Navigation-assisted vs robot-assisted unilateral biportal endoscopic lumbar interbody fusion for single-level lumbar degenerative disease: a retrospective comparative study

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KEY WORDS

lumbar degenerative disease, navigation--assisted, robot--assisted, unilateral biportal endoscopic lumbar interbody fusion

ABSTRACT

INTRODUCTION Lumbar degenerative disease (LDD) is increasingly common, and causes back and leg pain that impairs quality of life. Lumbar interbody fusion (LIF) is effective for patients with neural compression and segmental instability. Unilateral biportal endoscopic LIF (UBE-LIF) allows for minimally--invasive decompression and fixation, while navigation- and robot-assisted systems improve pedicle screw accuracy and intraoperative guidance.

AIM This study compared perioperative outcomes and clinical efficacy of navigation-assisted vs robot--assisted single-level UBE-LIF.

MATERIALS AND METHODS Patients with single-level LDD who underwent navigation-assisted (Na group; n = 23) or robot-assisted (Ra group; n = 29) UBE-LIF between January 2020 and December 2024 were retrospectively enrolled. Clinical outcomes were assessed using the Numeric Rating Scale, Oswestry Disability Index, and modified MacNab criteria. Pedicle screw placement and radiological parameters, including disc height, lumbar lordosis, and segmental lumbar lordosis, were evaluated, and IF was assessed at 12 months postoperatively.

RESULTS Endoscopic operative time was shorter in the Na group than in the Ra group (116.74 vs 127.86 min; $P = 0.03$), whereas screw insertion time and pedicle screw placement were superior in the Ra group (39.55 vs 46.52 min; $P = 0.001$ and 98.5% vs 92.4%; $P = 0.04$, respectively). Both groups showed comparable improvements in clinical outcomes, radiological parameters, and fusion rates, with similarly low complication rates.

CONCLUSIONS Navigation- and robot-assisted UBE-LIF are safe and effective procedures. Robot-assisted surgery offers higher screw accuracy and faster insertion, while the navigation-assisted approach reduces endoscopic operating time. Clinical outcomes and fusion rates between the 2 techniques are similar.

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INTRODUCTION With the acceleration of global population aging, the prevalence of lumbar degenerative disease (LDD) has continued to increase.[1-3] This condition is typically characterized by low back pain, radiating pain in the lower extremities, and intermittent claudication, all of which substantially impair patients' quality of life.[4] For individuals with significant neural compression and segmental instability, lumbar interbody fusion (LIF) was demonstrated to be an effective surgical treatment.[5-7] In recent years, with the widespread adoption of minimally-invasive spine surgery approaches, unilateral biportal endoscopic LIF (UBE-LIF) has been increasingly applied in clinical practice.[8,9] This technique utilizes independent viewing and working portals, allowing for neural decompression, intervertebral disc space preparation, and endplate management to be performed under direct endoscopic visualization, followed by percutaneous pedicle screw placement.[10,11] Previous studies have shown that UBE-LIF provides clinical outcomes comparable

to those of conventional open fusion procedures, while offering advantages, such as reduced soft tissue injury, lesser postoperative low back pain, and faster patient recovery; consequently, this technique has attracted increasing attention.[12,13]

In recent years, navigation-assisted technologies and robot-assisted systems have been widely utilized in spinal surgery.[14,15] Three-dimensional (3D) navigation technology not only facilitates accurate pedicle screw placement but also provides real-time 3D spatial localization during several critical steps of UBE endoscopic procedures, including the establishment of viewing and working portals, intraoperative real-time guidance, and determination of the extent of decompression.[16] This helps surgeons reduce loss of orientation, avoid unnecessary tissue injury, and improve operative efficiency. In addition, robotic systems enable intelligent preoperative planning of screw trajectories, and achieve stable, precise execution through robotic arms, thereby effectively reducing pedicle screw placement errors, improving implantation accuracy, decreasing intraoperative radiation exposure, and ultimately enhancing the overall safety and efficiency of the procedure.[17]

Although navigation and robotic technologies have been widely applied in spinal surgery, most existing studies have focused on comparisons with conventional fluoroscopy-guided techniques. Direct comparative evidence between navigation- and robot-assisted approaches in single--level UBE-LIF procedures remains limited.

