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Mid-term efficacy of non-contact orthopedic robot navigation in the treatment of lumbar spondylolisthesis

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Abstract

Objective This study was aimed to explore the mid-term efficacy of non-contact orthopedic robot navigation in the treatment of lumbar spondylolisthesis.

Methods The clinical data of young and middle-aged patients with lumbar spondylolisthesis were retrospectively analyzed and divided into an observation group and a control group according to surgical methods. The observation group was treated with minimally invasive transforaminal interbody fusion (MIS-TLIF) combined with orthopedic robot-navigated percutaneous pedicle screw fixation; while the control group underwent traditional posterior lumbar interbody fusion (PLIF). Perioperative indicators, waist and leg pain Visual Analog Scale (VAS) scores, Oswestry Disability Index (ODI), and complications were compared between groups.

Results A total of 32 patients with lumbar spondylolisthesis were included in this study, with the average age of 50.3 ± 2.7 years old. There were 17 patients in the observation group and 15 patients in the control group. Although the new surgical technique for the observation group may require longer operative time, it showed significant advantages in reducing intraoperative bleeding, postoperative drainage, and shortening hospital stay. These benefits might result in faster recovery for patients, reduced risk of complications, and improved overall quality of life. The new technology was also significantly better compared to the traditional method in terms of VAS scores and ODI at 1 week, 1 month, 3 months, and 6 months post-surgery. These results provided patients with better treatment options and potentially a faster path to recovery. One case with infectious incision in the observation group and one case with intraspinal hematoma formation in the control group were observed. However, there was no statistical difference in the complication rates between the two groups ($P > 0.05$).

Conclusion The non-contact orthopedic robot navigation for the treatment of lumbar spondylolisthesis was demonstrated to be minimally invasive, precise, and stable surgical method. It is a treatment option worth considering for suitable patients.

Keywords Spondylolisthesis, Orthopedic robot, MIS-TLIF, Intervertebral fusion

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Introduction

Lumbar spondylolisthesis is a condition caused by the relative displacement of adjacent vertebrae due to various reasons. It can lead to changes in the morphology and volume of the spinal canal, which compresses or stimulates nerve tissue, resulting in symptoms such as low back pain and intermittent claudication [1]. In recent years, the increasing trend of younger patients with lumbar spondylolisthesis has become a significant issue [2]. For patients with lumbar spondylolisthesis who require surgery, the ideal surgical plan should consider multiple factors to ensure full decompression and nerve relief while minimizing surgical trauma and maintaining lumbar spine stability [3]. Transforaminal lumbar interbody fusion (TLIF) and posterior lumbar interbody fusion (PLIF) are two classic procedures that effectively relieve nerve compression and ensure spine stability, but their high surgical trauma and postoperative complications limit their application. To address these issues, these procedures are continuously improved in clinical practice, such as using minimally invasive techniques like minimally invasive surgery - transforaminal lumbar interbody fusion (MIS-TLIF) and unilateral biportal endoscopic technique (UBE) to reduce surgical trauma and complications. Additionally, doctors need to choose the appropriate surgical method based on the patient's specific condition and strictly adhere to aseptic operation principles to reduce complications such as infection [4]. The development of minimally invasive spinal technology in treating traditional spinal diseases is significant, covering aspects such as endoscopic decompression, minimally invasive fusion, and deformity correction. In particular, microscope-assisted MIS-TLIF has been clinically confirmed to have small trauma, fast recovery, and a definite decompression effect [5]. MIS-TLIF combines the advantages of TLIF and PLIF while overcoming their disadvantages, providing better treatment effects and faster recovery times for patients. The improvement and optimization of this classic procedure has demonstrated the progress of medical science and technology, bringing good news to more patients [6]. The Spine Department of our hospital has been attempting innovation and technology integration in minimally invasive spinal surgery, combining robotic technology and navigation systems. A total of 32 related operations have been performed between February 2023 and February 2024, with pedicle screws directly implanted into the pedicle through a small skin incision, thereby improving the accuracy and safety of the operation. The data were collected for retrospective analysis, aiming to explore the mid-term efficacy of non-contact orthopedic robot navigation in the treatment of lumbar spondylolisthesis.

