majority being classified as rectangular, followed by cages featuring a circular cross-sectional shape. A single device had a crescent shape, while another had an ovular shape. It should be noted that the Luna 360 cage discussed in multiple studies is classified as rectangular since that is its shape during insertion. However, once this cage is inserted, it curls around inside the disc space resulting in a cylindrical geometry. The Optimesh device shown in Fig. 2 is ovular once deployed and filled with bone graft leading to its categorization. The

Table 2
Compiled fusion rate, subsidence, VAS back change, VAS leg change, and ODI change separated by material makeup of the devices

Material	# Of devices	# Of studies	# Of patients	Fusion rate	Subsidence	VAS back change	VAS leg Change	ODI change
Knitted polyethylene terephthalate	1	3	109	87.50%	"Mild"	-	-	* 15.84±18.17 (n=109)
#PEEK	2	6	286	85.57%	0.6 mm "Rare" "None"	3.30±4.03 (n=45)	2.6±3.35 (n=45)	24.73±20.07 (n=154)
#PEEK and Titanium	4	9	279	92.38%	1.38±1.8 "None"	3.53±2.82 (n=272)	3.98±3.26 (n=174)	21.84±19.02 (n=257)
Titanium	15	31	1623	93.56%	0.885 mm 13.7% >2 mm 4.7% >3 mm	5.6±1.91 (n=614)	6.0±2.86 (n=323)	35.16±14.59 (n=554)

* This value is significantly lower than all other categories (p<0.01)

† This value is significantly higher than all other categories (p<0.05)

‡ This value is significantly higher than PEEK (p<0.05) and significantly lower than Titanium (p<0.01)

§ This value is significantly higher than all other values in this category (p<0.01)

|| VAS, Visual Analog Scale

¶ ODI, Oswestry Disability Index

PEEK, Polyether ether ketone

Altera device is categorized as a crescent shape because, unlike the rectangular device, it has a somewhat banana-shaped curve and is intended to be placed in the disc space such that the curved edge sits along the anterior of the vertebral endplates. Based on VAS leg and VAS leg data, circular cages appear to be ideal, while ODI scores indicate that either circular or rectangular cages are preferable to cages in the crescent and ovalar categories. However, this interpretation should be approached cautiously due to the presence of only a single device in the crescent and ovalar categories. Other factors related to these individual devices may play a role. Also, note the significantly higher blood loss correlated with circular cages. Table 3 summarizes these findings.

The unexpanded size of the devices or insertion sizes varied from 5 to 22 mm in width and 5 to 12 mm in height. To compare height data, cages were separated based on whether their compressed width was less than or greater than 10 mm and whether their compressed height was less than or greater than 8 mm. Many devices offered multiple size options, and studies did not provide data regarding which size option was used for each procedure. These devices were categorized based on the average size of the different options. For device width, the group representing devices with a smaller insertion width resulted in significantly greater VAS back and ODI improvements while at the same time resulted in significantly less VAS leg improvement. Similarly, for insertion height, the devices that were inserted smaller had greater VAS back improvement, and lower ODI improvement, as summarized in Table 4. Published radiographic and clinical results for these devices are summarized in Table 5.

Most expandable cages in this review were made primarily for vertical expansion, but a few newer devices have begun to implement both vertical and lateral expansion. The maximum expansion capabilities of the devices found in the literature ranged from 0–200% for vertical expansion and 0% to 263% for horizontal expansion. Despite these maximum expansion capabilities, the surgeons associated with each study ultimately decided how much expansion was implemented in each patient based on their anatomical needs. It is theorized that the addition of lateral expandability will aid in reducing the occurrence of subsidence. Unfortunately, studies reported subsidence in different ways, with some reporting a mean, others reporting a percentage greater than 2 mm, still others reporting a percentage greater than 3 mm, and some simply reporting words like "Rare," "Mild," or "None." This variability in reporting made meaningful comparison impossible. However, it was found that devices with biplanar expandability were correlated with numerically greater improvements in all patient-reported outcomes, with both VAS back and ODI reaching the level of significance. Interestingly, the intraoperative blood loss was significantly higher for biplanar expanding cages, while the length of stay was shorter for biplanar expanding cages.