AIM This study compared the perioperative outcomes and clinical efficacy of navigation-assisted vs robot-assisted single-level UBE-LIF, focusing on surgical parameters, screw placement accuracy, and short-term radiological and functional outcomes in patients with LDD to inform surgical technique selection and optimize clinical practice.

MATERIALS AND METHODS

Patient selection This study retrospectively collected data of patients with LDD, who underwent surgical treatment at our institution between January 2020 and December 2024. The patients were allocated to the navigation-assisted group (Na group; n = 23) or the robot-assisted group (Ra group; n = 29) according to the treatment modality selected. The inclusion criteria were as follows: 1) age below 60 years; 2) a preoperative diagnosis of single-level LDD confirmed on radiography, computed tomography (CT), or magnetic resonance imaging, including lumbar spinal stenosis, lumbar disc herniation with segmental instability, or degenerative spondylolisthesis (grade I–II according to the Meyerding classification); 3) persistent low back pain, with or without radiation to the lower extremities, neurological deficits, or intermittent claudication, with symptoms consistent with the radiologically identified responsible segment; 4) failure of systematic conservative treatment for more than 3 months or progressive worsening of symptoms; 5) treatment with navigation- or robot-assisted UBE-LIF; and 6) minimum 12-month follow-up. The exclusion criteria comprised: 1) multilevel lumbar pathology involving the index segment; 2) a history of surgery at the operative level; 3) lumbar spondylolisthesis of Meyerding grade III or higher; 4) severe spinal deformity or severe osteoporosis; 5) lumbar disorders caused by nondegenerative etiologies, such as trauma, infection, or tumors; 6) severe comorbidities involving the heart, lungs, liver, or kidneys, that precluded surgical tolerance; and 7) incomplete follow-up data or loss to follow-up resulting in missing key clinical or radiological information.

Surgical techniques Navigation-assisted group After induction of general anesthesia, the patient was positioned prone, with a U-shaped cushion placed under the abdomen to reduce abdominal pressure and fully expose the target intervertebral level. Two 2-mm Kirschner wires were percutaneously inserted to a depth of approximately 2 cm into the contralateral posterior superior iliac spine, and a navigation reference frame equipped with 4 infrared reflective markers was then secured. Subsequently, a 3D C-arm scan was performed, and the imaging data were automatically transferred to the navigation system (StealthStation S7, Medtronic, Minneapolis, Minnesota, United States or Intelligent SpinePecker, Hicren, Ningbo, China). After image registration was completed, the surgeon used the real-time navigation interface in combination with a virtual probe to localize and mark the skin projection points of the viewing and working portals. The skin and fascia were incised, and the paraspinal muscles were bluntly separated using sequential dilators. After fluoroscopic confirmation of accurate positioning, a working cannula was inserted. A high-speed drill and Kerrison rongeurs were used to remove the inferior edge of the cranial lamina, thereby exposing the proximal attachment of the ligamentum flavum. The inferior articular process of the cranial vertebra and the superior articular process of the caudal vertebra were then addressed. After clear exposure of the medial wall of the ipsilateral pedicle, a navigation probe was used to confirm adequate ipsilateral decompression, and the ipsilateral ligamentum flavum was completely resected. When contralateral decompression was required, the base of the spinous process, the contralateral lamina, and the lateral recess were addressed, the contralateral ligamentum flavum was removed, and adequate decompression of the medial wall of the contralateral pedicle was confirmed using a probe. A nerve root retractor was used to gently mobilize the nerve root and dura medially, allowing exposure and removal of the herniated nucleus pulposus. The annulus fibrosus was incised with a scalpel, and the intervertebral space was distracted using an interbody spreader, followed by thorough endplate preparation with curettes.