Methods

Patients and grouping

This study was conducted after review by the Ethics Committee of Zhoushan Gu Hechuan Orthopedic Hospital.

Inclusion criteria were as follows: (1) Patients with the first diagnosis of lumbar spondylolisthesis, with a single segment involved as the responsible segment; (2) Patients with the age range of 35–58 years old; (3) Patients with obvious clinical symptoms, but ineffective results following conservative treatment; (4) Patients who were suitable for and accepted MIS-TLIF combined with orthopedic robot navigated percutaneous pedicle screw fixation, or accepted traditional PLIF surgery; (5) Patients who were able to accept follow-up requirements for more than 6 months.

Exclusion criteria were as follows: (1) Patients with trauma, infection or history of lumbar surgery; (2) Patients unable to tolerate general anesthesia or lumbar surgery; (3) Patients with cardiovascular disease or sequelae; (4) Patients with a Cobb angle of more than 25° spinal deformity and bone density T value <-2.5; (5) Patients with severe mental illness.

Patients were divided into the observation group and the control group according to different surgical methods. The observation group underwent MIS-TLIF combined with orthopedic robot navigated percutaneous pedicle screw fixation; while the control group underwent traditional PLIF. Before the start of the study, we obtained informed consent from all patients. This study was approved by the medical ethics committee of the hospital and in accordance with the relevant provisions of medical ethics.

There was no significant difference in gender, age, type of slip, lesion segment, degree of slip, course of disease, and comorbidities between the two groups ($P>0.05$), indicating that the two groups were comparable in terms of baseline data.

Preoperative preparation of patients

After admission, patients first underwent comprehensive blood biochemical examinations to assess their overall physical condition and surgical tolerance. These examinations included, but were not limited to, routine blood tests, liver and kidney function tests, electrolyte balance assessments, and coagulation function tests. To accurately understand the patient's lumbar spondylolisthesis, imaging examinations such as X-ray, computed tomography (CT), and magnetic resonance imaging (MRI) were performed. These examinations provided detailed information about the lumbar structure, the degree of spondylolisthesis, and any possible nerve damage, which served as an important basis for formulating the surgical plan. For patients with hypertension and diabetes,

preoperative drug control was administered to ensure that blood sugar and blood pressure remained stable during the operation, thereby reducing the risk of complications. One hour before the operation, both groups of patients received intravenous infusion of sensitive antibiotics to prevent infection, a routine preventive measure for surgical procedures.

Operation procedure

The operation was conducted under general anesthesia, with the patient positioned in the prone position. The procedure focused on the lumbar L4/5 segment, a common site of involvement in lumbar spondylolisthesis and the location of lesions in most patients in this study.

For the observation group, patients underwent surgical planning through spinal CT scans and data collection before surgery. The project team planned the angle and position of the pedicle screws according to the surgical method. After general anesthesia, the patient was placed in the prone position. The robotic device was installed along with a C-arm fluoroscopy instrument. The robotic device was positioned on the patient's head, and the C-arm machine was used for fluoroscopic scanning. The dual-ring positioning robot automatically adjusted the working robot arm to the planned pedicle screw implantation position based on the fluoroscopic results, and the frontal and lateral positions were again used to confirm the accuracy of the implantation site (Fig. 1A). Four longitudinal incisions were made at the L4 and L5 pedicles through the sleeve, each approximately 1 cm long. Fluoroscopy confirmed that the inner sleeve core was concentric and projected onto the pedicle (Fig. 1B). A Kirschner wire was accurately placed along the inner sleeve core onto the bone of the vertebral body to ensure precise positioning. With the assistance of the orthopedic robot navigation system, four pedicle screws were precisely placed to provide support for subsequent fixation. Two titanium rods were installed and fixed to stabilize the spinal structure. After these steps were completed, the slipped L4 vertebra was repositioned to ensure it was in the normal anatomical position. The L4/5 intervertebral space was located using fluoroscopy, and the needle insertion point was determined to be 2.5 cm from the center of the affected side. Puncture to the L4/5 facet