Table 3
Compiled radiographic and clinical data separated by the outer shape of expandable cages

Shape	# Of devices	# Of studies	# Of patients	Fusion rate	Subsidence	†VAS back change	‡VAS leg change	# ODI change	Intraoperative blood loss (ml)
Circular	3	10	873	94.24%	1.03 mm 15.6% > 2 mm 4.7% > 3 mm	*5.85±1.67 (n 116) 4.16±2.91 (n 99)	*7.1±1.23 (n 43) 4.74±2.75 (n 99)	‡30.57±6.45 (n 73) 14.06±20.35 (n 53) 15.84±18.17 (n 109)	§533.93±65.18 (n 126) ‡123.47±82.76 (n 99) 65.47±67.46 (n 109)
Crescent	1	6	198	87.19%	6.6% > 2 mm				
Ovular	1	3	109		“Mild”				
Rectangular	16	31	1117	51.90%	4.48±1.8 mm 15.87% > 2mm None, Rare	‡4.79±2.44 (n 739)	5.04±3.23 (n 400)	‡32.61±16.28 (n 711)	75.76±73.77 (n 388)

* This value is significantly higher than all other categories (p<.001).

† This value is significantly higher than the Crescent data (p<.05).

‡ These values are significantly higher than Crescent and Ovular data (p<.001).

§ This value is significantly higher than all other categories (p<.001).

|| This value is significantly lower than the circular category and significantly higher than ovular and rectangular (p<.001).

¶ VAS, Visual Analog Scale.

ODI, Oswestry Disability Index.

Table 4
Patient reported outcomes separated by insertion size

Insertion size (ml)	# Of devices	# Of studies	# Of patients	†VAS back change	‡VAS leg change	# ODI change
Insertion width < 10	9	24	946	*4.46±2.52 (n 384) 4.06±2.45 (n 304) §4.59±2.61 (n 439)	‡4.32±3.11 (n 261) 5.18±2.50 (n 127) 4.84±3.33 (n 291) 4.94±2.77 (n 178)	‡23.07±16.41 (n 465) 15.13±16.30 (n 287) ‡19.90±15.13 (n 387) 22.06±17.25 (n 446)
Insertion width ≥ 10	7	15	501			
Insertion height < 8	8	19	652			
Insertion height ≥ 8	10	23	899			

* This value is significantly higher than the ≥ 10 mm width category (p<.05).

† This value is significantly lower than the ≥ 10 mm width category (p<.05).

‡ This value is significantly higher than the ≥ 10 mm width category (p<.001).

§ This value is significantly higher than the ≥ 8 mm height category (p<.01).

|| This value is significantly lower than the ≥ 8 mm height category (p<.05).

¶ VAS, Visual Analog Scale.

ODI, Oswestry Disability Index.

Table 5
Radiographic and clinical results separated by studies using cages with and without lateral expandability

Bilateral expansion	# Of devices	# Of studies	# Of patients	Subsidence	[†] VAS back change	[†] VAS leg change	[‡] ODI change	Intraoperative blood loss (ml)	Length of stay (days)
No	12	22	1206	1 02 mm 13 72% >2 mm 4 7% > 3 mm None	*4 00±2 57 (n=401)	4 43±2 86 (n=174)	*18 19±16 77 (n=384)	*238 20 ±179 93 (n=634)	*7 08±3 57 (n=343)
Yes	5	19	722	2 16 mm Rare, None	4 68±2 37 (n=287)	4 73±2 97 (n=214)	26 64±14 96 (n=269)	408 39±86 74 (n=191)	3 89±2 04 (n=193)

* This value is significantly different from the group that did include lateral expansion (p< 001)

[†] VAS, Visual Analog Scale

[‡] ODI, Oswestry Disability Index

The last design feature that was compared in this review was the lordotic angle. Cages were split into 3 separate categories, including cages with continuous angle adjustability, cages that had discrete angle options, and cages with no lordotic angle adjustability. This design feature was compared to patient-reported outcomes in Table 6. Notably, cages with continuous angle adjustability had significantly higher improvements across all patient reported outcomes in this study, compared to both other groups. Cages with discrete options and cages with no lordotic correction show no statistical difference in terms of improvement in patient reported outcomes.

Though this study focused on how various features of expandable cages affect patient-reported outcomes, many other factors likely affect these outcomes. Surgical approach and study location are 2 of these factors investigated in this study. The approaches implemented across the different studies varied from the more traditional posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF) to the new lateral lumbar interbody fusion (LLIF) and the minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) and even a facet-sparing percutaneous approach (perCLIF). Table 7 summarizes the results of comparing these different approaches. While there are many correlations here between the different approaches and patient outcomes, it is noteworthy that the LLIF approach is correlated with the most significant VAS back and ODI improvements and is even statistically equivalent to perCLIF in having the greatest VAS leg improvement. PLIF procedures were correlated to significantly higher intraoperative blood loss, however it was previously found that circular cages were also correlated to higher intraoperative blood loss, as seen in Table 3. Nearly all the procedures done with circular cages were also performed via the PLIF approach, making it difficult to determine whether approach, or shape or even some other factor is the primary consideration for intraoperative blood loss.