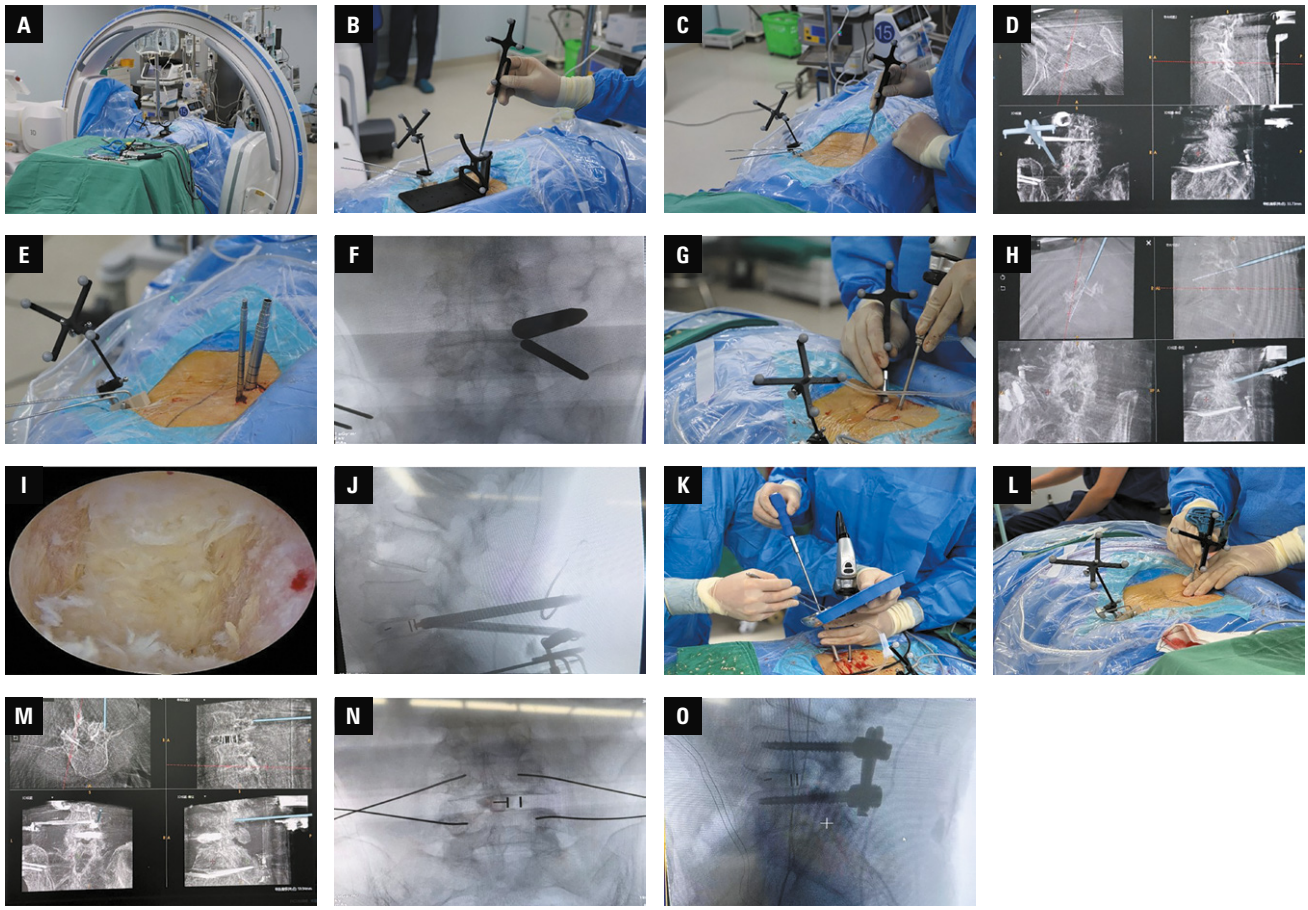

FIGURE 1 Navigation-assisted unilateral biportal endoscopic lumbar interbody fusion procedure; **A**, **B** – preoperative 3-dimensional scanning and navigation registration; **C**–**F** – establishment of the observation and working channels under navigation guidance, with satisfactory positioning confirmed on fluoroscopy; **G**, **H** – intraoperative real-time monitoring of instrument positioning using a virtual probe; **I**–**K** – intervertebral space preparation and placement of the cage, with satisfactory positioning confirmed on fluoroscopy, followed by interbody bone grafting; **L**–**N** – guidewire insertion under navigation, with correct placement confirmed on fluoroscopy; **O** – completion of pedicle screw insertion, with satisfactory alignment confirmed on fluoroscopy

Subsequently, a mixture of autologous bone and bone substitute was packed into the intervertebral space through a bone graft funnel, and an interbody cage was implanted. After fluoroscopic confirmation of satisfactory cage placement, the endoscope was reinserted to remove any residual bone fragments within the spinal canal, and to verify the integrity of the dural sac and the pulsation of the nerve roots. Considering that cage insertion may cause relative vertebral displacement, a repeat 3D C-arm scan was performed to update navigation registration. Under navigation guidance, guidewires were precisely placed, and, after fluoroscopic confirmation of ideal trajectories, bilateral pedicle screws were inserted along the guidewires and connected with rods. Final fluoroscopy confirmed satisfactory positioning of the instrumentation and interbody cage. Hemostasis was then thoroughly achieved, a drainage tube was placed, and the incision was closed in layers (**FIGURE 1**).

