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Review Article

Evolving Paradigms in Spinal Surgery: A Systematic Review of the Learning Curves in Minimally Invasive Spine Techniques

Kun Wu[1,*], Zhihe Yun[1,*], Siravich Suvithayasiri[2,3], Yihao Liang[4], Dimas Rahman Setiawan[5], Vit Kotheeranurak[6], Khanathip Jitpakdee[7], Enrico Giordan[8], Qinyi Liu[1], Jin-Sung Kim[9]

[1]Department of Orthopedics, The Second Hospital of Jilin University, Changchun, China
[2]Department of Orthopedics, Chulabhorn Hospital, Chulabhorn Royal Academy, Bangkok, Thailand
[3]Bone and Joint Excellence Center, Thonburi Hospital, Bangkok, Thailand
[4]Department of Orthopedics, The Second Clinical College of Guangzhou University of Chinese Medicine, Guangzhou, China
[5]Department of Neurosurgery, Medistra Hospital, Jakarta, Indonesia
[6]Department of Orthopedics, Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand
[7]Department of Orthopedics, Thai Red Cross Society, Queen Savang Vadhana Memorial Hospital, Sriracha, Thailand
[8]Department of Neurosurgery, Aulss 2 Marca Trevigiana, Treviso, Italy
[9]Department of Neurosurgery, Seoul St. Mary's Hospital, College of Medicine, The Catholic University of Korea, Seoul, Korea

Corresponding Author
Jin-Sung Kim
https://orcid.org/0000-0001-5086-0875

Department of Neurosurgery, Seoul St. Mary's Hospital, College of Medicine, The Catholic University of Korea, 222 Banpo-daero, Seocho-gu, Seoul 06591, Korea
Email: mdlukekim@gmail.com,
md1david@catholic.ac.kr

Co-corresponding Author
Qinyi Liu
https://orcid.org/0000-0001-8012-3147

Department of Orthopedics, The Second Hospital of Jilin University, Changchun, China
Email: liuqinyi_lqy@163.com

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*Kun Wu and Zhihe Yun contributed equally to this study as co-first authors.

Our research examines the learning curves of various minimally invasive lumbar surgeries to determine the benefits and challenges they pose to both surgeons and patients. The advent of microsurgical techniques since the 1960s, including advances in fluoroscopic navigation and intraoperative computed tomography, has significantly shifted spinal surgery from open to minimally invasive methods. This study critically evaluates surgical duration, intraoperative conversions to open surgery, and complications as primary parameters to gauge these learning curves. Through a comprehensive literature search up to March 2024, involving databases PubMed, Cochrane Library, and Web of Science, this paper identifies a steep learning curve associated with these surgeries. Despite their proven advantages in reducing recovery time and surgical trauma, these procedures require surgeons to master advanced technology and equipment, which can directly impact patient outcomes. The study underscores the need for well-defined learning curves to facilitate efficient training and enhance surgical proficiency, especially for novice surgeons. Moreover, it addresses the implications of technology on surgical accuracy and the subsequent effects on complication rates, providing insights into the complex dynamics of adopting new surgical innovations in spinal health care.

Keywords: Minimally invasive surgical procedures, Spine, Learning curve, Complications

INTRODUCTION

Since the mid-1960s, when Yasargil introduced the surgical microscope and microsurgical techniques from cranial to spinal surgery,[1,2] the field has seen a significant shift from open to minimally invasive procedures.[3] Advances in both hardware and software have played crucial roles in this transformation. Historically, spinal surgery methods have evolved dramatically, from an open lumbar laminectomy in the United States was performed in 1829,[4] to the use of modern endoscopes that access the spine through tiny 2–3 mm incisions.[5] Additionally, the field has progressed from relying on intraoperative lateral x-rays for evaluating pedicle screw placement[6] to using fluoroscopic navigation[7] and now, intraoperative computed tomography (CT) scans for precise image guidance.[8] These rapid technological advancements have driven the development of minimally invasive spinal surgery.

In 1997, Foley and Smith introduced microendoscopic discectomy (MED), offering a minimally invasive solution for treating herniated discs.[9] This was followed by Kambin and Hijikata's attempts at percutaneous discectomy, marking a new stage in endoscopic spinal surgery.[5,10] In spinal fusion, Mathews et al.[11] reported on laparoscopic approaches for anterior lumbar interbody fusion in 1995. Since then, several minimally invasive fusion techniques have emerged, including lateral lumbar interbody fusion (LLIF), minimally invasive surgery transforaminal lumbar interbody fusion (MIS-TLIF), unilateral biportal endoscopic transforaminal lumbar interbody fusion (UBE-TLIF), and endoscopic lumbar interbody fusion (ELIF). These methods aim to reduce recovery time, surgical trauma, and postoperative complications compared to traditional open surgery. Despite their benefits, minimally invasive spine surgeries present a steeper learning curve for surgeons compared to traditional open procedures.

This study investigates whether the pursuit of minimally invasive techniques benefits both patients and surgeons, particularly novice surgeons navigating this evolving landscape. The learning curve, defined as the number of cases or time required for a surgeon to master a technique, is essential for guiding targeted training, identifying early difficulties, and preventing overtraining[12] (Fig. 1). A well-defined learning curve helps trainees develop proficiency and achieve competence to perform surgeries independently with reasonable outcomes. However, the learning curve in spinal surgery is complex and lacks a standardized measurement. It can be assessed through graphical inspection, grouping, CUSUM, and regression, each with its own strengths and weaknesses.[13-15]

Our research evaluates the learning curves of various minimally invasive lumbar surgeries, focusing on parameters such as surgery duration, intraoperative conversions to open surgery, and complications. By examining these parameters, we aim to understand the trends and comprehensive assessment of these learning curves based on perioperative indicators. While minimally invasive techniques offer numerous benefits, including reduced hospital stays and less postoperative pain, they also pose challenges. The reliance on advanced technology and navigation systems requires surgeons to be proficient with these tools. Consequently, a surgeon's competence directly affects patient outcomes, making training and understanding learning curves even more critical. This paper consolidates research on the learning curve associated with minimally invasive spinal surgery, analyzing data on surgery duration, intraoperative conversions to open surgery, and complications. Based on the results discussion, we integrated relevant reviews from previous studies, providing a comprehensive examination of the learning curve in minimally invasive spinal surgery.

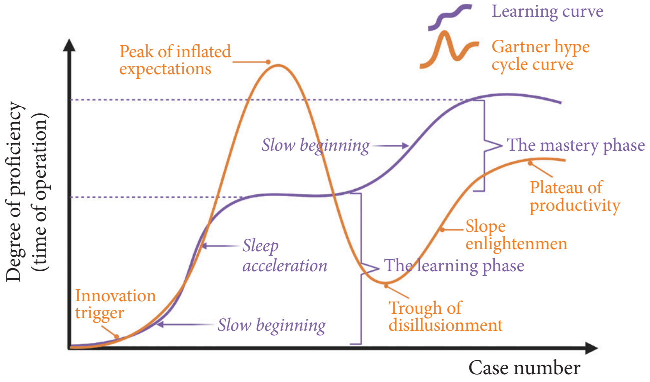

Fig. 1. The learning curve and gartner hype cycle curve (created with BioRender.com). The learning curve and the Gartner hype cycle curve exhibit entirely different development patterns.

MATERIALS AND METHODS

1. Search Strategy

We conducted a comprehensive electronic search of PubMed, Cochrane Library, and Web of Science databases, encompassing all available literature up to March 2024. Search terms included "learning curve," "spine," "minimally invasive," and "complications." The detailed search strategy is documented in the Supplementary data. Both MeSH (medical subject headings) terms and free-text terms were used to enhance search sensitivity. Additionally, we manually searched the reference lists of included studies and relevant systematic reviews to maximize the retrieval of pertinent studies.

2. Selection Criteria and Study Design

Inclusion and exclusion criteria were as follows: the study population consisted of individuals aged 18 and above with degenerative disc diseases, disc herniations, lumbar spinal stenosis (LSS), and spinal instability, including spondylolisthesis. Only randomized controlled trials (RCTs), prospective, and retrospective cohort studies related to minimally invasive lumbar surgery were included, excluding case controls, cross-sectional studies, case reports, systematic reviews, and meta-analyses. Cross-sectional studies and case reports exhibit inherent limitations, including data inaccuracies and a lack of rigor. Relevant systematic reviews and meta-analyses are deemed appropriate for inclusion in the discussion. Importantly, results from research articles relying on primary data must be derived from directly related studies. Additionally, studies involving duplicate publication, incomplete or unavailable data, and those where original authors could not be contacted for relevant information were excluded. We did not include multi-level MIS decompression or fusion studies in our analysis due to the significant heterogeneity among the study results, which could potentially skew the overall analysis of learning curve. Patients undergoing revision surgery or planned staged procedures were excluded. Revision surgery was defined as an unintended second surgery due to inadequate surgical technique, anesthesia manipulation, or infection-related complications.[16] Studies on spinal infections, tumors, and scoliosis were also excluded.