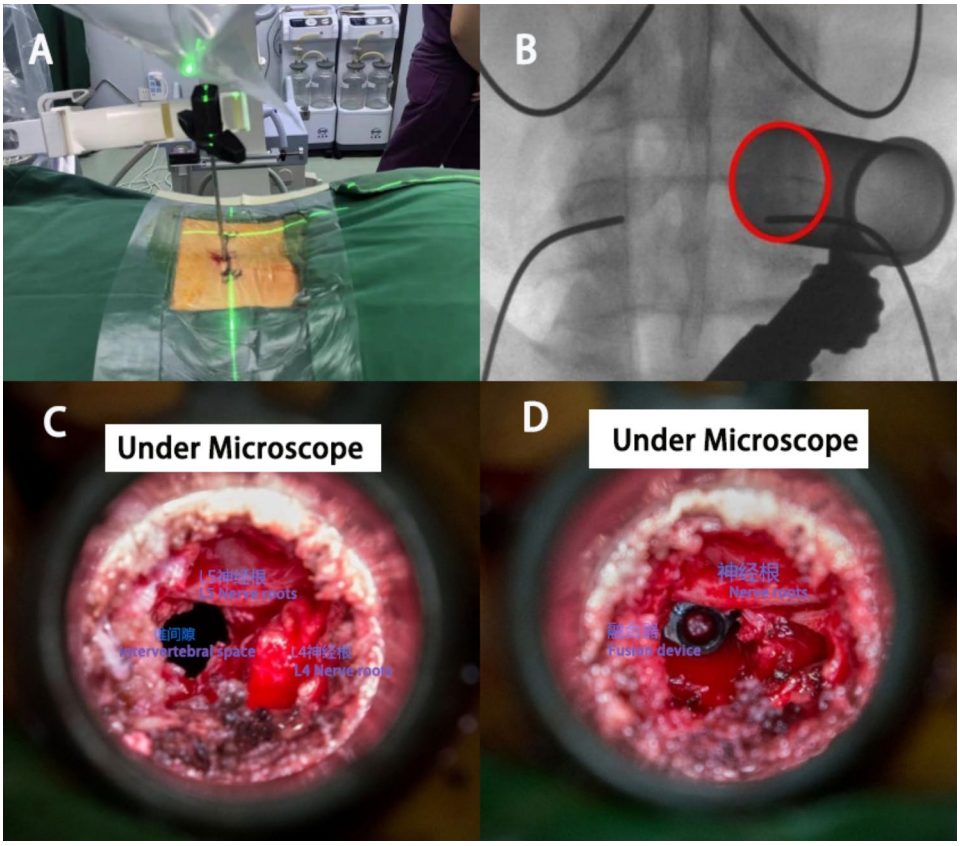

Fig. 1 Representative images during the operation. Captions: **(A)** The dual-ring positioning robot automatically adjusted the working robot arm to the planned pedicle screw implantation position based on the fluoroscopic results, and the frontal and lateral positions were again used to confirm the accuracy of the implantation site; **(B)** Fluoroscopy confirmed that the inner sleeve core was concentric and projected onto the pedicle; **(C)** The endplate cartilage was removed to prepare for the subsequent intervertebral disc implantation; **(D)** The implant was compacted to ensure tight integration with the surrounding bone

joint was performed, and the skin and subcutaneous tissue were longitudinally incised along this path. The incision length was approximately 3.5–4 cm. Special tools were used to expand the soft tissue to create a channel suitable for surgical operation. Under a microscope, an ultrasonic bone knife was used to precisely remove the facet joint of the affected L4/5 side, and the facet and intervertebral foramina were formed. The hyperplastic yellow ligament and part of the L4/5 lamina were removed to further expose the surgical field. After entering the spinal canal, the intervertebral disc, dura mater sac, and nerve roots were carefully examined to ensure there was no damage. The protruding intervertebral disc was exposed and incised, the nucleus pulposus was removed, and the spinal canal and the lateral recess nerve root canal were fully decompressed. The endplate cartilage was removed to prepare for the subsequent intervertebral disc implantation (Fig. 1C). The articular process bone fragments and suitable cages were implanted in the L4/5 intervertebral disc to ensure stability and accurate positioning of the implant. The implant was compacted to ensure tight integration with the surrounding bone (Fig. 1D). The surgical area was rinsed to ensure no residue remained. A multi-hole negative pressure drainage tube was left at the incision to remove postoperative exudate and blood accumulation. The incision was sutured layer by layer to ensure a tight closure and then the operation was completed.