Robot-assisted group After successful induction of general anesthesia, the patient was positioned prone with the abdomen supported on a U-shaped cushion to reduce intra-abdominal pressure and fully expose the target intervertebral level. Under conventional fluoroscopic guidance, endoscopic decompression of the spinal canal, nerve root release, and intervertebral space preparation were performed sequentially, following the same surgical approach and workflow as in the Na-group. Once interbody bone grafting and cage implantation were completed, 2 Kirschner wires (2 mm each) were percutaneously inserted into the contralateral posterior superior iliac spine to secure a reference frame equipped with 4 infrared reflective markers. A 3D intraoperative C-arm scan was then performed, with imaging data transmitted in real time to the navigation and robotic system (TiRobot, Tinavi Medical Technologies, Beijing, China). Based on the system-generated 3D reconstruction, the surgeon planned optimal pedicle screw trajectories. The robotic arm was then activated to automatically position at the entry points. Under physical guidance of the robotic sleeve, 4 guidewires were percutaneously inserted. After fluoroscopic confirmation of satisfactory guidewire placement, bilateral pedicle screws were sequentially inserted along the guidewires and connected with longitudinal rods. Final fluoroscopy confirmed proper positioning of

TABLE 1 Baseline demographic and clinical characteristics of the study patients

Characteristic		Navigation-assisted group (n = 23)	Robot-assisted group (n = 29)	*P* value
Age, y		66.74 (6.72)	68.45 (7.06)	0.38
Sex	Men	8 (34.8)	13 (44.8	0.46
	Women	15 (65.2)	16 (55.2)	
Body mass index, kg/m^2		25.35 (2.81)	24.48 (3.38)	0.28
Comorbidities	Hypertension	5 (21.7)	8 (27.6)	0.63
	Diabetes	7 (30.4)	11 (37.9)	0.57
Operation level	L3/L4	3 (13)	4 (13.8)	0.73
	L4/L5	15 (65.2)	16 (55.2)	
	L5/S1	5 (21.7)	9 (26.9)	
Diagnosis	Lumbar spinal stenosis	10 (43.5)	15 (51.7)	0.71
	Lumbar disc herniation	6 (26.1)	8 (27.6)	
	Degenerative lumbar spondylolisthesis	7 (30.4)	6 (20.7)	

Data are presented as mean (SD) or number (percentage).

TABLE 2 Perioperative parameters and surgical outcomes in the navigation-assisted and robot-assisted groups

Parameter	Navigation-assisted group (n = 23)	Robot-assisted group (n = 29)	*P* value
Endoscopic operative time, min	116.74 (13.84)	127.86 (20.47)	0.03
Screw insertion time, min	46.52 (7.69)	39.55 (6.87)	0.001
Total operative time, min	194.01 (23.45)	199.28 (19.12)	0.33
Estimated blood loss, ml	141.43 (13.86)	147.17 (14.91)	0.16
Hospitalization time, d	8.09 (1.78)	7.41 (1.66)	0.17
Total complication rate, n (%)	3 (13)	2 (6.9)	0.46

Data are presented as mean (SD) unless indicated otherwise.

the instrumentation and cage. Hemostasis was thoroughly achieved, a drainage tube was placed, and the incision was closed in layers.

Data collection This study systematically collected the patients' demographic data, including age, sex, body mass index, prior medical history, operative levels, and other relevant characteristics, and simultaneously recorded perioperative parameters, such as operative time, estimated blood loss, hospitalization time, and complications, among others. All patients were followed clinically for at least 12 months, with assessments conducted preoperatively, at 1 and 6 months postoperatively, and every 6 months thereafter. During follow-up, clinical outcomes were evaluated using the Numeric Rating Scale (NRS) and the Oswestry Disability Index (ODI), and the overall surgical effectiveness was assessed at the final follow-up according to the modified MacNab criteria. In radiological assessment, postoperative pedicle screw placement was evaluated on axial CT images and graded according to the Gertzbein–Robbins classification, with grades A and B considered satisfactory.[18] Postoperative radiological parameters included disc height (DH) of the surgical segment, lumbar lordosis (LL), and segmental lumbar lordosis (SLL). DH was defined as the average of the anterior and posterior intervertebral space heights, LL was defined as the Cobb angle between the superior endplate of L1 and the superior endplate of S1, and SLL was defined as the Cobb angle between the superior endplate of the upper vertebra and the inferior endplate of the lower vertebra of the surgical segment.[18,19] At 12 months postoperatively, IF was assessed on CT according to the Bridwell fusion grading system, with grades I and II considered successful fusion.[20]