According to the AO Spine MISS Spectrum, minimally invasive spine surgery is a suite of technology-dependent techniques and procedures that reduces local operative tissue damage and systemic surgical stress enabling earlier return to function striving for better outcomes than traditional techniques.[17,18] In our study, minimally invasive lumbar spine surgeries divide into following subtypes: (1) Discectomy involves removing a portion of a herniated disc to relieve nerve compression, easing pain and neurological symptoms. (2) Decompression is used to clear obstructions like bone spurs or ligaments that compress nerves, alleviating pain, numbness, and weakness. (3) Spinal fusion connects 2 or more vertebrae with bone grafts and metal instruments, such as screws and rods, to stabilize the spine and prevent painful motion. (4) Foraminotomy enlarges the nerve root exit spaces to decrease nerve pressure and relieve discomfort. (5) Dynamic stabilization uses flexible materials for spinal stabilization. However, robotic technology,[19] augmented reality (AR),[20] and virtual reality (VR) were considered auxiliary techniques and not the focus of this paper. Finally, minimally invasive lumbar spine surgeries were classified into 3 primary types: discectomy, decompression, and fusion. Results and discussions will elaborate separately on these types. Discectomy and decompression techniques included microscopic, microendoscopic, unilateral biportal endoscopic, or full-endoscopic methods. Decompression techniques incorporated unilateral laminotomy for bilateral decompression (ULBD). Fusion procedures included MIS-TLIF, LLIF, and others. The naming conventions for certain minimally invasive spine surgeries were derived from research conducted by Hofstetter et al.[21]

Primary outcomes of interest were surgical time and complications. Surgical time was assessed by identifying an asymptote, the case number where the learning curve stabilized. Patients were categorized into early and late groups based on this asymptote, with the early group comprising patients operated on before reaching the asymptote and the late group those after. Complications were broadly categorized approach-related complications and medical complications. Surgical site complications can be classified into intraoperative and postoperative occurrences. Intraoperative issues may include inadvertent durotomies, cerebrospinal fluid (CSF) leaks, and direct puncture injuries to nerve roots. Postoperative complications can involve new onset motor or sensory deficits, new radiculopathy, instrument breakage, and excessive removal of facet joints. Postoperative complications included wound and perineural hematoma, superficial skin and wound infections, and suture granulomas. Somatic complications encompassed more severe events such as pulmonary embolism, myocardial infarction, respiratory distress or failure, and specific complications tied to the surgical approach, such as dura tear, wound infection, and vascular complications.[22] Reoperation rates were not included in the complications category.

3. Data Extraction and Statistical Analysis

Data collection was independently performed by 2 researchers (KW and ZH). We recorded details such as authors, country, region, hospital, publication year, study design, surgical technique, disease, time span, patient volume, asymptote achievement/surgical time variability, complications, and the number of conversions to open surgery. Articles without explicit information on region and hospital were categorized under the primary author's affiliated region and institution. Any discrepancies were resolved through discussion with a third researcher (QY). The Cochrane risk-of-bias tool[23] was employed to assess the risk-of-bias in RCTs, and the Newcastle-Ottawa Scale (NOS)[24] was used to grade the quality of retrospective cohort studies. The NOS is a widely utilized quality assessment tool for case-control and cohort studies. It evaluates these studies through 3 main modules consisting of 8 items, focusing on the selection of study populations, comparability, and assessment of exposure and outcomes. The NOS utilizes a star system for semi-quantitative evaluation of literature quality. Comparability can receive a maximum of 2 stars, while other items can earn up to 1 star each, yielding a maximum score of 9 stars. A higher score re-

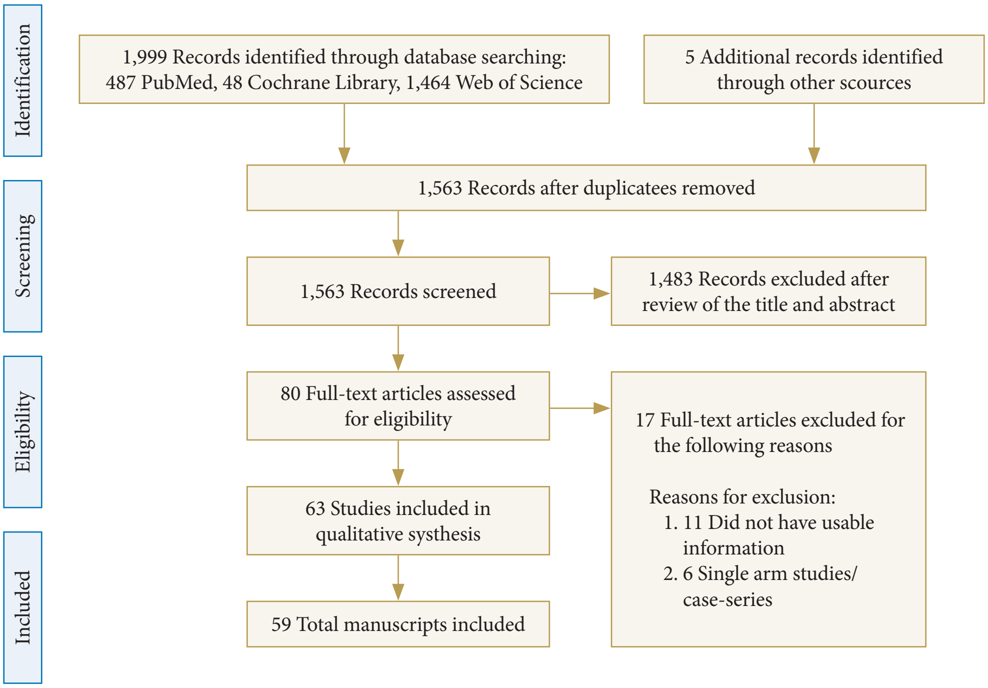

Fig. 2. Flow chart of the selection process for relative studies.

flects superior study quality. Assessments using the Cochrane and NOS were conducted independently by 3 authors, followed by a synthesis of their findings. Sensitivity analysis was conducted using the Mann-Kendall test to determine whether values exhibited a monotonic increasing or decreasing trend over time. Surgical times were divided into preasymptote and postasymptote categories, with linear relationships between surgical time, publication year, and asymptote status evaluated separately. In statistical outcomes, a z-value greater than 0 indicated an upward trend, whereas a z-value less than 0 indicated a downward trend.

We used statistical methods to investigate whether the frequency of procedures influenced the rate at which novices reached proficiency asymptotes. Data from articles containing both the total number of patients treated by novices and the duration of patient exposure (in months) were collected to calculate their ratio, measured as individuals per month. Asymptotic values represented proficiency. Regression statistical methods determined whether the frequency of procedures among novices impacted the rate at which they approached proficiency asymptotes across different procedures. For accuracy, only articles focused on individual novices were included, as articles involving multiple individuals performing procedures introduced uncertainty regarding procedural frequency. Articles providing duration only in years were assumed to start from January.

RESULTS

1. Identification and Selection of Studies

A total of 1,999 studies were initially identified, and after removing 436 duplicates, 1,563 potentially relevant studies were reviewed. Following title and abstract screening, 1,483 studies were excluded. Upon full-text review of the remaining studies, 59 articles describing the learning curves of minimally invasive spinal surgeries were included in the final analysis.[25-83] A flowchart detailing the study selection process is shown in Fig. 2. Supplementary Table 1 provides a quality assessment of each study based on the NOS. Most of the 58 retrospective or prospective studies scored above 6 stars, indicating decent quality. Additionally, the evaluation of the only included RCT using the Cochrane Risk of Bias Tool is presented in Supplementary Fig. 1, showing good quality results.

2. Analysis of Surgical Time Learning Curves

For novice surgeons, fusion surgery initially takes a long time, but as surgeons become more skilled, the time needed significantly decreases and levels off. In contrast, the difference in surgical time between MED and decompression is not as significant. Fig. 3 and Tables 1–3 illustrate how surgical time varies with increasing case numbers across different surgical techniques.

MED's asymptote typically ranges from 25–30 cases, while

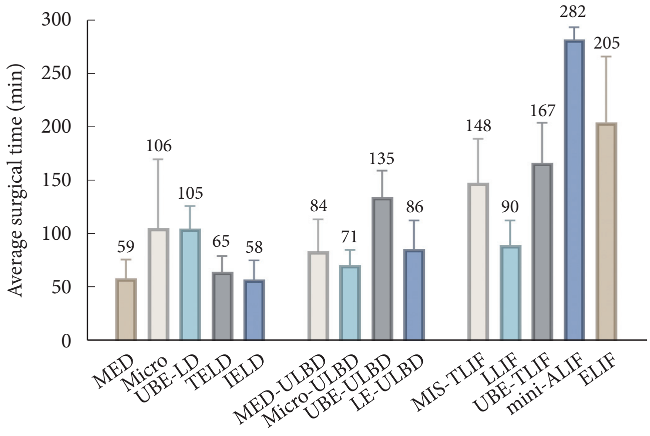

Fig. 3. The surgical time varies with increasing case numbers across different surgical techniques. The fusion techniques surgical time is longer than that for decompression techniques and discectomy techniques. MED, microendoscopic discectomy; UBE-LD, unilateral biportal endoscopic lumbar discectomy; TELD, transforaminal endoscopic lumbar discectomy; lELD, interlaminar endoscopic lumbar discectomy; ULBD, unilateral laminotomy for bilateral decompression; LE-ULBD, lumbar endoscopic ULBD; MIS-TLIF, minimally invasive surgery transforaminal lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; ALIF, nterior lumbar interbody fusion; ELIF, endoscopic lumbar interbody fusion.

for decompression, aside from lumbar endoscopic ULBD (LE-ULBD) with a 100-case asymptote, most asymptotes fall between 40–45 cases. For fusion surgery, the learning curve flattens after performing 31 to 35 cases. Once this level of experience is reached, interlaminar endoscopic lumbar discectomy (lELD) has the shortest surgical time for MED, while unilateral biportal endoscopic lumbar discetomy (UBE-LD) takes the longest. For decompression procedures, micro-ULBD is the fastest, and UBE-ULBD is the slowest. LE-ULBD has a surgical time notably shorter than UBE-ULBD, but longer than micro-ULBD. Among fusion techniques, mini-anterior lumbar interbody fusion (ALIF) takes the longest, while LLIF is the fastest among other fusion methods. Based on our comparative analysis of the average surgery times in case studies involving learning curves, we found that UBE-TLIF and ELIF, although newer minimally invasive surgical techniques, do not show a significant advantage in average surgery time during the learning curve compared to the traditional minimally invasive LLIF technique.

