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Minimally invasive laparoscopic and robotic anterior lumbar interbody fusion: a systematic review and future directions

Isabella Decker[1], Mohamad Bakhaidar[1,2*], Summer Shabana[1], Meriem Boukhiam[3], Sabino Zani Jr.[1] and Muhammad Abd-El-Barr[1]

Abstract

Introduction Anterior Lumbar Interbody Fusion (ALIF) is a commonly performed spine surgery procedure used to treat lumbar conditions such as degenerative disc disease, spondylolisthesis, and spinal deformities. Traditionally, it has been performed using open and mini-open surgical techniques. Recently, however, laparoscopic and robotic-assisted ALIF have gained attention for their potential benefits, including shorter recovery times, fewer complications, and improved patient outcomes. However, the safety, effectiveness, and long-term outcomes of these newer techniques remain to be fully compared to conventional methods.

Methods The systematic review was conducted in accordance with the PRISMA 2020 guidelines. MEDLINE and Cochrane databases were searched for studies on laparoscopic and robotic approaches to the anterior spine, with a focus on ALIF. Article selection and data extraction were independently conducted by two reviewers. Studies involving animal models, non-ALIF robotic techniques, or non-English publications were excluded.

Results A total of 650 articles were initially identified. After screening, a full-text review was conducted on 80 articles, of which 48 studies met the inclusion criteria: 42 focused on laparoscopic ALIF (L-ALIF) and 6 on robotic-assisted ALIF (R-ALIF). Laparoscopic ALIF achieved similar outcomes to mini-open methods, offering limited consistent benefits while presenting challenges such as a steep learning curve and a higher risk of retrograde ejaculation. Data on robotic-assisted ALIF, though limited, indicated improved precision and a reduced rate of intraoperative complications. However, high costs, logistical challenges, and the lack of substantial long-term outcome data remain significant barriers to the broader adoption of this technique in spine surgery.

Conclusion L-ALIF and R-ALIF present promising minimally invasive alternatives to mini-open ALIF approaches. L-ALIF yields outcomes similar to mini-open techniques, though its technical demands warrant careful consideration. R-ALIF shows potential for improved precision and reduced complications, but logistical and financial constraints limit its wider adoption. Future studies should focus on multicenter prospective trials, alongside efforts to reduce costs and enhance training, to refine the role of these techniques in optimizing patient outcomes.

Keywords Minimally invasive spine surgery, Anterior lumbar interbody fusion (ALIF), Laparoscopic spine surgery, Robotic-assisted spine surgery, Retroperitoneal approach, Robotic-assisted ALIF

*Correspondence:
Mohamad Bakhaidar
m.bakhaidar@hotmail.com
Full list of author information is available at the end of the article

Introduction

Spinal fusion is a commonly performed surgical procedure to address various pathologies such as disc degeneration, spondylolisthesis, traumatic spine injuries, and spinal deformity [1, 2]. While there are multiple approaches to achieving lumbar interbody fusion, the anterior interbody approach remains a cornerstone, providing a robust foundation for spinal fusion, particularly in complex and revision surgeries [3]. Anterior Lumbar Interbody Fusion (ALIF) is widely used in spine surgery, especially for low lumbar spine fusions, with growing adoption since its early descriptions. ALIF offers several advantages over other spine fusion approaches, including full ventral visualization, lordosis restoration, disc height restoration, and decreased disruption to paraspinal muscles and ligaments [1, 4, 5]. Though, ALIF carries distinct surgical risks, including potential vascular injury due to the mobilization of the great vessels, bowel injury, retrograde ejaculation, and lymphatic vessel injury [4, 6, 7]. Moreover, ALIF frequently requires an access surgeon, adding complexity to surgical planning and execution [5, 7].

Various surgical techniques are utilized to access the anterior spine, including open, mini-open, laparoscopic, and robotic-assisted approaches [8]. The traditional open ALIF technique involves a transperitoneal abdominal approach, while the mini-open approach minimizes incision size and employs a muscle-splitting technique resulting in reduced blood loss, shorter operative times, and less postoperative pain [4, 6, 9–13]. The laparoscopic approach (L-ALIF) was developed to further reduce surgical morbidity, utilizing three to four small incisions for endoscopic access [14]. While this technique has demonstrated benefits, including reduced postoperative pain and shorter recovery times, it also presents challenges such as a steep learning curve, longer operative times, and increased risk of complications like retrograde ejaculation. [7, 15–18] Building on laparoscopic principles, robotic-assisted ALIF (R-ALIF) has emerged as an advanced minimally invasive alternative, integrating robotic platforms such as the da Vinci Surgical Robot [19, 20]. Robotic systems provide dexterity and tremor filtration, potentially improving outcomes over traditional laparoscopic techniques [18, 21]. However, the application of robotic surgery for retroperitoneal access in spine surgery is still in its early stages and underexplored, but it holds considerable potential for future use [21].

As technology advances, the demand for minimally invasive surgery (MIS) techniques grows, especially in spine surgery. A comprehensive review of laparoscopic and robotic approaches for retroperitoneal access in spinal surgery is lacking. This systematic review aims to provide an up-to-date summary of the literature on L- and R-ALIF, focusing on the current practices, and potential future directions [22].