Statistical analysis All statistical analyses were performed using SPSS Statistics software, version 25.0 (IBM Corp., Armonk, New York, United States). Continuous variables were expressed as mean (SD) or median with interquartile range (IQR), and categorical variables were presented as frequencies and percentages. Between-group comparisons of continuous variables were conducted using the independent-samples *t* test or the Mann–Whitney test, whereas categorical variables were compared using the χ^2 test or the Fisher exact test. Within-group comparisons between the preoperative and final follow-up measurements were performed using the paired-samples *t* test. All statistical tests were 2-sided, and a *P* value below 0.05 was considered significant.

Ethics This retrospective study was approved by the Ethics Committee of Beijing Shijitan Hospital,

TABLE 3 Radiological parameters before and after surgery in the navigation-assisted and robot-assisted groups

Parameter		Navigation-assisted group (n = 23)	Robot-assisted group (n = 29)	*P* value
DH, mm	Preoperatively	7.01 (1.32)	7.37 (1.03)	0.28
	12 months postoperatively	10.95 (1.42)	11.52 (1.39)	0.15
LL, °	Preoperatively	37.74 (9.37)	35.25 (7.65)	0.3
	12 months postoperatively	42.15 (6.37)	40.14 (4.02)	0.17
SLL, °	Preoperatively	6.67 (1.97)	7.26 (2.15)	0.32
	12 months postoperatively	11.79 (1.39)	12.29 (1.28)	0.19
Screw assessment (Gertzbein–Robbins classification)	A	72 (78.3)	104 (89.7)	–
	B	13 (14.1)	10 (8.6)	–
	C	6 (6.5)	2 (1.7)	–
	D	1 (1.1)	0	–
	Satisfactory screw placement (A+B), n (%)	85 (92.4)	114 (98.3)	0.04
Fusion rate (Bridwell fusion grading system)	Grade I	16 (69.6)	22 (75.9)	–
	Grade II	4 (17.4)	4 (13.8)	–
	Grade III	2 (8.7)	3 (10.3)	–
	Grade IV	1 (4.3)	0	–
	Successful fusion, n (%)	20 (87)	26 (89.7)	0.76

Data are presented as mean (SD) unless indicated otherwise.

Abbreviations: DH, disc height; LL, lumbar lordosis; SLL, segmental lumbar lordosis

Capital Medical University (IIT2024-035-003), and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to surgery.

RESULTS Demographic characteristics of the patients are summarized in **TABLE 1**. No differences were observed between the groups in terms of age, sex, surgical level, or other baseline variables. Regarding surgery-related parameters, there were no differences in total operative time, estimated blood loss, or length of hospital stay; however, the endoscopic operating time was markedly shorter in the Na group than the Ra group (116.74 vs 127.86 min; $P = 0.03$), whereas the screw insertion time was shorter in the Ra group (39.55 vs 46.52 min; $P = 0.001$). The overall complication rate was 6.9% in the Ra group and 13% in the Na group, with no difference between them. Specifically, 2 dural tears and 1 transient lower-extremity sensory disturbance occurred in the Na group, while 1 dural tear and 1 transient lower-extremity sensory disturbance were observed in the Ra group; all patients achieved satisfactory symptom relief after standardized conservative treatment (**TABLE 2**).

Radiological results showed no differences between the 2 cohorts in terms of preoperative DH, LL, or SLL. At 12 months postoperatively, all of the above parameters were improved, as compared with preoperative values in both groups; however, no significant intergroup differences were observed. According to the Gertzbein–Robbins classification, a total of 116 pedicle screws were placed in the Ra group (104 grade A, 10 grade B, and 2 grade C screws), whereas 92 screws were placed in the Na group (72 grade A, 13 grade B, 6 grade C, and 1 grade D screw). The rate of satisfactory screw placement was slightly higher in the Ra group than the Na group (98.3% vs 92.4%; $P = 0.04$). In addition, the fusion rate was 89.7% in the Ra group and 87% in the Na group, with no significant intergroup differences (**TABLE 3**).