Studies of the countries represented in this article about discectomy and decompression found that India had the highest proportion (43%) among microendoscopic techniques. For full-endoscopic techniques, China and South Korea accounted for the largest shares, with 25.9% and 29.6%, respectively. China and South Korea also had the highest proportion in unilateral biportal endoscopic techniques, at 25% and 50%. In microscopic surgery techniques, the United States had a share of 33.3%. Varying attitudes and professional capabilities towards specific minimally invasive spine techniques across countries or regions may contribute to differences in the learning curves of beginners adopting new technologies.[84,85]

To investigate whether there are differences in the study of operative times within the learning curve of the same surgical technique based on the year of publication. The Mann-Kendall test (Supplementary Table 2) indicating that only MIS-TLIF shows a significant negative monotonic trend ($z = -0.73$, $z = -0.24$), though not statistically significant ($p = 0.46$, $p = 0.81$). Transforaminal endoscopic lumbar discectomy (TELD) ($p = 0.76$, $p = 0.54$) and lELD ($p = 0.26$, $p = 0.99$) do not show significant negative monotonic trends or statistical significance. This suggests no statistically significant relationship between surgical time and year for various minimally invasive techniques. Supplementary Table 3 shows the results of regression analysis for the impact of procedure frequency on the rate of reaching proficiency asymptotes. Due to limitations in data availability, only TELD, lELD, MIS-TLIF, and MED were considered. Among these, only TELD ($p = 0.031$) exhibits a significant correlation between procedure frequency and the rate of reaching proficiency asymptotes. lELD ($p = 0.59$), MIS-TLIF ($p = 0.26$), and MED ($p = 0.50$) do not display any statistically significant correlation.

3. Complications in Minimally Invasive Techniques

1) Discectomy techniques

Thirty-one studies on discectomy techniques were included (Table 1). These comprised one study on microdiscectomy (52 patients); 6 studies on MED (419 patients); 15 studies on TELD (1,122 patients); 8 studies on lELD (493 patients); and 2 studies on UBE-LD (187 patients).

Microdiscectomy, one of the earliest techniques, has the fewest learning curve-related studies, with only 1 paper reporting a 10% complication rate (3 of 30). Notably, 66.7% of these complications were dural tears resulting in CSF leaks.

MED remains widely used, with an overall complication rate of 7.6% (26 of 344). Dural tears were the most common complication (50% of cases). Other frequent complications included inadvertent removal of the facet joint (5 of 26). Jhala et al.[75] reported 41% (5 of 12) of total complications occurring before 25 cases, while Rong et al.[77] reported all complications occurring in the first 20 cases. UBE-LD had an overall complication rate of 4.6% (9 of 187), with dural tears constituting 33.3% (3 of 9)

Table 1. The main features of the articles included on discectomy techniques

Study	Study design	Surgical technique	Dis-ease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications	Conversion to open
Nowitzke[82] 2005	Prospective	MED	LDH	Brisbane, Australia	The Princess Alexandra Hospital	An individual surgeon not previously exposed to this procedure	35	July 2001–December 2003	Case 30	None	None
Jhala[75] 2010	Retrospective	MED	LDH	Ahmedabad, India	Chirayu Hospital	A single surgeon	100	August 2002–December 2005	None	In initial 25 cases: 5 Postoperative discitis: 4 In all 100 cases: 12 Inadvertent removal of the facet joint: 5 Minor dural punctures: 7	1 Case nerve root injury
Rong[77] 2008	Prospective	MED	LDH	China	None	Nine-year experience as an orthopedic clinician	50	June 2002–February 2003	Case 20	All occurred in the initial 20 procedures: 5 CSF leakage: 1 Readjusted due to inaccuracy in vertebral Localization: 1 Delayed wound healing: 1 Dural tear: 2	None
Marappan[51] 2018	Prospective	MED	LDH	India	Stanley Medical College	None	40	2003–2007	Case 20	None	None
Jain[46] 2020	Retrospective	MED	LDH	Mumbai, India	Bombay Hospital and Research Centre	A 2-year fellowship-trained surgeon	120	2008–2016	Case 25-30	All 120 cases: 4 Dural tear: 4	None
McLoughlin[79] 2008	Prospective	Microdiscectomy	LDH	Saskatchewan, Canada	University of Saskatchewan	A single surgeon	52	None	Case 15	All occurred first 30 cases: 3 Dural tear to CSF: 2 A root sleeve tear: 1	1 Case dural tear
Wiese[83] 2004	Prospective	Microdiscectomy	LDH	Bochum, Germany	Josef Hospital	One experienced surgeon, 7 less experienced surgeons	None	January 1981–June 2000	None	None	None
Chen[37] 2022	Retrospective	UBE-LD	LDH	Hefei, China	The Second Hospital of Anhui Medical University	A senior orthopedic doctor	97	November 2018–May 2020	Case 24	In all 97 cases: 4 Dural injury: 2	None
Lee[80] 2008	Prospective	TELD	LDH	Korea	Wooridul Spine Hospital	Surgeon had performed about 200 cases of open microdiscectomy	51	November 2004–October 2005	Case 35	All occurred in the initial 34 procedures: 2	4

(*Continued*)

Table 1. The main features of the articles included on discectomy techniques (Continued)

Study	Study design	Surgical technique	Dis- ease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications	Conversion to open
Morgenstern[81] 2007	Prospective	TELD	LDH	Barcelona, Spain	Centro Médico Teknon	One orthopedic surgeon who had experience performing open spine surgery and knee and shoulder arthroscopic surgery	144	January 2001–June 2005	Case 35	None	None
Son[39] 2021	Retro- spective	TELD	LDH	Seoul, South Korea	Gachon University College of Medicine	One surgeon at a single institute started to perform PETLD from September 2014	48	September 2014–August 2017	Case 26	All occurred in the initial 25 procedures: 4 Exciting nerve root: 4	1 Case
Yang[41] 2020	Retro- spective	TELD	LDH	Sichuan, China	West China Hospital	Before using PETD for LSS, the author observed 10 cases treated with this surgery at a spinal endoscopy center and practiced on cadavers 5 times.	75	July 2015–September 2016	Case 35	All 75 cases: 4 Dural tear and insufficient enlargement of bony lateral recess: 1 Nerve root injury, residual osteophyte, and neck pain: 1 Dural tear, residual osteophyte, neck pain: 1 Nerve root injury: 1	1 Case
Fleiderman[29] 2023	Retro- spective	TELD	LDH	Santiago, Chile	Hospital del Trabajador	A single surgeon	41	June 2013–2020	Case 20	None	None
Ransom[44] 2020	Retro- spective	TELD	LDH	California, USA	Monterey Spine and Joint Center	Two traditionally trained “apprentice” surgeons	20	None	Case 15	None	None
Gadjradj[36] 2022	RCT	TELD	LDH	Netherlands	4 General hospitals	Three surgeons were trained in the PTED-procedure by a senior surgeon.	304	None	None	Repeated surgery within 1 year: 24	7
Chaichankul[70] 2012	Prospective	TELD	LDH	Bangkok, Thailand	Phramongkutklao Hospital and College of Medicine	None	50	None	None	None	None
Wu[55] 2016	Retro- spective	TELD	LDH	Shanghai, China	An affiliated Tenth People’s Hospital of Tongji University	Ten-year experience of open spine surgery	120	June 2011–August 2013	None	None	2

(*Continued*)

Table 1. The main features of the articles included on discectomy techniques (Continued)

Study	Study design	Surgical technique	Disease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications	Conversion to open
Tenenbaum[72] 2011	Retrospective	TELD	LDH	Israel	Department of Orthopedic Surgery Sheba Medical Center	None	150	None	None	In all 150 cases: 2 Postsurgery hypoesthesia: 1 One deep wound infection: 1	None
Maayan[28] 2023	Retrospective	TELD	LDH	New York, USA	Hospital for Special Surgery	A single surgeon	55	December 2020–2022	Case 31	None	None
Wang[65] 2013	Retrospective	TELD	LDH	Chongqing, China	Xinqiao Hospital, Third Military Medical University	More than 10 years of experience of open spine surgery and with little professional training of PELD.	120	September 2005–May 2011	None	None	None
Ahn[61] 2015	Retrospective	IELD	LDH	Seoul, Korea	Gangnam Severance Spine Hospital	None	215	August 2012–January 2014	Case 35	None	None
Xu[62] 2014	Prospective	IELD	LDH	Jiangsu, China	Department of Orthopedics of Jinling Hospital	The same team of surgeons	36	March 2011–March 2012	Case 20	0	2 Cases narrow interlaminar space
Son[43] 2020	Prospective	IELD	LDH	Incheon, South Korea	Gachon University College of Medicine	A single surgeon	27	September 2014–August 2016	Case 18	In all 27 cases: 2 Incidental intraoperative tiny durotomy: 2	0
Joswig[56] 2016	Prospective	IELD	LDH	Gallen, Switzerland	Cantonal Hospital St. Gallen	Two spinal surgeons	76	None	Case 40	In all 76 cases: 4	0
Wang[71] 2011	Prospective	IELD	LDH	Changsha, China	Second Xiangya Hospital of Central South University	Two fellowship-trained spine surgeons	30	None	Initial 8: 107.9 min After 10 cases: 68.5 min After 20 cases: 43.2 min	All occurred in the initial 20 procedures: 2 Dural tears: 2	2
Hsu[67] 2013	Retrospective	TELD	LDH	Taipei, Taiwan	Buddhist Tzu Chi Hospital	The senior author observed 3 cases of transforaminal approach and 3 cases of interlaminar approach	34	July 2006–July 2009	Case 10	In all 56 cases: 8 Transient nerve injuries: 2 Disc reherniation: 2 Reoperation: 4	2
		IELD					22		Case 33		None

(*Continued*)

Table 1. The main features of the articles included on discectomy techniques (Continued)

Study	Study design	Surgical technique	Disease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications	Conversion to open
Olinger[27] 2023	Prospective	TELD	LDH	IA, USA	University of Iowa	Single surgeon	44	September 2017–February 2019	Median operative time: 52 min	None	None
		IELD					46		Median operative time: 73 min		
Zelenkov[40] 2020	Prospective	TELD	LDH	Moscow, Russia	Burdenko National Medical Research Center for Neurosurgery	Single surgeon	16	February 2013–March 2015	Case 7	In all 16 cases: 0	0
		IELD					41		Case 17	In all 41 cases: 4 Dural ruptures: 4	0

CSF, cerebrospinal fluid; PETLD, percutaneous endoscopic transforaminal lumbar discectomy; LSS, lumbar spinal stenosis; PTED, percutaneous transforaminal endoscopic discectomy; PELD, percutaneous endoscopic lumbar discectomy; MED, microendoscopic discectomy; TELD, transforaminal endoscopic lumbar discectomy; lELD, interlaminar endoscopic lumbar discectomy; UBE-LD, unilateral biportal endoscopic lumbar discectomy; LDH, lumbar disc herniation.

of these. For full-endoscopic lumbar discectomy, the overall complication rate for TELD was 1.9% (12 of 644), with dural tears, delayed wound healing/infection, hypoesthesia, nerve root injuries, and excessive facet resection at 16.7% (2 of 12), 8.3% (1 of 12), 8.3% (1 of 12), 41.6% (5 of 12), and 16.7% (2 of 12), respectively. lELD had an overall complication rate of 5.7% (12 of 210), with dural tears constituting 66.7% (8 of 12). Other complications such as delayed wound healing/infection, hypoesthesia, nerve root injuries, and excessive facet resection were not reported.