Methods

Study eligibility and inclusion criteria

We conducted this systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We included all peer-reviewed studies that evaluated laparoscopic and robotic approaches to the anterior spine in the context of anterior lumbar fusion [23]. Robotic approaches included those using the da Vinci robot or similar platforms to access the retroperitoneal space. Articles discussing laparoscopic or robotic approaches to the anterior spine within a context unrelated to spine surgery were excluded. We excluded articles that focused on robotic-assisted spine surgery for pedicle screw placement or navigation, as this was beyond the scope of our work. We also excluded cadaveric and animal studies. Only peer-reviewed original articles were included while meeting abstracts without full-text availability and articles not published in English were excluded. No restrictions were applied based on publication year, publication status, or study design.

Search strategy

We performed a MEDLINE search using the following terms: (ALIF OR Anterior Lumbar Interbody Fusion OR (retroperitoneal approach and spine) OR anterior spine approach OR anterior spine exposure OR (anterior and lumbar) OR (anterior and spine) AND (laparoscopic OR robot OR robotic)) [24]. Additionally, the Cochrane Central Register of Controlled Trials was searched using relevant terms and keywords. To augment the scope of our literature retrieval beyond the primary databases, we examined the initial 20 pages of Google Scholar, or 400 articles, employing identical search terms to ensure consistency with the MEDLINE and Cochrane queries. Studies published from inception through November 2024 were identified. The reference lists of included studies were also reviewed to identify any potentially missed articles.

Study selection process

Study eligibility was assessed independently by ID, SS, and BM. After resolving duplicates, we initiated the study selection process with title and abstract screening, followed by the retrieval of full-text articles for studies deemed relevant. Disagreements during abstract screening were deferred to full-text review, where conflicts were resolved by consensus between ID and SS or, if unresolved, by consultation with a third author (MB), ensuring consistent application of inclusion criteria. Figure 1

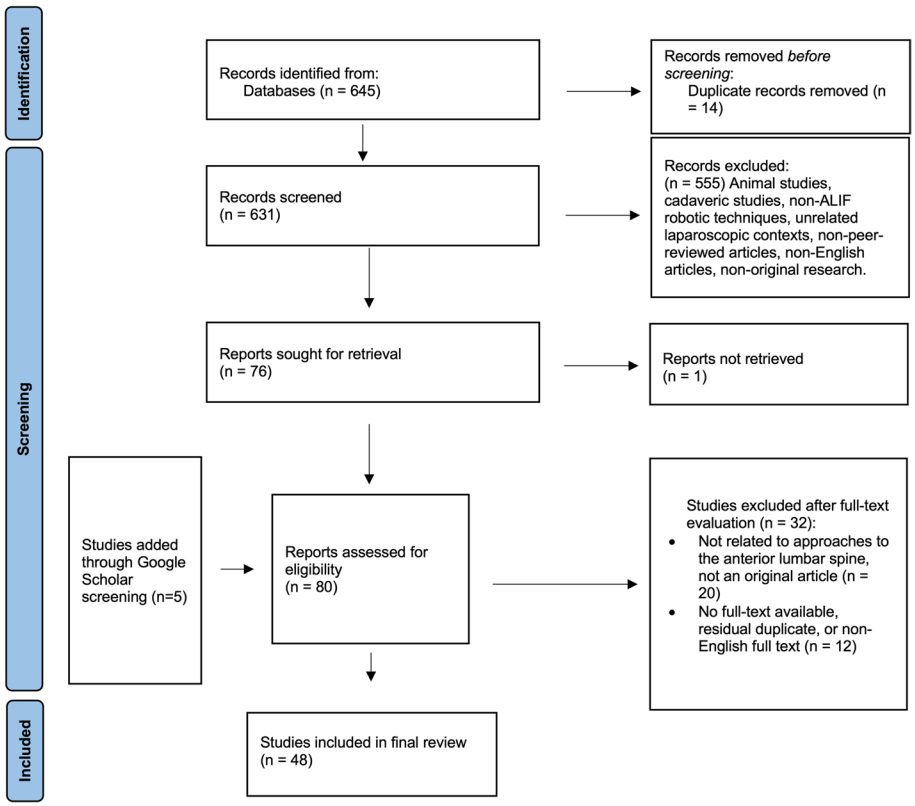

Fig. 1 PRISMA flow diagram of study searches and inclusion and exclusion criteria

is a flow diagram illustrating the study selection process in accordance with the PRISMA protocol. We used the Rayyan platform (Rayyan AI tool, accessible at https://www.rayyan.ai/) to manage this systematic review. Rayyan is a free software tool designed to facilitate systematic review production, which we used to screen articles for inclusion at both the abstract and full-text levels.

We summarized the included articles and collected data on the objective of each study, the study design, the number of included patients, and the reported outcomes.

Results

Overview

We initially identified 650 articles through our search. After removing duplicates, 636 articles remained for title and abstract screening. Additional articles were screened and identified using Google Scholar. Following these processes, 80 articles were selected for full-text evaluation, and 48 articles (42 discussing L-ALIF and 6 discussing R-ALIF) were ultimately included in the review. Tables 1 and 2 summarize the included articles.

Laparoscopic ALIF

Of the 42 articles discussing laparoscopic approaches to ALIF, the majority were published over two decades ago, with 37 articles (88.1%) published before 2004. The peak in publications appears to have occurred in the late twentieth century and early twenty-first century. Among the included 42 articles, 25 studies were retrospective in nature (59.5%), most of which were retrospective chart reviews (19 articles) or case studies (5 articles), along with three retrospective cohort studies. The three retrospective cohort studies examined an L-ALIF group in comparison to open or mini-open ALIF techniques. They found that L-ALIF was associated with less blood loss, reduced ileus, and faster recovery compared to open techniques [25–27]. However, operative times were reported to be longer in the L-ALIF group [25, 26], though Cowles et al. noted improved operative efficiency toward the latter part of their L-ALIF cohort [26]. Additionally, Rodriguez et al. reported that the laparoscopic technique was $1,374 more expensive than the mini-open technique [27].