Studies were categorized as being within and outside the United States. The significant differences in both intraoperative blood loss and length of hospital stay indicate that procedural differences between healthcare systems in various countries likely had a substantial effect on outcomes unrelated to device design (Table 8).

While these results come with multiple possible confounding factors, it was found that these may prove to be robust. Results were initially calculated using only 36 of the 49 final studies with little changes noted in the results. The inclusion of the additional 13 studies in most cases simply reinforced the initial results by taking the difference into the range of statistical significance. Two exceptions include cage geometry, where initially rectangular cages were identified as superior, the additional data now indicates that circular cages perform as well or better than rectangular cages. The second exception is the finding that the LLIF approach is correlated with significantly improved

Table 6
Patient reported outcomes separated by different lordotic correction functionality

Lordotic correction	# Of devices	# Of studies	# Of patients	VAS back change	VAS leg change	¶ODI change
Continuous	5	9	377	*6.23±1.90 (n 297)	†5.69±3.84 (n 109)	*44.46±14.31 (n 297)
Discrete options	10	24	1306	4.29±2.35 (n 330)	4.65±2.98 (n 231)	19.68±14.45 (n 322)
None	4	11	481	4.21±2.71 (n 304)	4.61±2.69 (n 129)	§24.85±18.08 (n 261)

* This value is significantly higher than all other categories (p<.001).

† This value is significantly higher than all other categories (p<.05).

§ This value is significantly higher than the “discrete options” category (p<0.001) and lower than the “continuous” category (p<0.001).

|| VAS, Visual Analog Scale.

¶ ODI, Oswestry Disability Index.

VAS back and ODI scores compared to all other approaches assessed.

Discussion

A substantial body of literature explores whether static or expandable spinal fusion cages are superior. Clinical studies typically address this question by comparing cohorts of patients implanted with a static cage to cohorts implanted with an expandable cage. In these studies, all patients in the cohort receive nearly identical cages except for slight size variations. These studies are valuable, but taken alone, they cannot answer the question of superiority as the entire study represents only a single design point for both the static and expandable cages. No consideration of cage design features can be taken into account in these types of studies. A few systematic reviews and meta-analyses have compiled these clinical studies to comprehensively compare aggregated

data [6,9–11]. However, these reviews have yielded conflicting conclusions. Instead of grouping cages into the broad categories, static and expandable, we propose that a more nuanced approach that differentiates cages by design features is needed to understand the issues better and develop better devices that achieve optimal outcomes. Our present work focused solely on expandable cages and showed that different design features were correlated with varying patient-reported outcomes.

Based only on improvements noted in VAS and ODI scores noted in the present study, an optimal device would theoretically be made of titanium, have a circular or rectangular shape, an insertion width of less than 10 mm and an insertion height greater than or equal to 8 mm. Furthermore, this device would offer both vertical and lateral expandability with a continuously adjustable lordotic angle. However, it is noteworthy that none of the devices included in this review match this profile. A few devices were close, lacking

Table 7
Radiographic and clinical results separated by surgical approach

Surgical approach	# Of studies	# Of patients	Subsidence	††VAS back change	††VAS leg change	‡‡ODI change	Intraoperative blood loss (ml)	Length of stay (days)
LLIF	7	293	“None”	*6.24±2.16 (n 270)	6.25±3.98 (n 81)	¶47.82±15.73 (n 270)	¶35.50±44.42 (n 177)	**5.21±2.30 (n 244)
MIS TLIF	20	739	3.38 mm	*3.81±2.58 (n 378)	‡4.08±2.95 (n 227)	21.49±17.12 (n 481)	¶93.14±74.45 (n 309)	3.07±2.14 (n 244)
percLIF	7	201	1.40 mm	5.48±1.90 (n 177)	6.82±1.93 (n 55)	18.37±6.03 (n 140)	¶174.84±70.28 (n 109)	**4.69±2.81 (n 98)
PLIF	7	801	1.03 mm 16.31% > 2 mm 4.7% at > 3 mm	†5.88 (n 177)	†5.34 (n 55)	†24.16 (n 140)	415.32±212.33 (n 424)	¶8.69±1.55 (n 141)
TLIF	8	218	11.34% > 2 mm “None”	4.90±2.59 (n 61)	§5.03±3.18 (n 61)	§25.17±18.42 (n 61)	156.60±74.20 (n 10)	#8.87±5.78 (n 84)

* This value is significantly different from all other approaches included in the analysis (p<.01).

† No standard deviation or variance was reported. These values are not included in significance calculations.

‡ This value is significantly different from both the LLIF and percLIF approaches (p<.001).

§ This value is significantly different from the percLIF approach but not statistically different from any other approach (p<.05).

|| This value is significantly different from all other approaches included in the analysis (p<.001).

¶ This value is significantly different from all other approaches except the TLIF approach (p<.001).