2) Decompression techniques

Twelve studies on decompression techniques were included (Table 2). These comprised 4 studies on micro-ULBD (547 patients); 2 studies on MED-ULBD (537 patients); 3 studies on LE-ULBD (384 patients); and 3 studies on UBE-ULBD (199 patients).

Overall complication rates were highest for micro-ULBD (12.4%), followed by LE-ULBD (10.7%), UBE-ULBD (6.5%), and MED-ULBD (3%). LE-ULBD had the highest rate of excessive facet resection (25.9%), while dural tears were most common in micro-ULBD (71.8%), MED-ULBD (56.2%), and UBE-ULBD (46.2%).

3) Fusion techniques

Nineteen studies on fusion techniques were included (Table 3), encompassing 10 studies on MIS-TLIF (874 patients); 5 studies on LLIF (228 patients); 1 study on UBE-TLlF (57 patients); 1 study on mini-ALIF (127 patients); and 2 studies on ELIF (129 patients).

MIS-TLIF, one of the earliest minimally invasive spinal fusion techniques, showed an overall complication rate of 9% (80 of 874). Rates for dural tears, CSF leakage, delayed wound healing/infection, and hypoesthesia were 18% (14 of 80), 3% (2 of 80), 10% (8 of of 80), and 1% (1 of 80), respectively. Other complications such as epidural hematomas, hardware misplacement (cage/pedicle screw), and pseudarthrosis were 5% (4 of 80), 20% (16 of 80), and 11% (9 of 80), respectively. Other fusion techniques—LLIF, UBE-TLlF, mini-ALIF, and ELIF—had overall complication rates of 25% (57 of 228), 5% (3 of 57), 25% (32 of 127), and 5% (7 of 129), respectively. Each technique had its unique complications, with LLIF having urinary retention and urinary tract infection rates of 32% (9 of 28) and 3% (1 of 28), respectively.

4) Foraminotomy

Our study's examination of the learning curves associated

Table 2. The main features of the articles included on decompression techniques

Study	Study design	Surgical technique	Disease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications	Conversion to open
Mannion[68] 2012	Retrospective	Micro-ULBD	LSS	Queensland, Australia	Princess Alexandra Hospital	Senior spine surgeon	50	None	None	In all 50 cases: 12 Dura tear: 9 Severe back pain: 1 Inadequate decompression: 1 Fixation: 1	1
Ahn[58] 2016	Retrospective	Micro-ULBD	LDH/LSS	Chicago, USA	Rush University Medical Center	A single surgeon	100	2009–2014	None	In all 100 cases: 12 Inadvertent removal of the facet joint: 5 Minor dural punctures: 7	1 Nerve root injury
Park[32] 2022	Retrospective	Micro-ULBD	LSS	Korea	Korea University Ansan Hospital	The operator had 1 year's fellowship training	194	April 2017–June 2020	Case 29	In all 194 cases: 27 Dural tear: 23 Hematoma: 2 Incomplete decompression: 1 Wrong level surgery: 1	None
Parikh[78] 2008	Prospective	Micro-ULBD	LSS	New York, USA	New York Presbyterian Hospital	Two surgeons	230	2004–2007	55% decrease in procedure time from initial case to case 230	In all 230 cases: 20 Intraoperative dural tears: 19 A superficial wound infection: 1	None
Nomura[54] 2015	Retrospective	MED-ULBD	LSS	Wakayama, Japan	Sumiya Orthopaedic Hospital	The first author of this report had 10 years of experience as an orthopedic clinician	480	November 2006–January 2015	Case 30	In all 480 cases: 10 Dural tears: 9 Epidural hematoma: 1	None
Lee[53] 2018	Retrospective	LE-ULBD	LSS	Seoul, Korea	Peter's Hospital	A single surgeon with experience performing traditional spinal surgery cases (> 3,000 cases)	132	August 2012–August 2017	In the late period of the learning curve, mean operative time was shortened by two-thirds	None	None
Lee[49] 2019	Retrospective	LE-ULBD	LDH/LSS	Seoul, Korea	The Leon Wiltse Memorial Hospital	A single surgeon	223	November 2013–February 2018	Case 100	In all 223 cases: 24 Dura tear: 5 Motor weakness: 4 Dysthesia: 5 Postoperative hematoma: 3 Excessive facet resection: 7	None

(*Continued*)

Table 2. The main features of the articles included on decompression techniques (Continued)

Study	Study design	Surgical technique	Dis-ease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications	Conver-sion to open
Park[48] 2019	Retrospective	UBE-ULBD	LSS	Seongnam, Korea	Seoul National University College of Medicine	The surgeon was proficient in open and microscopic ULBD for LSS	60	June 2017–January 2018	Case 58	In all 60 cases: 6 Dura tear: 3 Hematoma: 1 Incomplete decompression: 2	None
Choi[57] 2016	Retrospective	UBE-ULBD/UBE-LD	LDH/LSS	Jinju, Korea	Barun Hospital	The surgeon had 8 years of experience in spine surgery	23	January–May of 2015	None	None	None
Xu[30] 2022	Retrospective	UBE-LD	LDH/LSS	China	Hangzhou Hospital of Traditional Chinese Medicine	The same surgeon who had extensive experience in percutaneous endoscopic lumbar discectomy (PELD)	90	December 2019–December 2020	Case 32	In all 90 cases: 5 Dura tear: 1 Epidural hematoma: 1 Residue: 3	None
		UBE-ULBD					107		Case 67	In all 107 cases: 7 Dura tear: 3 Epidural hematoma: 1 Nerve root injury: 3	None
Wu[26] 2023	Prospective	LE-ULBD	LSS	Singapore, Singapore	National University of Singapore	A single fellowship-trained spine surgeon	29	April 2020–April 2021	None	Three suffered incidental durotomies	2
		UBE-ULBD					32			No one	0
Sairyo[74] 2010	Retrospective	MED-ULBD	LSS	Kawasaki, Japan	Teikyo University Mizonokuchi Hospital	A single surgeon	57	None	None	In all 57 cases: 6	None
		MED					74			In all 74 cases: 5	None

ULBD, unilateral laminotomy for bilateral decompression; MED-ULBD, microendoscopic discectomy ULBD; UBE-ULBD, unilateral biportal endoscopic ULBD; LE-ULBD, lumbar endoscopic ULBD; UBE-LD, unilateral biportal endoscopic lumbar discectomy; LDH, lumbar disc herniation; LSS, lumbar spinal stenosis.

Table 3. The main features of the articles included on fusion techniques

Study	Study design	Surgical technique	Disease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications
Lau[73] 2011	Prospective	MIS-TLIF	Spondylolisthesis	San Francisco, USA	University of California San Francisco	Senior spine surgeon	10	Between 2005–2008	None	In all 10 cases: 4 Cardiopulmonary event and deep wound infection: 1 Superficial wound infection: 1 Pseudarthrosis: 1 Instrumentation malposition requiringreoperation: 1
Kumar[50] 2019	Prospective	MIS-TLIF	Degenerative spondylosis and spondylolisthesis	New York, USA	Icahn School of Medicine at Mount Sinai	The surgeon completed a residency in Orthopedic Surgery followed by a fellowship in Spine surgery	109	between 2011–2015	Case 38	In all 109 cases: 11 Epidural hematomas requiring operative evacuation: 2 Failed hardware requiring revision: 2 Pseudarthrosis requiring revision: 2 Recurrent stenosis requiring revision: 2 Adjacent segment pathology requiring revision surgery: 3
Silva[66] 2013	Prospective	MIS-TLIF	Degenerative spondylolisthesis and recurrent lumbar disc herniation, etc.	Porto, Portugal	Hospital São João	Senior spine surgeon	150	None	Case 40	In all 150 cases: 19 Dural tears: 8 Persistent neurogenic bladder, perineal hypesthesia: 1 Severe postop sciatica (transient): 3 Superficial wound infection: 2 Deep wound infection & meningitis: 1 Persistent motor radiculopathy: 1 Screw malposition requiring revision: 1 Extradural hematoma (reintervention): 1 Myocardial infarction: 1
Park[59] 2015	Prospective	MIS-TLIF	Spondylolisthesis, foraminal stenosis and foraminal disc herniation, etc.	Goyang, Korea	National Health Insurance Service Ilsan Hospital	None	124	October 2003–May 2007	None	In all 124 cases: 11 Temporary postoperative neuralgia: 3 Deep wound infections: 2 Pedicle screw misplacements: 2 Cage migrations: 2 Dural tear: 1 Grafted bone extrusion: 1
Lee[64] 2014	Prospective	MIS-TLIF	Spondylolisthesis, spinal stenosis	Singapore	Singapore General Hospital	A single surgeon	90	2005–2009	Case 44	All occurred in the initial 44 procedures: 3
Schizas[76] 2009	Prospective	MIS-TLIF	Isthmic spondylolisthesis, asymmetrical disc disease with foraminal stenosis, etc.	Lausanne, Switzerland	Hôpital Orthopédique de la Suisse Romande	A single surgeon	18	None	30% decrease in procedure time from initial case to case 12	In all 18 cases: 3 Dural tear: 1 Brachial plexus palsy: 1 Root paresis: 1

(*Continued*)