Regarding clinical efficacy, both cohorts demonstrated postoperative improvements in NRS back and leg pain, as well as ODI scores, in comparison with preoperative values ($P < 0.001$). At all postoperative follow-up time points, no intergroup differences were observed in NRS back pain, NRS leg pain, or ODI scores (**FIGURE 2**). At the final follow-up, clinical satisfaction assessed using the modified Macnab criteria showed an excellent/good rate of 86.2% in the Ra group, including 17 excellent and 8 good cases, and 82.6% in the Na group, with 13 excellent and 6 good cases, and no significant differences between the cohorts (**TABLE 4**).

DISCUSSION With the rapid advancement of spine surgery, navigation and robotic technologies have been increasingly and widely applied in this field.[21,22] Previous studies have separately investigated the advantages of navigation- or robot-assisted techniques over conventional fluoroscopy-guided surgery in terms of safety, accuracy, and radiation exposure[23-26]; however, studies directly comparing navigation and robotic technologies in UBE-LIF for the treatment of LDDs remain scarce. Therefore, the present study was designed to compare the clinical outcomes and surgery-related characteristics of these 2 assistive modalities in single-level UBE-LIF procedures.

UBE-LIF is a minimally-invasive fusion technique in which neural decompression, IF, and internal fixation are performed under direct endoscopic visualization.[27] In comparison with traditional