The remaining 17 articles included prospective non-comparative single-arm studies (12 articles), prospective cohort studies (4 articles), and a single randomized controlled trial (RCT). Chung et al. randomized 54 patients to either the L-ALIF or open mini-ALIF procedure [28]. Similarly, three out of the four prospective cohort studies compared L-ALIF with various forms of open ALIF

Table 1 Summary of the Included Studies on L-ALIF

No	Title	Authors	Year	Study Design	Aim of the Study	N	Conclusion
1	Laparoscopic lumbar discectomy: case report	Obenchain	1991	Case report	To examine the feasibility and safety of laparoscopic lumbar discectomy in a L5-S1 disc herniation	1	Laparoscopic discectomy was performed successfully on an outpatient basis, providing evidence that the laparoscopic approach is safe for the L5-S1 space
2	Outpatient laparoscopic lumbar discectomy: description of technique and review of first twenty-one cases	Obenchain et al	1993	Prospective cohort study	To establish proof of concept for the anterior laparoscopic approach as an alternative to percutaneous posterolateral lumbar discectomy	21	Anterior discectomy allows for a direct approach to the vertebrae compared to the angled posterior approach and results in decreased cost, pain, and instability with earlier return to work
3	Laparoscopic laser lumbar diskectomy. Operative technique and case report	Slotman & Stein	1995	Case report	To share the results of a unique technique for L5-S1 laparoscopic anterior lumbar discectomy in a single patient, using a Nd:YAG contact laser to open the disc annulus	1	The patient reported immediate pain relief and had a short postoperative hospital stay, showing laparoscopic laser lumbar discectomy may be a cost-effective alternative to other methods
4	Laparoscopic discectomy with anterior lumbar interbody fusion. A preliminary review	Mathews et al	1995	Case series	To determine if the L5-S1 space could be safely accessed by the laparoscopic anterior transperitoneal approach	5	Patient outcomes were positive, mostly because of the presence of a skilled laparoscopist on the team and the use of MRI to plan the procedure
5	The incidence of complications in endoscopic anterior thoracolumbar spinal reconstructive surgery. A prospective multicenter study comprising the first 100 consecutive cases	McAfee et al	1995	Prospective non-comparative study	To evaluate the early perioperative complications from anterior laparoscopic interbody stabilization at the L4-L5 and L5-S1 joint	22	The laparoscopic approach resulted in two cases of bone graft infection but most significantly had both an extensive operative time and greatly prolonged hospital stay
6	Laparoscopic lumbar diskectomy: preliminary report of a minimally invasive anterior approach to the herniated L5-S1 disk	Slotman & Stein	1995	Retrospective chart review	To establish proof of concept for the laparoscopic anterior approach to the L5-S1 lumbar discectomy	7	All patients experienced immediate and complete relief of pain without any complications and with a short postoperative hospital stay
7	Laparoscopic lumbar discectomy	Zelko et al	1995	Retrospective chart review	To determine if posterior percutaneous nucleotome placement is advantageous when combined with an anterior transperitoneal laparoscopic discectomy	23	All patients experienced a successful discectomy and nucleotome placement while most stayed in the hospital for less than a day postoperatively
8	Transperitoneal laparoscopic approach to lumbar discectomy	Cloyd et al	1995	Retrospective chart review	To describe the process used to achieve the laparoscopic exposure for anterior resection of the lumbar disc	15	Some patients experienced persistent postoperative pain, but it was also noted that procedural efficiency could be enhanced with improved instrumentation
9	New possibilities in L2-L5 lumbar arthrodesis using a lateral retroperitoneal approach assisted by laparoscopy: preliminary results	De Peretti et al	1996	Case series	To report the surgical techniques and outcomes for patients undergoing a video-assisted retroperitoneal laparoscopic ALIF	4	Complications included instability and a uterine wound that resulted from insufficient experience with the technique, but overall there was minimal blood loss

Table 1 (continued)