Table 3. The main features of the articles included on fusion techniques (Continued)

Study	Study design	Surgical technique	Disease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications
Garcia[35] 2022	Retro-spective	MIS-TLIF	Lumbar spondylolisthesis and degenerative disc disease	Florida, USA	Mayo Clinic	A single spinal surgeon with experience in open TLIF and no previous experience in MIS-TLIF	100	None	Case 58	In all 58 cases: 6 Malpositioned right L5 screw: 1 Incidental durotomy: 1 Bone graft extrusion into left L5 foramen: 1 Bilateral foot drop: 1 Retroperitoneal hematoma: 1 Readmission for pain control: 1
Nandyala[63] 2014	Prospective	MIS-TLIF	Degenerative disk disease or spondylolisthesis with stenosis	Chicago, USA	Rush University Medical Center	Senior spine surgeon	65	July 2008–April 2011	Case 33	In all 65 cases: 12 Implant screw displacements: 6 Pseudarthrosis: 2 Graft migration: 3 Surgical site infection: 1
Lee[69] 2012	Prospective	MIS-TLIF	LDH/LSS/ spondylolisthesis	Seoul, Korea	Soonchunhyang University Seoul Hospital	A single surgeon	86	None	Case 30	In all 86 cases: 9 Screw malposition: 2 Deep wound infection: 2 Pseudarthrosis: 4 Re-exploration for removing bone graft fragments extruding from the cage that were irritating the nerve root: 1
Wang[42] 2020	Retro-spective	MIS-TLIF	LDH/LSS/ spondylolisthesis	Chongqing, China	Third Military Medical University	A single surgeon	122	March 2016–August 2017	Case 25	Cerebrospinal fluid leakage: 2
Warren[38] 2021	Retro-spective	LLIF	Spondylolisthesis	California, USA	Stanford University	A single surgeon	None	January 2013–October 2019	None	None
Ng[60] 2015	Prospective	LLIF	Lumbar stenosis	Singapore	Tan Tock Seng Hospital	Two senior spine surgeon	None	April 2012–August 2014	None	None
Jacob[34] 2022	Retro-spective	LLIF	Degenerative spond Degenerative scoliosis, etc.	Chicago, Illinois, USA	Rush University Medical Center	A single surgeon	179	July 2006–March 2021	Linear model predicted at case 34	In all 179 cases: 28 Urinary retention: 9 Urinary tract infection: 1 Altered mental status: 2 Arrhythmia: 2 Dysphagia: 3 Ileus: 2 Nausea/vomiting: 9

(*Continued*)

Table 3. The main features of the articles included on fusion techniques (Continued)

Study	Study design	Surgical technique	Disease	Region	Hospital	Training background	Sample size	Time span	Asymptote: number/time	Complications
Silva[47] 2019	Retrospective	LLIF	Spondylolisthesis and disc disease, etc.	Porto, Portugal	Faculty of Medicine, University of Porto	A single surgeon	None	February 2015–March 2018	None	None
Liu[52] 2018	Prospective	LLIF	Spondylolisthesis	Chongqing, China	Affiliated Xinqiao Hospital, The Third Military Medical University	Senior spine surgeon	49	None	Case 15	In all 49 cases: 29 Donor site pain: 15 Thigh numbness and pain: 8 Psoas and quadriceps weakness: 3 Sympathetic nerve injury: 2 Paralytic ileus: 1
Mirza[33] 2022	Retrospective	mini-ALIF	Degenerative spondylolisthesis and degenerative disk disease, etc.	Wisconsin, USA	University of Wisconsin School of Medicine and Public Health	All patients underwent the anterior approach by the same surgeon	127	January 01, 2010–December 31, 2018	Case 25	In all 127 cases: 32 30-day readmission/ED visits: 14 DVT (deep vein thrombosis): 3 Delayed return of bowel function: 3 Lower extremity swelling, pain, and cramps: 6 Superficial wound complication (infection or hematoma): 7 Deep infection: 1 UTI (urinary tract infection): 1
Kim[45] 2020	Retrospective	UBE-TLIF	Degenerative spondylolisthesis and isthmic spondylolisthesis	Busan, Korea	Himnaera Hospital	A single surgeon	57	January 2017–December 2018	Case 34	In all 57 cases: 3 Postoperative spinal epidural hematoma: 1 Cage subsidence: 1 Transient paralysis: 1
Zhao[25] 2023	Retrospective	ELIF	Moderate to severe stenosis and spondylolisthesis, etc.	Zhejiang, China	Affiliated People's Hospital, Hangzhou Medical College	This surgeon has 15 years of attending spine surgeon experience	93	October 2017–April 2020	Case 25	In all 93 cases: 4 Contralateral nerve root compression: 2 Infection: 1 Severe radiculopathy: 1
Tan[31] 2022	Retrospective	ELIF	LDH/LSS/spondylolisthesis	Hunan, China	The Second Xiangya Hospital	Two fellowship-trained spine surgeons	36	None	Case 10	All occurred in the initial 24 procedures: 3 Dural tear: 1 Incomplete reduction requiring open-access revision: 1 Postoperative nerve root symptom: 1

MIS-TLIF, minimally invasive surgery transforaminal lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; ALIF, nterior lumbar interbody fusion; UBE-TLIF, unilateral biportal endoscopic transforaminal lumbar interbody fusion; ELIF, endoscopic lumbar interbody fusion; LDH, lumbar disc herniation; LSS, lumbar spinal stenosis.

with various minimally invasive spinal surgeries, though thorough, regrettably did not retrieve enough analysis for the research related to the foraminotomy. By omitting the analysis for foraminotomy, we might not fully understand the nuances and potential challenges new surgeons face with this technique. During retrieving of the relevant literature, there is only one published by Alessandro and colleagues examined the learning curve of 2 spine surgeons who used lumbar foraminotomy in 200 patients with lumbar disc herniation and foraminal stenosis. Their study revealed that the median operative time was 56 minutes before the surgeons reached the learning curve, decreasing to 37 minutes after surpassing it (> 100 patients). Initially, 86% of patients reported excellent to good outcomes during follow-up, whereas 14% were dissatisfied. In the final year of the study, patient satisfaction increased to 94%, with only 6% remaining dissatisfied 30 days after the intervention.[86]

DISCUSSION

This paper evaluates the learning curve of minimally invasive lumbar surgeries using 3 primary criteria: surgery duration, conversions to open surgery, and complications. Typically, as surgeons gain experience, surgery duration decreases. Published evidence indicates that in minimally invasive lumbar discectomy, the reoperation rates for both the lELD and MED groups are not significantly different, whether evaluated within 2 years postsurgery or later.[87] Studies on different lumbar fusion techniques for spinal stenosis suggest that MIS-TLIF is associated with a significantly higher incidence of reoperation compared to ELIF.[88] This implies that once the learning curve for minimally invasive lumbar techniques is mastered, using reoperation rates to assess the effectiveness of various methods is meaningful. However, for beginners, unforeseen cases may require conversion to open surgery for better exposure and familiarity.[12] This may explain why much of the literature on the learning curve often employs intraoperative conversion to open surgery rather than reoperation rates as a metric. Complications serve as a critical benchmark for proficiency, distinguishing minimally invasive from open surgeries. We examine the relationship between surgical time, complications, and the learning curve in the existing literature on minimally invasive lumbar surgery.

1. Trends and Keyword Analysis in New Minimally Invasive Lumbar Techniques

To understand the development and progression of new lumbar minimally invasive techniques, we conducted a bibliometric analysis using the Web of Science database. Our search with keywords “lumbar,” “minimally invasive,” “new,” and “technology” identified 634 papers from 1999 to 2024. The analysis revealed a general upward trend in research, particularly intensifying from 2014 onwards (Fig. 4A). Keyword analysis showed a significant focus on fusion techniques (10%), with terms related to diskectomy and decompression also prominent. Complications accounted for 6% of the keywords, highlighting concerns about patient outcomes (Fig. 4B and C). Recent studies have increasingly focused on learning curves, reflecting a growing interest in optimizing training for these techniques (Fig. 4D). The Mann-Kendall test indicated no significant difference in surgery time between early and late phases of these techniques, suggesting that newer minimally invasive approaches do not necessarily offer a time advantage.

2. Learning Trends in Discectomy, Decompression, and Fusion Techniques

1) Discectomy techniques

In discectomy, complications for beginners have decreased as techniques have advanced. However, dural tears remain common, particularly in microdiscectomy and MED techniques, where they account for 66.7% and 50% of complications, respectively. Beginners should focus on avoiding dural tears through thorough preparation and precise techniques. In full-endoscopic lumbar discectomy, the TELD and lELD techniques differ significantly. TELD often requires foraminotomy,[89] which can lead to higher rates of hypoesthesia[90] and excessive facet resection.[91,92] In contrast, lELD, commonly used at L5–S1, avoids this, leading to different complication profiles. Beginners in TELD must be cautious of nerve root injuries,[93,94] while those in lELD should be vigilant about avoiding dural tears.[93]

Interestingly, the learning curves for biportal endoscopy were similar to, if not greater than, those for uniportal endoscopy. This contradicts the current consensus that biportal endoscopy involves a more gradual learning curve. One possible explanation is that many studies included in our analysis were from China, where most spine surgeons are orthopedic surgeons without microscopic technique training, unlike neurosurgeons in other countries. Our results indicate that the initial placement of channels in biportal procedures is more challenging for some surgeons than in uniportal ones. This suggests that beginners in various countries or regions may benefit from personalized learning when learning new minimally invasive spinal techniques. Identifying techniques that suit their specific circumstances and local conditions, followed by in-depth study, may be a more effective approach.