This value is significantly different from all other approaches except the PLIT approach (p<.001).

** These values are not significantly different from each other, but together are different from all other approaches (p<.001).

†† VAS, Visual Analog Scale.

‡‡ ODI, Oswestry Disability Index.

Table 8
Clinical results separated by study location

Within the United States	# Of studies	# Of patients	Intraoperative blood loss (ml)	Length of stay in hospital (days)
Yes	32	1594	*191.93±158.47 (n 855)	*2.47±1.56 (n 466)
No	18	693	412.35±76.22 (n 179)	9.28±3.76 (n 321)

* This value is significantly lower than the international category ($p < .0001$).

either continuous lordotic adjustment or biplanar expandability.

Another systematic review categorized expandable cages based on their expansion capabilities, grouping cages offering biplanar expansion (both laterally and vertically) and comparing them with cages that provide uniplanar expansion (vertically) [70]. That study found a significant improvement in fusion rates for cages that expand in 2 planes, although no other outcomes achieved statistical significance. The authors pointed out the lack of direct comparative studies, which could account for this lack of significance. No other reviews were identified that focused exclusively on expandable cages or attempted to correlate patient outcomes with these devices' wide variety of features.

Limitations to this study include the difficulty of accounting for confounding factors, variability in reporting methods exemplified by the numerous ways subsidence was documented and the lack of details regarding the cages used in many studies. While this study explored the effects of surgical approach and study location, finding that surgical approach significantly affected patient reported outcomes and study location had a significant effect on blood loss and hospital stays, several other confounding factors could also be at play. Such factors include patient demographics, body mass index, comorbidities, severity and type of spinal condition being treated, surgeon experience, postoperative care, smoking status, patient socioeconomic status, etc. As the body of literature regarding expandable fusion cages grows, future reviews could be more exclusive to mitigate the effects of these confounding factors. Additionally, more high-quality randomized controlled trials comparing distinct expandable cages, like the 2 included in this review [67,68], would be invaluable in more definitively determining the optimal design parameters without the presence of so many confounding factors. Subsidence is an important radiographic parameter in analyzing the success of lumbar fusion procedures. However, it was reported using several different methods including the mean amount of subsidence, a percentage of patients with subsidence greater than 2 or 3 mm, and with terms like "none," "rare," or "mild" making any meaningful comparison difficult. For future studies we advocate for a more consistent reporting paradigm for this radiographic parameter.

Additionally, providing greater detail regarding the design features of expandable interbody devices in future

publications may be crucial for gaining a deeper understanding of this topic. An additional 77 studies could potentially have been included in this review had the authors reported more details about the devices used. In many of the included studies, the only information provided about the cages was the name and manufacturer, requiring additional cage-specific retrieval of the details from manufacturers' websites and brochures.

It should be noted that, as is common with newer devices, many of the studies included in this review are at a high risk of bias with 12 of the included studies being funded by the manufacturer of the device being investigated, and an additional 16 having one or more authors reporting to be consultants or employees of the manufacturers of the devices they are investigating. Together 28 of 49 were identified as being at risk of bias due to this conflict of interest. Efforts to minimize reporting bias were undertaken through the use of a systematic search strategy, specific inclusion criteria, and requiring multiple independent reviewers to screen all articles.

Despite these limitations, this investigation into expandable lumbar spinal fusion cages has suggests that different design features are correlated with different patient-reported outcomes. These findings warrant further studies which could also investigate additional design features not included in this study, namely the ability of the device to be packed with bone graft, the control of the expansion force during implantation, and the use of plasma sprayed surfaces for osseointegration.

Conclusion

This study offers insights into how the design features of expandable cages influence clinical outcomes. Rectangular cages made from titanium, featuring biplanar expandability and continuous lordotic correction, appear advantageous, though no current devices match this profile. The variability in surgical approaches and study locations highlights the need for standardized reporting and consideration of systemic factors in future research. These findings suggest the necessity for a more nuanced categorization of expandable lumbar fusion cages and additional research into the effects of design parameters on surgical outcomes.

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The study protocol for this systematic review was not preregistered.

Data, code, and materials used in this study are available upon reasonable request from the corresponding author.

Declaration of competing interest

One or more of the authors declare financial or professional relationships on ICMJE-TSJ disclosure forms.

CRedit authorship contribution statement

Daniel Orr: Writing review & editing, Writing original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ron Anderson:** Writing review & editing, Visualization, Methodology. **Anna Jensen:** Writing review & editing, Visualization, Formal analysis, Data curation. **Tyler Peterson:** Writing review & editing, Visualization, Software, Formal analysis, Data curation. **John Edwards:** Writing review & editing, Formal analysis. **Anton E. Bowden:** Writing review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

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Supplementary materials

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