No	Title	Authors	Year	Study Design	Aim of the Study	N	Conclusion
10	Laparoscopic fusion of the lumbar spine in a multicenter series of the first 34 consecutive patients	Regan et al	1996	Prospective non-comparative study	To describe the laparoscopic ALIF technique development and to examine its use on the first 34 patients undergoing this approach to ALIF	34	The laparoscopic technique results in minimal complications, so long as a skilled laparoscopic surgeon is present, and may lead to early hospital discharges
11	A prospective study of laparoscopic spinal fusion. Technique and operative complications	Mahvi & Zdeblick	1996	Prospective non-comparative study	To determine the safety and feasibility of transperitoneal laparoscopic ALIF	20	Patients had a minimal postoperative hospital stay with most reporting significant pain relief and complete fusions
12	Laparoscopic discectomy with anterior interbody fusion of L5-S1	Olsen et al	1996	Retrospective chart review	To evaluate loss of disc space, lumbar instability, and complications resulting from laparoscopic ALIFs	75	Laparoscopic approach should become the standard for ALIFs, as it resulted in no major complications, reduced hospital stays, and significant pain reduction
13	Laparoscopic lumbar discectomy: description of transperitoneal and retroperitoneal techniques	Obenchain & Cloyd	1996	Retrospective chart review	To examine the feasibility and outcomes of patients undergoing a transperitoneal and retroperitoneal laparoscopic ALIF	29	The laparoscopic technique could easily be performed by a surgeon with moderate laparoscopic skills but may associated with lower fusion rates
14	Laparoscopically assisted spinal surgery	Henry et al	1997	Retrospective chart review	To report the techniques and outcomes associated with both a transperitoneal and retroperitoneal approach to the laparoscopic ALIF	76	The retroperitoneal laparoscopic approach resulted in a longer operating time and postoperative stay but had fewer conversions and allowed for multiple level surgery compared to the transperitoneal approach
15	Laparoscopic fusion of the lumbar spine: minimally invasive spine surgery. A prospective multicenter study evaluating open and laparoscopic lumbar fusion	Regan et al	1999	Prospective multicenter cohort study	To compare outcomes and safety of the open retroperitoneal versus laparoscopic transperitoneal approaches	831	The laparoscopic group demonstrated less blood loss and a shorter postoperative hospital stay but high operative times that decreased as surgeons' experience increased
16	Laparoscopic anterior lumbar interbody fusion. Technical note	McLaughlin	1999	Prospective non-comparative study	To describe the operative technique and outcomes of transperitoneal laparoscopic ALIF approach	32	Laparoscopic ALIF has many benefits, including decreased blood loss and postoperative pain, but did lead to retrograde ejaculation in several male patients
17	Laparoscopic approach to L4-L5 for interbody fusion using BAK cages: experience in the first 58 cases	Regan et al	1999	Retrospective chart review	To compare the outcomes, blood loss, and operative times of multiple approaches, depending on vascular anatomy, to the laparoscopic ALIF	58	Laparoscopic ALIF was completed either below, above, or between the great vessel bifurcation, but there were no differences in blood loss, operative times, or hospital stay among the difference techniques

Table 1 (continued)

No	Title	Authors	Year	Study Design	Aim of the Study	N	Conclusion
18	A prospective comparison of surgical approach for anterior L4-L5 fusion: laparoscopic versus mini anterior lumbar interbody fusion	Zdeblick & David	2000	Prospective cohort study	To compare laparoscopic and mini-open approaches to ALIF in operative time, blood loss, postoperative stay, complications, and exposure	50	The laparoscopic and mini-open groups had similar operative times, blood loss, and length of stay, but the laparoscopic group had more complications and higher rates of inadequate exposure of the spine
19	Comparison of insufflation vs retractional technique for laparoscopic-assisted intervertebral fusion of the lumbar spine	Hannon et al	2000	Prospective cohort study	To compare the standard CO_2 transperitoneal insufflation and the more difficult retroperitoneal gasless retraction technique to access the retroperitoneal space for laparoscopic ALIF	35	The gasless retraction method resulted in a greater operative time and more than double the complications, indicating that the transperitoneal insufflation should be used for the anterior approach to laparoscopic interbody fusions
20	Transperitoneal laparoscopic exposure for lumbar interbody fusion	Lieberman et al	2000	Prospective non-comparative study	To explore techniques and complications of laparoscopic exposure of the anterior lumbar to treat degenerative disc disease	47	Laparoscopic exposure resulted in minimal mean blood loss with few complications besides several events of malpositioned cages and two transient retrograde ejaculation cases
21	Laparoscopic anterior lumbar fusion	Hawasli et al	2000	Prospective non-comparative study	To examine the outcomes and feasibility of laparoscopic ALIF while evaluating the effects of metoclopramide to decrease postoperative ileus and hospital stays	30	Metoclopramide use with proper presurgical bowel preparation led to decreased hospital stay in patients undergoing a laparoscopic ALIF, but the ALIF technique was determined to be best for the L5-S1 level
22	Laparoscopic lumbar interbody spinal fusion	Heniford et al	2000	Retrospective chart review	To report techniques and outcomes of the laparoscopic ALIF approach performed by one surgical team	140	Among the large patient group, there were multiple different complications, including vascular injury, bowel disturbance, conversion to the open approach, deep vein thrombosis, and retrograde ejaculation
23	Minimally invasive 360 degrees instrumented lumbar fusion	Thalgott et al	2000	Retrospective chart review	To explore the clinical and radiological outcomes of a combined anterior BERG and posterior screw fixation approach to ALIF	46	The BERG approach combined with posterior screws resulted in high rates of fusion, adequate pain relief, and minimal blood loss
24	Efficacy of the laparoscopic approach for anterior lumbar spinal fusion	Cowles et al	2000	Retrospective cohort study	To compare the immediate outcomes of patients either undergoing an open or laparoscopic ALIF	75	The laparoscopic group had significantly less blood loss and postoperative ileus but longer operating room times, a trend that improved over time and experience

Table 1 (continued)