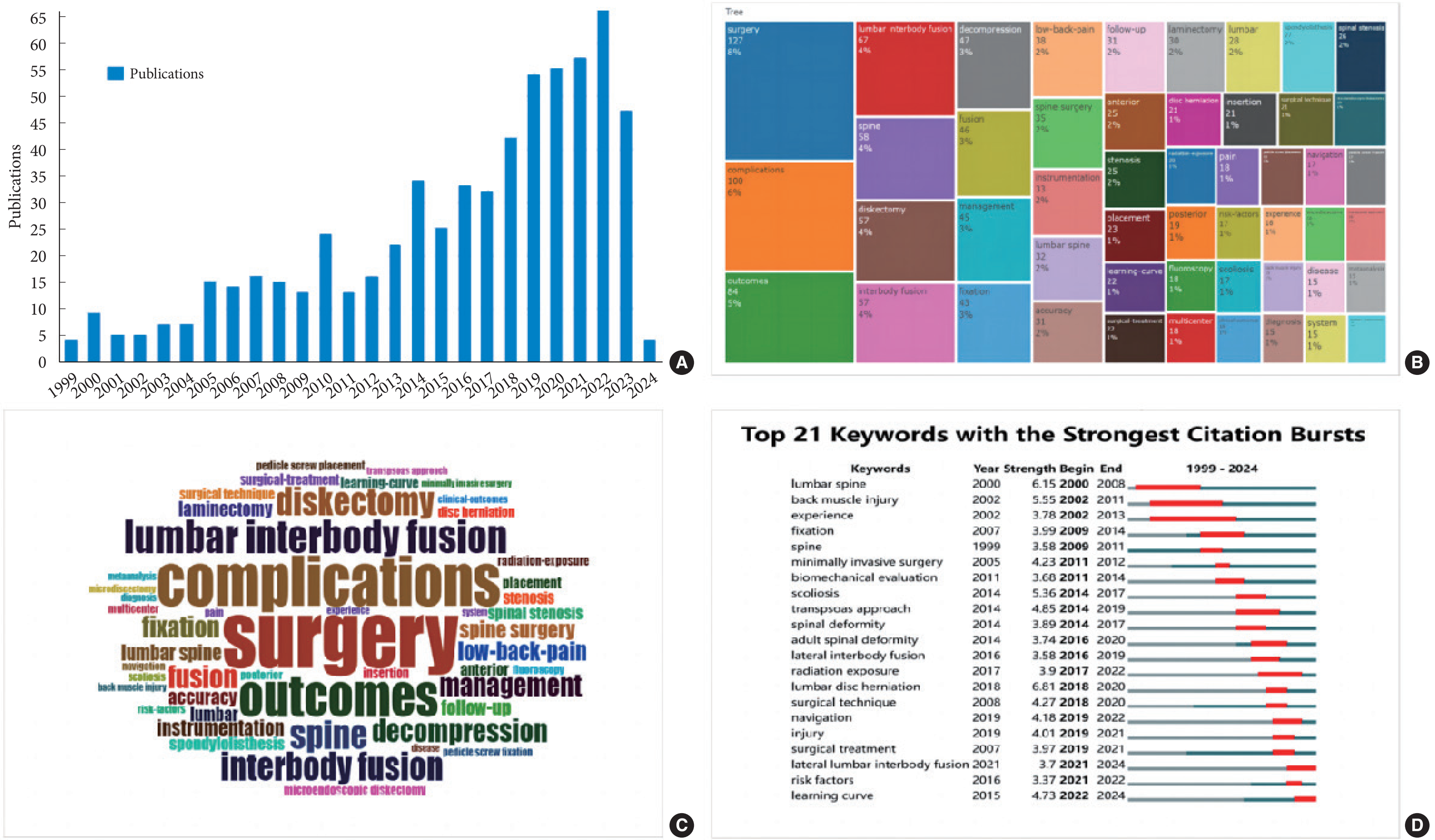

Fig. 4. The figure in trends and keyword analysis in new minimally invasive lumbar techniques (A: the annual trends of publications, B: cluster analysis of hot word frequency, C: WordCloud-Keyword emergence analysis, D: top 21 keywords with the strongest citation bursts). A consistent upward trend in related new minimally invasive lumbar techniques researches.

2) Decompression techniques

For decompression techniques, beginners frequently encounter excessive facet resection and dural tears, primarily due to the unilateral approach for bilateral decompression.[95,96] This involves drilling for ipsilateral decompression and then contralateral decompression through a dorsal entry.[49] Preoperative imaging is essential for understanding patient anatomy, and intraoperative fluoroscopic projections help optimize entry angles.[97] Tool selection is also critical; manual tools like Kerrison rongeurs are recommended over electric tools to reduce complication rates.[98] LE-ULBD has a surgical time notably shorter than UBE-ULBD, but longer than micro-ULBD. This suggests that LE-ULBD falls in the middle of the learning curve when compared to these techniques. Specifically, LE-ULBD's endoscopic approach might offer a balance between the effectiveness afforded by the micro-ULBD, which has the shortest surgical times, and the visibility and precision of the UBE-ULBD, which appears to take the longest. This issue is often explained by the extent of trauma associated with decompression exposure. Micro-ULBD operates in a semi-open mode, resulting in greater trauma and a broader exposure range. This is beneficial for beginners, as it facilitates quicker identification of decompression targets and leads to shorter surgery durations. The primary distinction between LE-ULBD and UBE-ULBD is that LE employs a single-channel approach, whereas UBE uses a dual-channel approach. These methods may influence surgical duration for beginners, suggesting that those using the single-channel LE might adapt more readily and complete surgeries more quickly.

Each ULBD technique has unique complications, with decompression being more challenging for beginners than discectomy.[99-101] Endoscopic laminectomy for LSS requires dealing with adhesions and thinner dura mater, making it technically demanding. Surgeons should begin with endoscopic discectomy for herniated discs before progressing to LSS decompression. Statistical analysis confirms (Fig. 5) that discectomy requires fewer cases to reach proficiency compared to ULBD, emphasizing the importance of starting with simpler procedures.

3) Foraminotomy technique

Although Lumbar foraminotomy presents a viable and effective alternative for managing foraminal stenosis, the procedure's steep learning curve and the scarcity of comprehensive practical documentation can create challenges for beginners.[102] Mastery of this technique requires a deep understanding of the anatomical course of the nerve root, which must be carefully targeted for decompression based on radiographic images. Further

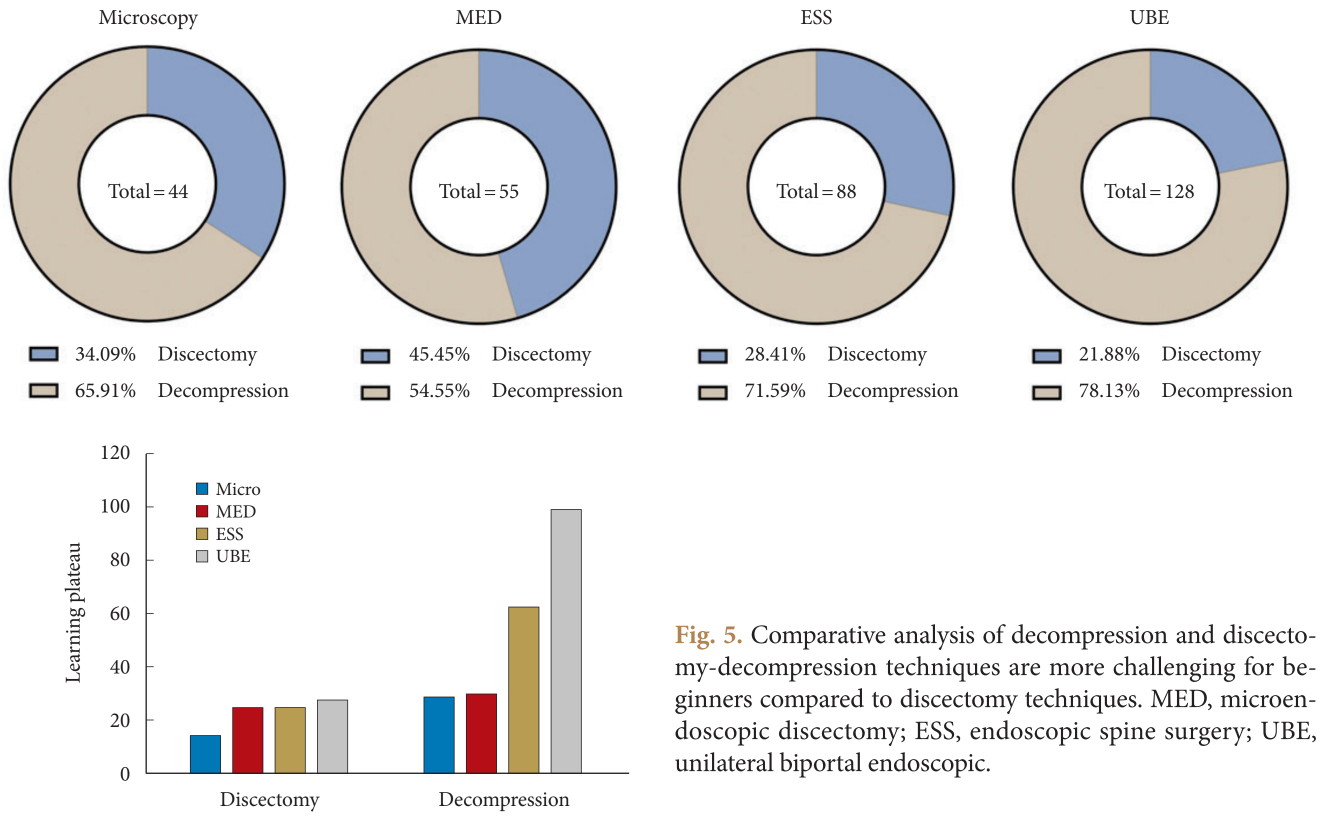

Fig. 5. Comparative analysis of decompression and discectomy-decompression techniques are more challenging for beginners compared to discectomy techniques. MED, microendoscopic discectomy; ESS, endoscopic spine surgery; UBE, unilateral biportal endoscopic.

complicating the procedure is the fact that hypertrophy of the superior articular process and ligamentum flavum are often the primary causes of foraminal stenosis. These anatomical structures frequently undergo deformation and lack clear anatomical boundaries, making it exceedingly difficult to thoroughly remove the hypertrophied tissue. Beginners must be particularly mindful of these challenges, as incomplete resection can lead to persistent symptoms or recurrence. Moreover, achieving complete decompression of the nerve root, from the axillary region to the lateral exit zone, without causing excessive disturbance to the surrounding tissues is another critical hurdle. This step is crucial to avoid complications such as nerve injury or excessive bleeding, which can arise from improper handling or misalignment of surgical instruments.[103,104] To mitigate this risk, it is imperative that the positioning needle does not cross the posterior vertebral line during the initial setup.[105]