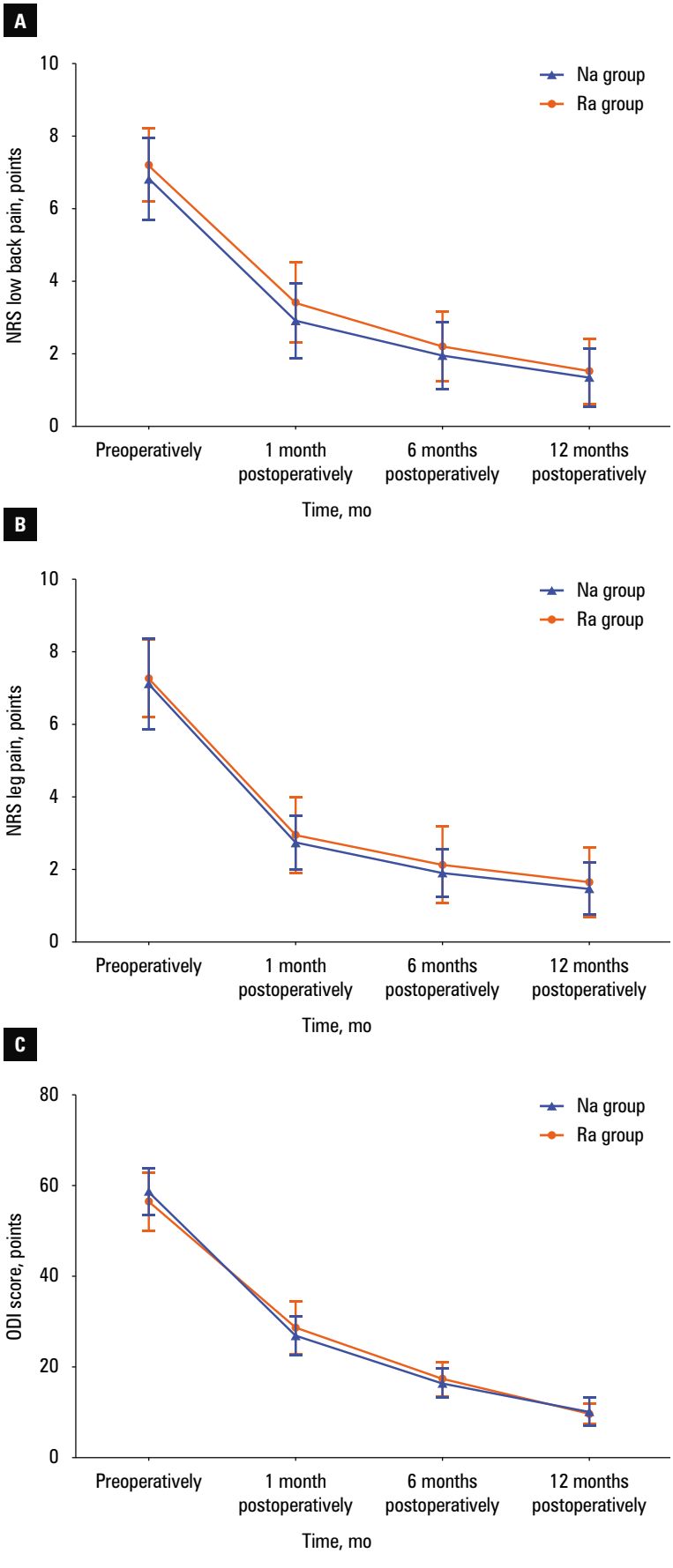

FIGURE 2 Pre- and postoperative NRS and ODI scores in the groups; **A**, **B** – NRS scores for low back (**A**) and leg (**B**) pain before surgery and at follow-up; **C** – ODI scores before surgery and at follow-up

Abbreviations: NRS, Numeric Rating Scale; ODI, Oswestry Disability Index

posterior LIF, UBE-LIF can significantly reduce paraspinal muscle injury, decrease intraoperative blood loss, and shorten postoperative hospital stay, while achieving comparable or even superior clinical outcomes in terms of pain relief and functional improvement.[28-30] The results of this study showed that the endoscopic operating time was relatively shorter in the Na group than the Ra group. This finding suggests that during the decompression phase of UBE-LIF, differences in surgical workflow still exist between the 2 modalities. The advantages of robot-assisted technology in UBE-LIF are primarily reflected in the planning and accuracy of pedicle screw placement, whereas during the actual endoscopic decompression process, the surgeon still relies on intraoperative fluoroscopy to confirm the operative position and extent, which may result in a slightly longer decompression time. In contrast, navigation-assisted technology can provide continuous and intuitive intraoperative references for endoscopic procedures through 3D imaging. During the decompression phase, especially in bilateral decompression, precise control of the decompression range places higher demands on the surgeon.[31] With real-time feedback provided by the navigation system, the surgeon can clearly determine the current position and decompression boundaries on the navigation interface, reducing the need for repeated fluoroscopy and thereby improving the fluency and safety of endoscopic manipulation. Furthermore, in the cases of severe spinal degeneration or pronounced facet hypertrophy, the visualization interface and virtual probe function of the navigation system make endoscopic procedures more intuitive and continuous, which helps enhance decompression efficiency and overall surgical safety.

During the screw placement phase, both the pedicle screw insertion time and placement accuracy were superior in the Ra group, as compared with the Na group, which is generally consistent with prior reports.[32,33] Previous studies have shown that both robot- and navigation-assisted screw placement achieve significantly higher accuracy and operational efficiency than conventional freehand placement under fluoroscopic guidance.[34-36] However, this study further suggests that, between these 2 advanced assistive modalities, robot-assisted system may offer additional advantages in terms of standardization and accuracy of pedicle screw placement, as it can perform intraoperative visualized trajectory planning for pedicle screws and execute the predetermined path precisely through the robotic arm,[37] thereby substantially reducing human error and ensuring more standardized screw trajectories with minimal deviation. In contrast, although navigation--assisted screw placement provides real-time positioning feedback, the actual insertion of the screws still heavily relies on the surgeon's manual operation, with potential errors primarily arising from operative stability and variations in surgical experience. Therefore, in this highly standardized and precision-demanding phase of the procedure,

TABLE 4 Clinical outcomes in the navigation-assisted and robot-assisted groups

Outcome		Navigation-assisted group (n = 23)	Robot-assisted group (n = 29)	*P* value[a]
NRS low back pain score, points	Preoperatively	6.83 (1.15)	7.21 (1.01)	0.21
	1 month postoperatively	2.91 (1.04)	3.41 (1.12)	0.11
	6 months postoperatively	1.96 (0.93)	2.21 (0.98)	0.35
	12 months postoperatively	1.45 (0.83)	1.52 (0.91)	0.49
	P value[b]	<0.001	<0.001	–
NRS leg pain score, points	Preoperatively	7.13 (1.25)	7.28 (1.07)	0.65
	1 month postoperatively	2.74 (0.75)	2.97 (1.05)	0.39
	6 months postoperatively	1.91 (0.67)	2.14 (1.06)	0.38
	12 months postoperatively	1.58 (0.74)	1.66 (0.97)	0.47
	P value[b]	<0.001	<0.001	–
ODI score, points	Preoperatively	58.78 (5.32)	56.59 (6.43)	0.19
	1 month postoperatively	26.96 (4.34)	28.76 (5.87)	0.26
	6 months postoperatively	16.52 (3.26)	17.45 (3.74)	0.35
	12 months postoperatively	10.26 (3.21)	9.72 (2.43)	0.49
	P value[b]	<0.001	<0.001	–
Surgical effectiveness (modified MacNab criteria)	Excellent	13 (56.5)	17 (58.6)	–
	Good	6 (26.1)	8 (27.6)	–
	Fair	3 (13)	4 (13.8)	–
	Poor	1 (4.3)	0	–
	Excellent/good, n (%)	19 (82.6)	25 (86.2)	0.72