No	Title	Authors	Year	Study Design	Aim of the Study	N	Conclusion
25	Gasless endoscopic anterior lumbar interbody fusion utilizing the B.E.R.G. approach	Thalgott et al	2000	Prospective non-comparative cohort study	To explore the feasibility of the gasless, balloon-assisted endoscopic approach to ALIFs	202	The BERG approach offers similar results as other techniques with minimal complications, short post-op stays, and decreased conversions to open as the surgeons became more familiar with the technique
26	Laparoscopic anterior lumbar interbody fusion precipitating pituitary apoplexy	Liu et al	2001	Case report	To describe a rare complication of pituitary apoplexy following a laparoscopic ALIF procedure	1	Laparoscopic techniques to ALIF can result in rare complications, which must be quickly recognized and surgically treated
27	Laparoscopic anterior lumbar interbody fusion with rhBMP-2: A prospective study of clinical and radiographic outcomes	Kleeman et al	2001	Prospective non-comparative cohort study	To determine if discogenic pain could be treated by a laparoscopic approach to an ALIF using rhBMP-2 instead of autogenous bone	22	Laparoscopic ALIF using rhBMP-2 led to complete satisfaction, reduction in leg and back pain, and functional improvements while achieving fusion in all the patients studied
28	Low fusion rate after L5–S1 laparoscopic anterior lumbar interbody fusion using twin stand-alone carbon fiber cages	Pellisé et al	2002	Prospective non-comparative study	To evaluate the long-term outcomes and fusion rates of L5-S1 laparoscopic ALIF	12	Using twin stand-alone laparoscopic carbon-fiber cages, only one in five patients had successful fusion three years after surgery
29	Laparoscopic anterior lumbar interbody fusion at L4-L5: an anatomic evaluation and approach classification	Kleeman et al	2002	Retrospective chart review	To determine classifications of approach based on vascular anatomy for the laparoscopic ALIF approach	139	Using MRI or CT to determine individual anatomy and therefore laparoscopic approach can minimize the risks of retrograde ejaculation associated with laparoscopic ALIF
30	Laparoscopic lateral L4-L5 disc exposure	Brody et al	2002	Retrospective chart review	To determine proof of concept for laparoscopic anterior exposure of L5-S1 with an anterolateral exposure to L4-5 level	5	The authors' transperitoneal approach allowed for complete exposure to L5-S1 and L4-5 levels while limiting the manipulations of major vascular structures, the sympathetic chain, and ureter
31	Is laparoscopic anterior lumbar interbody fusion a useful minimally invasive procedure?	Liu et al	2002	Retrospective chart review	To determine the effects and outcomes of a laparoscopic ALIF as a form of minimally invasive surgery treatment for patients with degenerative disc disease and mechanical back pain	14	The laparoscopic ALIF had less blood loss but similar fusion rates to other approaches, but the significant learning curve resulted in a longer operating time without the benefit of a shorter hospital stay
32	Anterior Access to the Lumbar Spine: Laparoscopic versus Open	Rodriguez et al	2002	Retrospective cohort study	To compare operation times, morbidity, analgesia, and blood loss in the laparoscopic versus open approaches to the anterior spine	65	The only differences between the two techniques were a shorter operative time and less blood loss in the laparoscopic approach, which was also more expensive

Table 1 (continued)

No	Title	Authors	Year	Study Design	Aim of the Study	N	Conclusion
33	Comparison of the mini-open versus laparoscopic approach for anterior lumbar interbody fusion: a retrospective review	Kaiser et al	2002	Retrospective cohort study	To compare complications, postoperative hospital stays, and intraoperative parameters between patients undergoing a laparoscopic or mini-open ALIF	98	Compared to mini-ALIF technique, laparoscopic surgery led to a longer operative time, shorter length of stay, lower overall complication rate, and higher rate of occurrence for retrograde ejaculation
34	Comparative study of laparoscopic L5–S1 fusion versus open mini-ALIF, with a minimum 2-year follow-up	Chung et al	2003	Randomized controlled trial	To compare postoperative results and long-term outcomes between open and laparoscopic techniques for ALIF	54	Laparoscopic and open techniques were similar in blood loss, hospital stay, fusion rates, and 2-year reported pain, but the laparoscopic approach had a much longer operative duration
35	Balloon-assisted endoscopic retroperitoneal gasless (BERG) technique for anterior lumbar interbody fusion (ALIF)	Vazquez & Gireesan	2003	Retrospective chart review	To examine the outcomes and complications of the BERG approach, preceded by laparoscopic approach, to access the anterior spine for ALIF with multiple interbody fusion devices	46	The BERG approach resulted in minimal complications or blood loss and allows for the use of any interbody cage
36	Video-assisted versus open anterior lumbar spine fusion surgery: a comparison of four techniques and complications in 135 patients	Escobar et al	2003	Retrospective chart review	To compare the complications and outcomes of four ALIF techniques, including transperitoneal with insufflation and retroperitoneal endoscopic techniques	135	The highest rates of complication were shown in the transperitoneal video-assisted insufflation group and the minilaparotomy group, with retrograde ejaculation, vascular problems, and conversion to the open procedure included
37	"Does size matter?" A comparison of balloon-assisted less-invasive vs conventional retroperitoneal approach for anterior lumber interbody fusion	Farooq & Grevitt	2004	Retrospective chart review	To compare the outcomes of the conventional open approach to the balloon-assisted endoscopic retroperitoneal technique	35	The balloon-assisted approach resulted in shorter operative times for single-level fusions, fewer complications, less blood loss, and shorter time to mobilization and hospital stays
38	L5-S1 laparoscopic anterior interbody fusion	Frantzides et al	2006	Retrospective chart review	To evaluate the outcomes and complications of the laparoscopic approach to ALIF in a L5-S1 space	28	Although it has a steep learning curve, all patients had successful fusion, with only a few patients requiring a reoperation
39	Laparoscopically assisted retroperitoneal spinal surgery	Regan et al	2006	Retrospective chart review	To explore the outcomes and complications of laparoscopic retroperitoneal ALIFs	124	The laparoscopic approach is safe, leads to shorter hospital stays compared to the open approach, and had a complication rate of 5.6%
40	Laparoscopic approach for lumbar spinal fusion	Nepomnayshy et al	2006	Prospective non-comparative cohort study	To describe the technique and report the outcomes of laparoscopic ALIFs	11	With no intra- or post-operative complications, only one case was converted to the open technique