4) Fusion techniques

Complications in minimally invasive fusion techniques differ from those in decompression, with fusion facing unique hardware issues such as cage or pedicle screw misplacement. Each fusion technique presents distinct complications based on the surgical approach and hardware used.[106-110] LLIF's lateral approach poses risks like vascular injury and lumbar plexus damage.[111-116] ALIF is associated with approach-related complications such as retrograde ejaculation and vascular injuries.[117-119]

5) "New" minimally invasive spinal techniques

Currently, there is insufficient evidence to demonstrate the practicality of many new minimally invasive spinal technologies. These techniques, while promising smaller incisions and quicker recovery times, often present challenges such as limited fields of view, making the learning process more difficult. New methods are continually emerging, frequently without comprehensive evidence to support their effectiveness. For instance, Dai et al.[120] developed the dual-door endoscopic channel method (UBED) using a Y-drain from soft plastic tubing for stability and space adjustment, but its effectiveness remains unclear. Similarly, Hamid Abbasi's transfacet oblique lateral lumbar interbody fusion (OLLIF) adapts OLLIF to previously unreachable cases,[121] yet it primarily represents an enhancement of the existing OLLIF technique. Yuhang Ma's mini-open TLIF combines percutaneous pedicle screws with a smaller incision and subperiosteal dissection,[122] differing only slightly from traditional TLIF. Despite these innovations, some experts warn that these less invasive methods can lead to increased complications and longer surgery times.[123]

The evolution of minimally invasive techniques is inevitable. Just as posterior lumbar interbody fusion was initially dismissed in 1944[124] (Henry Briggs and Paul Milligan, are often deemed to do the first posterior interbody fusions) but eventually became a staple in spinal surgery, new minimally invasive techniques might face initial skepticism before achieving widespread acceptance and revolutionary impact. The steep learning curve associated with these techniques necessitates strategies to flatten it, reduce complications, and provide novice surgeons with foresight.

3. How to Shorten Learning Curves for New Minimally Invasive Lumbar Surgeons

New technologies not only drive surgical progress but also ease learning curves and reduce beginner-led complications.[125,126] Navigation systems, for example, can enhance accuracy and reduce radiation exposure in surgeries with limited visibility. Fan et al.[127] found isocentric navigation useful for trajectory planning and puncture guidance, aiding surgical progress. Intraoperative navigation systems improve pedicle screw placement accuracy.[128,129] with Shin et al.[130] finding computer-assisted navigation superior to traditional open techniques. Current systems, like the O-arm's StealthStation, use reference markers for multi-dimensional imaging,[131] while new skin-feature tracking alternatives generate a virtual grid from multi-view image analysis to reduce intraoperative movements.[132] Robotic-assisted techniques further enhance time, accuracy, and radiation exposure reduction.[133-136] Fan et al.[127] describe the expansion of robotic spinal surgery into various endoscopic procedures, guiding discography in percutaneous cervical discectomy.

Apart from using assistive technology, beginners must adequately prepare themselves. This includes visualizing the entire anatomical structure to avoid violating anatomical directions, which requires substantial theoretical knowledge before undertaking procedures. Practice is crucial in developing the necessary mindset and skills for minimally invasive spinal surgery. Studies show that surgeons who practiced beforehand had lower complication rates and learned new techniques faster. Wiese et al.[83] found that microdiscectomy requires a training course and extensive supervised surgery. Standardized steps can aid in identifying anatomical landmarks clearly. Ransom et al.[44] noted that practice and mentorship help traditionally trained spine surgeons integrate endoscopy into their practice. They found that performing lumbar endoscopic decompression alongside senior surgeons, identifying endoscopic surgical anatomy through

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video, and simulating surgeries on cadavers were beneficial.

The development of VR and AR offers new avenues for immersive training.[137,138] VR allows for 3-dimensional visualization of anatomical structures, which can be manipulated and repositioned,[139,140] while AR overlays computer-enhanced imaging onto real-world anatomical models.[141] Both simulations enable beginners to practice specific skills in a controlled environment. Studies by Luciano et al.[142] and Gasco et al.[143] show that VR training significantly reduces errors and improves accuracy in procedures like pedicle screw placement.

Beginners need to anticipate and address complications associated with minimally invasive spinal surgery. Comprehensive theoretical knowledge and practical simulation training are essential. For example, CSF leaks are a major hurdle; immediate repair is crucial, yet challenging. Training models, like the perfusion-based simulation used by Buchanan et al.,[144] can significantly reduce the time needed for dura mater repair after CSF leaks.

In summary, we categorize the methods in easing the learning curve into 3 main areas: utilizing assistive technologies, beginners' own efforts to smooth the learning curve, and gaining the ability to handle complications. In addition, access to professional training plays a significant role in easing the learning curve. This underscores the importance of developing professional training programs and training personnel.

4. Limitations

This paper has several limitations. Many studies did not disclose whether surgeons had in-depth training in specific techniques, making it unclear if the surgeons had consistent mindsets and abilities, which raises doubts about the results' accuracy. This raises questions about whether the effects observed by beginners in the included literature are due to the inherent trends of the learning curve itself, which casts doubt on the accuracy of the results. Additionally, the included studies on conversions to open surgery were primarily focused on minimally invasive decompression, with insufficient quantity and quality for comprehensive analysis. As a critical component of the learning curve in minimally invasive surgery, future research should conduct in-depth studies on the indicator of the conversions to open surgery in spinal minimally invasive procedures. In fusion studies, many did not specify the number of segments, making comparisons of surgery times across different segment numbers less accurate. Our use of the Mann-Kendall test for sensitivity analysis showed that surgery time did not vary significantly with the year for the same technique. Due to limited literature on learning curves in minimally invasive spine techniques, we only explored trends in MIS-TLIF, MED, TELD, and lELD. The regression analysis suggests that only TELD shows a correlation between procedure frequency and the rate of reaching proficiency asymptotes. The extensive time span of novice surgical patient operation dates dilutes the concept of frequency, compromising statistical rigor. Furthermore, the lack of patient information prevents defining individual surgery difficulty. Beginners usually face easier surgeries initially, reducing early complications, but as they progress to more complex cases, complication rates may increase.[145] Some studies showed higher complication rates in the later stages of training. This underscores the need for RCTs to ensure scientific rigor and prevent varying difficulty levels from affecting learning curves.[123] Despite the challenges, future research must prioritize high-quality RCTs for meaningful results.

CONCLUSION

Our research explored the learning curve of minimally invasive lumbar surgery by analyzing surgical duration, conversion rates to open surgery, and complications. The findings indicate that while minimally invasive surgery offers significant benefits, it also presents a steep learning curve with unique challenges. Complication rates vary across different techniques: discectomy, decompression, and fusion each have distinct risks. Fusion techniques often face hardware-related complications, whereas discectomy and decompression pose challenges due to their differing surgical approaches. The evolution of minimally invasive lumbar surgery introduces both opportunities and challenges, necessitating a balance between technological advancements and comprehensive training. Tailored strategies and further research are essential to optimize outcomes and ensure surgeon proficiency. It is noteworthy that exploring higher-quality RCTs and standardized training programs related to the learning curve of minimally invasive spinal surgery are key to shortening the learning curve for beginners.

NOTES

Supplementary Materials: Supplementary data, Tables 1-3, and Fig. 1 can be found via https://doi.org/10.14245/ns.2448838.419.

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ORCID

Kun Wu: 0000-0001-9049-4072
Zhihe Yun: 0000-0002-9447-6987
Siravich Suvithayasiri: 0000-0001-5597-701X
Yihao Liang: 0009-0004-5674-4241
Dimas Rahman Setiawan: 0009-0007-5373-9625
Vit Kotheeranurak: 0000-0002-9593-429X
Khanathip Jitpakdee: 0000-0003-2533-6398
Enrico Giordan: 0000-0002-8863-116X
Qinyi Liu: 0000-0001-8012-3147
Jin-Sung Kim: 0000-0001-5086-0875

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Supplementary Data.

Search Strategy

PubMed (487)

((((Learning Curve[Title/Abstract]) OR (Curve, Learning[Title/Abstract])) OR (Learning Curves[Title/Abstract]))) AND ((((((((((((((lumbar spine[Title/Abstract]) OR (Lumbar Vertebrae[Title/Abstract])) OR (Vertebrae, Lumbar[Title/Abstract])) OR (spine[Title/Abstract])) OR (Vertebral Column[Title/Abstract])) OR (Column, Vertebral[Title/Abstract])) OR (Columns, Vertebral[Title/Abstract])) OR (Vertebral Columns[Title/Abstract])) OR (Spinal Column[Title/Abstract])) OR (Column, Spinal[Title/Abstract])) OR (Columns, Spinal[Title/Abstract])) OR (Spinal Columns[Title/Abstract])) OR (Vertebra[Title/Abstract])) OR (Vertebrae[Title/Abstract]))

Cochrane (48)

#1	MeSH descriptor: [Learning Curve] explode all trees	316
#2	(Curve, Learning):ti,ab,kw OR (Learning Curves):ti,ab,kw	2881
#3	MeSH descriptor: [Lumbar Vertebrae] explode all trees	3857
#4	(Vertebrae, Lumbar):ti,ab,kw OR (lumbar spine):ti,ab,kw	11951
#5	MeSH descriptor: [Spine] explode all trees	6952
#6	(Vertebral Column):ti,ab,kw OR (Column, Vertebral):ti,ab,kw OR (Columns, Vertebral):ti,ab,kw OR (Vertebral Columns):ti,ab,kw OR (Spinal Column):ti,ab,kw	528
#7	(Column, Spinal):ti,ab,kw OR (Columns, Spinal):ti,ab,kw OR (Spinal Columns):ti,ab,kw OR (Vertebra):ti,ab,kw OR (Vertebrae):ti,ab,kw	8658
#8	#1 OR #	2881
#9	#3 OR #4 OR #5 OR #6 OR #7	16628
#10	#8 AND #9	48