Data are presented as mean (SD) unless indicated otherwise.

a Independent samples *t* test (intergroup comparisons)

b Paired samples *t* test (intragroup comparisons of preoperative and final follow-up values)

Abbreviations: see **FIGURE 2**

robot-assisted technology may be more effective in enhancing both the efficiency and accuracy of the screw placement.

Previous studies have reported that the complication rate after fluoroscopy-guided UBE-LIF ranged from approximately 5% to 12%.[38,39] In the present study, the complication rates observed in both groups were within the ranges reported in the literature, suggesting that, with standardized surgical protocols and appropriate patient selection, both assistive modalities can achieve an acceptable level of safety in UBE-LIF procedures. Regarding clinical outcomes, the results of this study showed that both groups experienced marked postoperative improvements in NRS and ODI scores, as compared with preoperative values, while no significant intergroup differences were observed. This finding indicates that both robot- and navigation-assisted techniques can achieve satisfactory short-term clinical outcomes in UBE-LIF procedures. Further radiological evaluation showed that postoperative DH, LL, and SLL were all notably improved in comparison with preoperative values in both groups, with no differences between them. These findings are generally consistent with previous studies,[40,41] suggesting that both robot- and navigation-assisted techniques achieve comparable effectiveness in restoring DH, improving sagittal alignment parameters, and maintaining short-term radiological stability. Moreover, previous studies have reported satisfactory fusion rates after UBE-LIF,[30,42] and the fusion outcomes in both groups in this study were generally consistent with these reports, further supporting the feasibility of achieving reliable fusion and radiological stability with both assistive modalities in single-level UBE-LIF.

Limitations This study has several limitations. First, it was a single-center retrospective analysis with a relatively small sample size; therefore, multicenter prospective studies with larger cohorts are warranted to validate our findings. Second, the follow-up was relatively short, which precluded a comprehensive assessment of adjacent segment degeneration and long-term fusion stability. Future studies with extended follow-up are needed to provide more robust, long-term outcome data. In addition, although all procedures were performed by surgeons who had completed their learning curves, intersurgeon variability could not be entirely eliminated and may have influenced operative efficiency and screw placement accuracy. Finally, as the surgeons were required to temporarily leave the operating room during 3D C-arm scanning to avoid radiation exposure, precise radiation dose measurements could not be obtained. Future investigations may incorporate more advanced personal radiation monitoring devices, such as wearable dosimeters, to achieve

more accurate assessments of intraoperative radiation exposure.

CONCLUSIONS This study demonstrates that both navigation- and robot-assisted techniques are safe and effective for single-level UBE-LIF in the treatment of LDDs, with comparable short-term clinical and radiological outcomes. Navigation-assisted technology, through intraoperative 3D visualization and real-time spatial feedback, enhances the efficiency of endoscopic decompression, whereas robot-assisted technology shows potential advantages in improving pedicle screw placement efficiency and accuracy. In the future, the integration of navigation and robotic systems may further optimize the UBE-LIF surgical workflow and enhance operative precision and efficiency.

ARTICLE INFORMATION

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CONTRIBUTION STATEMENT JS and SL contributed equally and were primarily responsible for the study design, data collection, and drafting of the manuscript. SY and YZ participated in the study design and contributed to the manuscript review and editing. WL and MY assisted with data analysis and manuscript revision. LD conceived the study, supervised its implementation, and finalized the manuscript. All authors read and approved the final version of the manuscript.

CONFLICT OF INTEREST None declared.

AI STATEMENT Artificial intelligence was not used in the preparation of this manuscript.

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