Table 1 (continued)

No	Title	Authors	Year	Study Design	Aim of the Study	N	Conclusion
41	Balloon-assisted endoscopic retroperitoneal gasless approach (BERG) for lumbar interbody fusion: is it a valid alternative to the laparoscopic approach?	Gazzeri et al	2007	Prospective cohort study	To analyze the results of the endoscopic approach to the anterior spine for patients undergoing fusion and to compile data on endoscopic ALIF techniques from international literature	20	The endoscopic ALIF resulted in no perioperative complications, no conversions to open technique, and fusion was achieved in almost all the patients
42	Six-year outcomes of anterior lumbar interbody arthrodesis with use of interbody fusion cages and recombinant human bone morphogenetic protein-2	Burkus et al	2009	Prospective multicenter cohort study	To report the six-year clinical and radiologic outcomes of patients who either underwent a laparoscopic or open stand-alone ALIF	277	The group that underwent a laparoscopic ALIF had shorter hospital stays, fewer reoperations, and lower back pain and disability scores at six years postoperative compared to the open group

[9, 14, 25–30, 32, 33, 35, 37, 40, 42–48, 71–95]

Table 2 Summary of Included Studies on R-ALIF

No	Title	Authors	Year	Study Design	Aim of the Study	N	Conclusion
1	The da Vinci robotic surgical assisted anterior lumbar interbody fusion. Technical development and case report	Beutler et al	2013	Case report	To develop surgical technique for the anterior transperitoneal approach to the lumbar spine using a da Vinci robot (DVR)	1	DVR provides increased visualization and tissue dissection compared to traditional laparoscopic methods, while keeping blood loss minimal
2	Technique and surgical outcomes of robot-assisted anterior lumbar interbody fusion	Lee et al	2013	Retrospective chart review study	To determine the outcomes and safety of the da Vinci S Surgical Robot in ventral spine dissection within an ALIF procedure	11	There were no vascular complications or conversions to the open procedure, with all patients showing radiologic evidence of fusion
3	Minimally invasive, robot-assisted, anterior lumbar interbody fusion: a technical note	Lee et al	2013	Case series	To establish proof of concept for DVR-assisted ALIF	2	Robotic assistance resulted in complete fusion and the same outcomes as laparoscopic ALIFs, with only a small increase in complexity of the procedure
4	Da Vinci robot-assisted laparoscopic retroperitoneal debridement for lumbar septic spondylodiscitis: A two-case report	Ye et al	2022	Case series	To determine to feasibility of robot-assisted laparoscopic retroperitoneal approach for lumbar spondylodiscitis	2	DVR use led to decreased pain and adequate fusion in the two patients reported, but the robot is limited when in use on bones or hard tissue
5	Da Vinci meets Globus Excelsius GPS: A totally robotic minimally invasive anterior and posterior lumbar fusion	Yuk et al	2023	Case report	To provide proof of concept for the first completely robotic anterior lumbar fusion with supplemental percutaneous posterior instrumented fusion	1	All-robotic ALIF is safe, resulted in reduced back and leg pain, and achieved appropriate placement of the fusion cage
6	Da Vinci robotic assistance for anterolateral lumbar arthrodesis: results of a French multicentric study	Loniewski et al	2024	Retrospective multi-center chart review study	To examine the outcomes and complications of the DVR in anterolateral lumbar corpectomies and OLIFs	10	OLIF and anterolateral lumbar discectomy resulted in high fusion and low complication rates, as well as improved access in patients with high BMI's

[18, 21, 31, 53, 61, 96]

[9, 29, 30]. Chung et al. reported that L-ALIF for L5–S1 demonstrated similar clinical and radiological outcomes compared to open mini-ALIF but required a significantly longer operative duration [28].

Robotic ALIF

Looking at R-ALIF, we identified only six articles through our systematic review, all of which were retrospective in nature, including two case reports and two small case series (each involving two patients). The first report, published by Lee et al., described the use of the da Vinci S Surgical Robot for spinal exposure during ALIF [31]. In the same year, Lee et al. reported a retrospective chart review of a single-center experience with R-ALIF [18]. They reported 11 consecutive patients who underwent R-ALIF and concluded that the technique is safe and could offer potential benefits for patients undergoing ALIF. There is a disparity in the volume of literature comparing L-ALIF and R-ALIF, with a clear paucity of studies discussing the robotic approach. This scarcity likely reflects technological barriers (e.g. recent development of robotic systems), high costs, and slow adoption rates in spine surgery, limiting available evidence.

Discussion

Laparoscopic ALIF (L-ALIF): What Does the Evidence Say?

Over the past 25 years, numerous studies have examined the laparoscopic approaches to the anterior spine. In 1991, Obenchain reported the feasibility of using the laparoscopic approach to perform anterior lumbar discectomy [32]. Following that, Cloyd et al. reported their group's experience with 15 lumbar discectomies using the laparoscopic access to the anterior lumbar spine [33]. The first report of L-ALIF was published by Zucherman et al. in 1995, making a milestone in evolving this technique to be used in spinal fusion [34]. Many early studies noted that L-ALIF posed certain technical challenges, highlighting the significant learning curve and the need for careful attention to anatomical variations [17, 29, 35]. Mahvi and Zdeblick illustrated this learning curve by reporting that complications occurred only in the first four patients undergoing laparoscopic ALIF, while all 16 subsequent patients experienced no complications [36]. Similarly, Regan et al. conducted a large prospective series comparing L-ALIF to open ALIF across multiple centers and demonstrated a decrease in operative time as surgeons gained experience with the laparoscopic technique [29]. Moreover, some early comparative studies stated that an obstacle to laparoscopy is the lack of additional fixation devices [10], but many newer techniques use laparoscopic in conjunction with posterior pedicle screw fixations to improve stability of the fused vertebrae [30, 31]. Some studies even propose an anterior approach to pedicle screw placement to reduce incisions and operative time while improving stability [37–39].