Web of Science (1464)

1: ((TS = (Learning Curve)) OR TS = (Curve, Learning)) OR TS = (Learning Curves)

Results: 83892

2: ((((((((((((TS = (Lumbar Vertebrae)) OR TS = (Vertebrae, Lumbar)) OR TS = (lumbar spine)) OR TS = (Spine)) OR TS = (Vertebral Column)) OR TS = (Column, Vertebral)) OR TS = (Columns, Vertebral)) OR TS = (Vertebral Columns)) OR TS = (Spinal Column)) OR TS = (Column, Spinal)) OR TS = (Columns, Spinal)) OR TS = (Spinal Columns)) OR TS = (Vertebra)) OR TS = (Vertebrae) Date

Results: 394022

3: #1 AND #2

Results: 1464

Supplementary Table 1. Risk of bias summary for non-RCTs: reviewers' judgments about each risk of bias item per included non-RCTs

Study	Selection	Comparability	Outcome
Nowitzke[82] 2005	☆☆	☆☆	☆☆☆
Jhala[75] 2010	☆	☆	☆☆☆
Rong[77] 2008	☆	☆	☆☆☆
Marappan[51] 2018	☆	☆☆	☆☆☆
Jain[46] 2020	☆	☆☆	☆☆☆
McLoughlin[79] 2008	☆	☆☆	☆☆☆
Wiese[83] 2004	☆	☆☆	☆☆☆
Chen[37] 2022	☆☆	☆☆	☆☆☆
Lee[80] 2008	☆	☆	☆☆☆
Morgenstern[81] 2007	☆	☆☆	☆☆☆
Son[39] 2021	☆☆	☆☆	☆☆☆
Yang[41] 2020	☆☆	☆☆	☆☆☆
Fleiderman[29] 2023	☆☆	☆☆	☆☆☆
Ransom[44] 2020	☆	☆☆	☆☆☆
Gadjradj[36] 2022	☆☆	☆☆	☆☆☆
Chaichankul[70] 2012	☆	☆☆	☆☆☆
Wu[55] 2016	☆	☆☆	☆☆☆
Tenenbaum[72] 2011	☆	☆☆	☆☆☆
Maayan[28] 2023	☆	☆☆	☆☆☆
Wang[65] 2013	☆	☆☆	☆☆☆
Ahn[61] 2015	☆☆	☆☆	☆☆☆
Xu[62] 2014	☆☆	☆☆	☆☆☆
Son[43] 2020	☆	☆	☆☆☆
Joswig[56] 2016	☆	☆☆	☆☆☆
Wang[71] 2011	☆☆	☆☆	☆☆☆
Hsu[67] 2013	☆	☆☆	☆☆☆
Zelenkov[40] 2020	☆☆	☆☆	☆☆☆
Olinger[27] 2023	☆	☆☆	☆☆☆
Mannion[68] 2012	☆	☆☆	☆☆☆
Ahn[58] 2016	☆	☆☆	☆☆☆
Park[32] 2022	☆☆	☆☆	☆☆☆
Parikh[78] 2008	☆	☆☆	☆☆☆
Nomura[54] 2015	☆	☆	☆☆☆
Lee[53] 2018	☆☆	☆☆	☆☆☆
Lee[49] 2019	☆☆	☆☆	☆☆☆
Park[48] 2019	☆	☆	☆☆☆
Choi[57] 2016	☆☆	☆☆	☆☆☆
Xu[30] 2022	☆	☆☆	☆☆☆
Wu[26] 2023	☆☆	☆	☆☆☆
Sairyo[74] 2010	☆	☆☆	☆☆☆
Lau[73] 2011	☆☆	☆☆	☆☆☆
Kumar[50] 2019	☆☆	☆☆	☆☆☆
Silva[66] 2013	☆☆	☆☆	☆☆☆
Park[59] 2015	☆	☆☆	☆☆☆
Lee[64] 2014	☆	☆☆	☆☆☆
Schizas[76] 2009	☆	☆☆	☆☆☆
Garcia[35] 2022	☆☆	☆☆	☆☆☆
Nandyala[63] 2014	☆☆	☆☆	☆☆☆
Lee[69] 2012	☆☆	☆☆	☆☆☆
Wang[42] 2020	☆	☆☆	☆☆☆
Warren[38] 2021	☆☆	☆☆	☆☆☆
Ng[60] 2015	☆	☆☆	☆☆☆
Jacob[34] 2022	☆☆	☆☆	☆☆☆
Silva[47] 2019	☆	☆☆	☆☆☆
Liu[52] 2018	☆☆	☆☆	☆☆☆
Mirza[33] 2022	☆	☆☆	☆☆☆
Kim[45] 2020	☆☆	☆☆	☆☆☆
Zhao[25] 2023	☆☆	☆☆	☆☆☆
Tan[31] 2022	☆	☆☆	☆☆☆

RCT, randomized controlled trial.

Supplementary Table 2. Mann-Kendall test

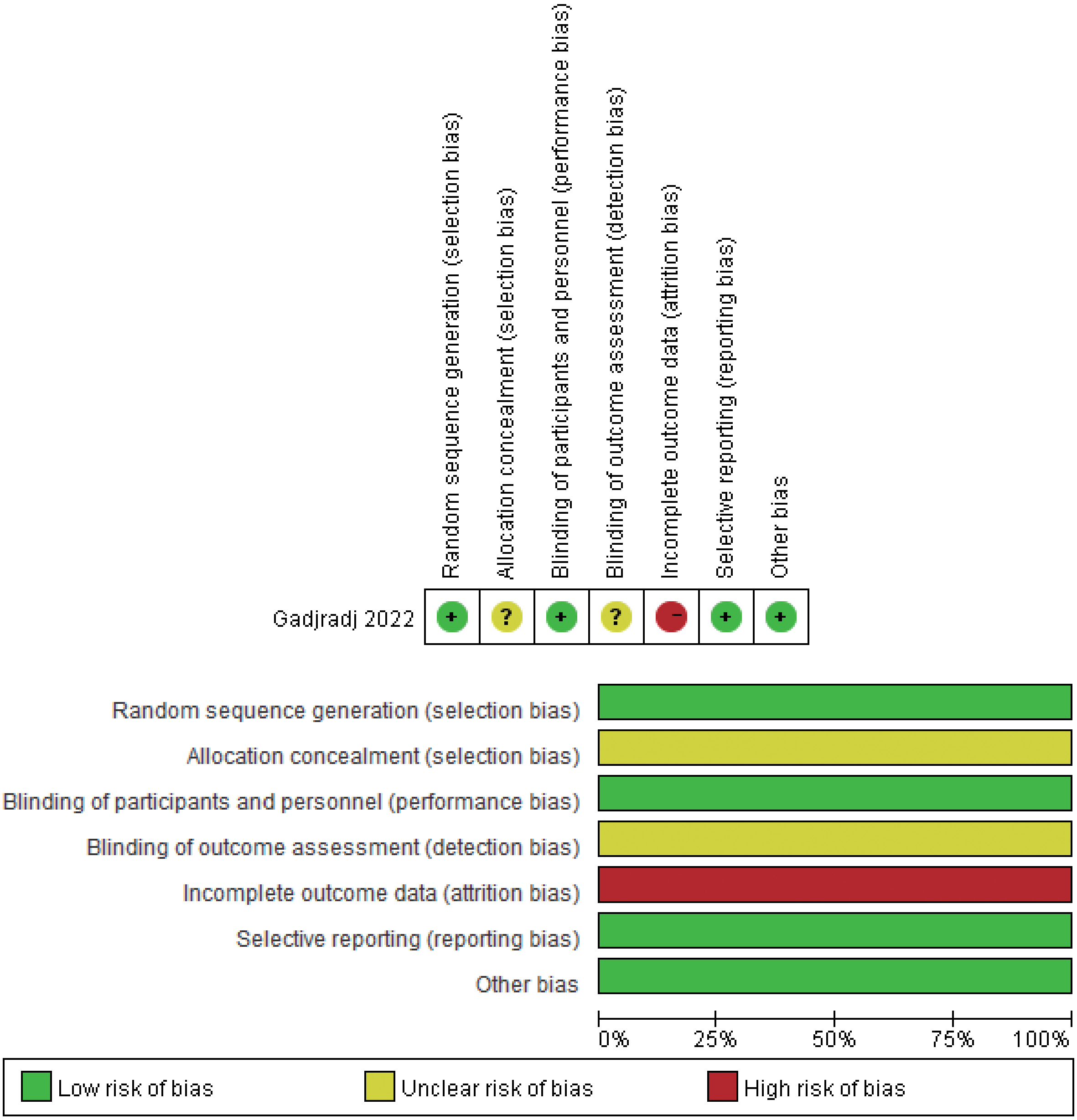
	Z	p-value	tau
TELD			
Early	0.30038	0.7639	0.1428571
Late	0.61478	0.5387	0.2503131
lELD			
Early	-1.1272	0.2597	-0.4666667
Late	0	1.0000	0.06666667
MIS-TLIF			
Early	-0.73485	0.4624	-0.4
Late	-0.24495	0.8065	-0.2

TELD, transforaminal endoscopic lumbar discectomy; lELD, interlaminar endoscopic lumbar discectomy; MIS-TLIF, minimally invasive surgery transforaminal lumbar interbody fusion.

Supplementary Table 3. Regression analysis

	Logistic regression		Analysis of variance
	R^2	Adjusted R^2	Significance F
MED	0.254	-0.120	0.497
TELD	0.725	0.657	0.031
lELD	0.172	-0.241	0.585
MIS-TLIF	0.548	0.322	0.260

MED, microendoscopic discectomy; TELD, transforaminal endoscopic lumbar discectomy; lELD, interlaminar endoscopic lumbar discectomy; MIS-TLIF, minimally invasive surgery transforaminal lumbar interbody fusion.



Supplementary Fig. 1. Risk of bias for randomized controlled trial.