Once the laparoscopic ALIF approach was more widely used, studies began to compare the L-ALIF to the open and mini-open ALIF techniques to determine relative efficacy. The complication profile of L-ALIF did not differ significantly from other ALIF techniques and included risks such as abdominal adhesions, visceral injuries [10, 25, 40], ileus [40, 41], ureter or uterine injury [25, 42], and instability or limited fusion [42–45]. While earlier studies identified pneumoperitoneum as a unique complication, various techniques, including gasless and retractional access, have been developed to minimize this risk [46, 47]. While complications vary among studies, many articles reported higher rates of retrograde ejaculation in the laparoscopic procedure, likely from injury to the superior hypogastric plexus [9, 25, 28, 43, 48]. Although laparoscopic techniques were expected to reduce tissue disturbance, some studies reported no significant difference in operative blood loss [9, 28, 41]. Similarly, some reports found no significant differences in postoperative hospital stays or postoperative pain [9, 28]. On the other hand, some studies have reported conflicting data regarding blood loss and patient outcomes favoring L-ALIF [14, 35, 49]. Prospective studies comparing L-ALIF with the open technique were conducted to address this inconsistency. Regan et al. reported a large prospective cohort study that was done across multiple United States centers, comparing 240 L-ALIF patients to 591 open ALIF patients [29]. L-ALIF showed less blood loss and short operative time but was associated with longer operative time when compared to open technique [29]. They reported comparable operative complication rates between the two groups except for device-related revision rate which was significantly higher in the L-ALIF group [29]. Chung et al. conducted an RCT with 22 patients in each arm, comparing outcomes between L-ALIF and mini-open ALIF [28]. While the small number of included patients was a limitation, the study concluded that outcomes were similar across the groups but reported a statistically significant increase in operative times without any significant advantages to L-ALIF compared to open mini-ALIF [28]. Two-year follow-up did not show a significant difference in clinical and radiological outcomes between the two groups [28].

In recent years, L-ALIF appears to have fallen out of favor, as reflected by the limited contemporary literature discussing its use. The mini-open approach has largely become the preferred method for ALIF. The available evidence suggests that the potential advantages of L-ALIF are outweighed by its drawbacks, including prolonged operative times, a steeper learning curve, and a possible higher complication rate. These challenges

are particularly evident in multi-level fusions, where the L-ALIF approach increases procedure duration and exposes patients to extended anesthesia times [9, 25]. Notably, much of this evidence derives from retrospective studies, which, across the laparoscopic and robotic approaches, constitute approximately 59.5% of the 42 studies evaluated in this review, potentially introducing selection bias or inconsistencies in outcome reporting that may accentuate complications such as retrograde ejaculation while diminishing less pronounced benefits. Given the qualitative nature of this review and the predominance of retrospective data, definitive conclusions about the relative benefits and drawbacks of L-ALIF remain cautious.

Robotic ALIF: The Emerging Frontier in MIS Spine Surgery?

Over the past three decades, robotic-assisted surgical systems have dramatically transformed surgery across multiple specialties, introducing a higher degree of accuracy and control [20]. Since the FDA approval of the da Vinci system for general surgery in 2000, [50] it has seen wide acceptance in applications extending to urology [51], gynecology [19], abdominal [52], and, increasingly, spinal surgery [21, 53]. The da Vinci platform provides a high-resolution 3D vision, along with advanced instruments that allow for overcoming many limitations of traditional laparoscopic surgery and provide increased dexterity and visibility [20, 54–56]. In addition, robotic platforms provide superior ergonomics by allowing surgeons to operate from a console with stable camera positioning and natural hand–eye coordination [20, 56, 57]. In ALIF, robotic assistance can provide minimally invasive and safe access to the retroperitoneal space through precise dissection around critical anatomical landmarks, such as the iliac vessels and presacral sympathetic plexus [21, 31]. The robotic systems were also shown to minimize the potential for complications, such as nerve damage and retrograde ejaculation [21, 58, 59].

Preliminary studies have shown the feasibility of R-ALIF with promising results. Animal model studies suggested that the da Vinci surgical robot enhances precision and reduces tissue retraction in ALIF [60]. In 2013, the first successful human case of R-ALIF marked a milestone in the clinical adoption of the robotic approach [31, 53]. Additional studies have further confirmed the safety and efficacy of R-ALIF at multiple disc levels, including L5-S1 and L4-L5, with studies showing positive results and virtually no complications [18]. In more recent studies, hybrid [61] and fully robotic [21] spinal fusions have demonstrated both safety and positive clinical outcomes. Loniewski et al. reported a series of 10 robotic-assisted spine fusion procedures performed across multiple centers in France, including six oblique lumbar interbody fusion (OLIF) procedures and four lumbar corpectomies carried out through an anterolateral approach [61]. They demonstrated the feasibility of using robotic platforms to perform transperitoneal approaches for anterior and anterolateral access to the spine [61]. In addition, the da Vinci Xi system was experimented on in a swine model for extreme lateral lumbar interbody fusion (XLIF) and demonstrated improved neurovascular protection [62], highlighting its potential role in other approaches to the spine. These findings bring into light the promising future of robotic systems in spinal surgery and suggest that with ongoing advancements in technology, fully robotic procedures may become increasingly feasible [21].

While the advantages are there, implementing robotic platforms in spine surgery faces several limitations that must be addressed for broader adoption. While R-ALIF shows promise, challenges with cage placement and exposure remain. In animal models, the kyphotic curvature and narrow disc spaces complicate the positioning of large lordotic cages, necessitating the use of smaller cages in ALIF [63, 64]. In human surgeries, these challenges are heightened by the need for additional laparoscopic tools to adequately prepare the disc space and insert the cage [64]. Specialized access ports, like the GelPoint system, can improve exposure by maintaining pneumoperitoneum, but the placement of these large cages still often require hybrid or mini-open methods for better alignment and positioning [53, 65]. Similarly, in robotic XLIF, cage insertion often requires manual manipulation with fluoroscopy due to spatial limitations, reflecting challenges that could also arise in R-ALIF [62]. Another major challenge is the steep learning curve associated with robotic technology. Surgeons and the entire surgical team should expect robotic approaches to require more time and effort, particularly during the early stages of implementation [66, 67]. However, as experience is gained, the robotic approach should become more efficient. Additionally, the lack of tactile feedback is another notable limitation that can impact the learning curve [68]. Switching from L-ALIF to R-ALIF in resource-limited settings presents practical difficulties. The high cost of robotic systems, such as the da Vinci platform, and their ongoing maintenance can restrict use in areas with tight healthcare budgets [69, 70]. This may increase gaps in surgical care access. Although many hospitals already have robotic platforms for other indications, dedicating such systems exclusively to spine surgery may not be feasible. One significant consideration is the logistical challenges posed by the large size of robotic systems and the need for specially trained personnel [68]. The robot's substantial footprint can make maneuvering difficult in crowded operating rooms, especially when other technologies, such as C-arms, navigation systems, or other

spine robotic-based navigation systems, are also in use. These spatial requirements might further complicate the integration of robotic platforms into spine surgery workflows. To overcome these barriers, interdisciplinary collaboration between spine surgeons, general surgeons, and biomedical engineers could accelerate the development of cost-effective robotic solutions and standardized training protocols, enhancing accessibility and proficiency.

In summary, R-ALIF offers several advantages, including enhanced accuracy and potentially improved outcomes. However, these benefits come with significant costs, a steep learning curve, and certain limitations. As technology advances and accessibility improves, wider adoption of robotic-assisted spinal surgery could open new directions to more advanced MIS procedures and improvement of patient outcomes.

Limitations

This study has several limitations. The majority of the studies included in the systematic review are retrospective in nature, which makes it challenging to generate higher levels of evidence. The exclusion of non-English studies may limit the review's comprehensiveness, potentially missing relevant international data. Additionally, there is substantial heterogeneity among the included studies, particularly in terms of definitions, which limits the interpretation of the data. Despite these challenges, we have made every effort to draw meaningful conclusions from the available data and summarize them in the discussion. Furthermore, data on R-ALIF is scarce, with only six studies included in our review. Almost half of the available literature on R-ALIF has been published in the past 2 years, suggesting that more studies on this topic are likely to emerge in the near future. Finally, due to the aforementioned limitations, a quantitative analysis of the articles was not conducted; instead, we provided a general overview of the existing literature.

Future directions

Future research should focus on fostering collaboration between laparoscopic/robotic surgeons and spine surgeons to optimize patient care. While R-ALIF has been described in the literature, to the authors' knowledge, it has yet to be presented as a video article in a peer-reviewed journal. Video articles, which have gained popularity in recent years, offer a unique type of publication that can bridge knowledge gaps and provide clearer insights into surgical techniques. Larger series and cohort studies comparing R-ALIF with other ALIF approaches could provide valuable insights into our understanding of R-ALIF.

Conclusion

In this review, we provided a comprehensive systematic review of the current status, evolution, and comparative effectiveness of L-ALIF and R-ALIF. Our review of the literature shows that while L-ALIF reached its peak around the beginning of the current century, it appears to have been largely abandoned. The evidence indicates that laparoscopic ALIF yields outcomes broadly similar to mini-open ALIF, though its technical demands warrant careful consideration. The introduction of R-ALIF shows promise, with early evidence suggesting potential reductions in complications, such as nerve injury, as well as improved recovery times. While the initial data are encouraging, further research is essential to definitively establish the role of R-ALIF in spine surgery. Future research should not only prioritize multicenter prospective studies but also explore specific strategies, such as cost-reduction initiatives for robotic platforms or structured training programs to flatten the learning curve and enhance accessibility and efficacy.

Abbreviations

ALIF	Anterior lumbar interbody fusion
L-ALIF	Laparoscopic anterior lumbar interbody fusion
MIS	Minimally invasive surgery
OLIF	Oblique lumbar interbody fusion
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
R-ALIF	Robotic anterior lumbar interbody fusion
RCT	Randomized controlled trial
XLIF	Extreme lateral lumbar interbody fusion

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Author details
[1]Department of Neurosurgery, Duke Health, Duke University, Durham, NC, USA. [2]Division of Neurosurgery, Department of Surgery, Faculty of Medicine, King Abdulaziz University, Jeddah, Saudi Arabia. [3]Mohammed VI Faculty of Medicine, Mohammed VI University of Sciences and Health, Casablanca, Morocco.

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