The structure and working interface of the double-ring robot are shown in Fig. 2A and B, intraoperative reduction is shown in Fig. 2C and D, robot-simulated screw placement is shown in Fig. 2E, and incision size is shown in Fig. 2F.

For the control Group, the patient after general anesthesia was placed in the prone position. A longitudinal incision approximately 15 cm long was made along the midline of the waist. The skin, subcutaneous tissue, fascia, and other layers were carefully dissected until the paraspinal muscles on both sides were exposed. The paraspinal muscles were then meticulously peeled away to fully expose the facet joints. A positioning pin was inserted at the estimated L4/L5 pedicle position. A C-arm X-ray fluoroscopy machine was used to verify the interarticular space and confirm the accuracy of the positioning pin. Pedicles on both sides of L4 and L5 were selected, and a total of four pedicle screws were sequentially inserted. Subsequently, two titanium rods were installed to stabilize the spinal structure. With the assistance of the pedicle screws and titanium rods, the L4 vertebral body was reduced. If reduction was challenging, a reduction gun could be used to facilitate the process. The L4 spinous process and L4/5 lamina were removed to better expose the surgical area. According to the patient's symptoms, the medial part of the inferior facet of the L4 vertebra on the side with more severe symptoms and the corresponding medial part of the superior facet of the L5 vertebra were removed to completely decompress the spinal canal and nerve roots. The dura mater sac and nerve roots were gently retracted to the opposite side to fully expose the intervertebral disc (L4/5). The L4/5 annulus fibrosus was cut, the nucleus pulposus was removed, and the endplate cartilage was removed to prepare for the subsequent intervertebral disc implantation. The resected articular process bone fragments and bone blocks containing a suitable cage were implanted into the intervertebral disc to ensure stability and accurate positioning of the implant. The implant was compacted to achieve tight integration with the surrounding bone. After the operation, the surgical area was rinsed with normal saline to ensure no residue remained. A multiporous negative pressure drainage tube was placed at the incision to drain exudate and blood postoperatively. The incision was sutured layer by layer to ensure a tight closure and then the operation was completed.

Postoperative treatment

Antibiotics were routinely administered intravenously for 36 to 48 h after surgery to prevent infection at the surgical site. The drainage tube can be removed 36 to 72 h after surgery, depending on the amount and properties of the drainage fluid. In the early postoperative period, patients were instructed to perform exercises such as ankle pumps and straight leg raises. These exercises helped to promote blood circulation, reduce lower limb swelling, prevent deep vein thrombosis, and strengthen leg muscles. Between 96 and 120 h after surgery, patients may begin wearing a lumbar brace and get out of bed with the guidance and assistance of a doctor. The lumbar brace provided additional support and protection, reducing the load and torsion on the lumbar spine. Patients were required to continue wearing the lumbar brace for 3 to 3.5 months.

Observation indicators

Perioperative indicators included operation time, intraoperative blood loss, postoperative drainage volume, and length of hospital stay. The Visual Analog Scale (VAS) was used to assess waist and leg pain levels before surgery and at 1 week, 1 month, 3 months, and 6 months after surgery. The VAS ranged from 0 to 10, with 0 representing no pain and 10 representing severe pain.: The Oswestry Disability Index (ODI) was employed to evaluate spinal function before surgery and at 1 week, 1 month, 3 months, and 6 months postoperatively. Complications during surgery, such as nerve root canal injury and dural tear, were carefully monitored and documented. Postoperatively, complications like intraspinal hematoma formation and infection were also tracked.

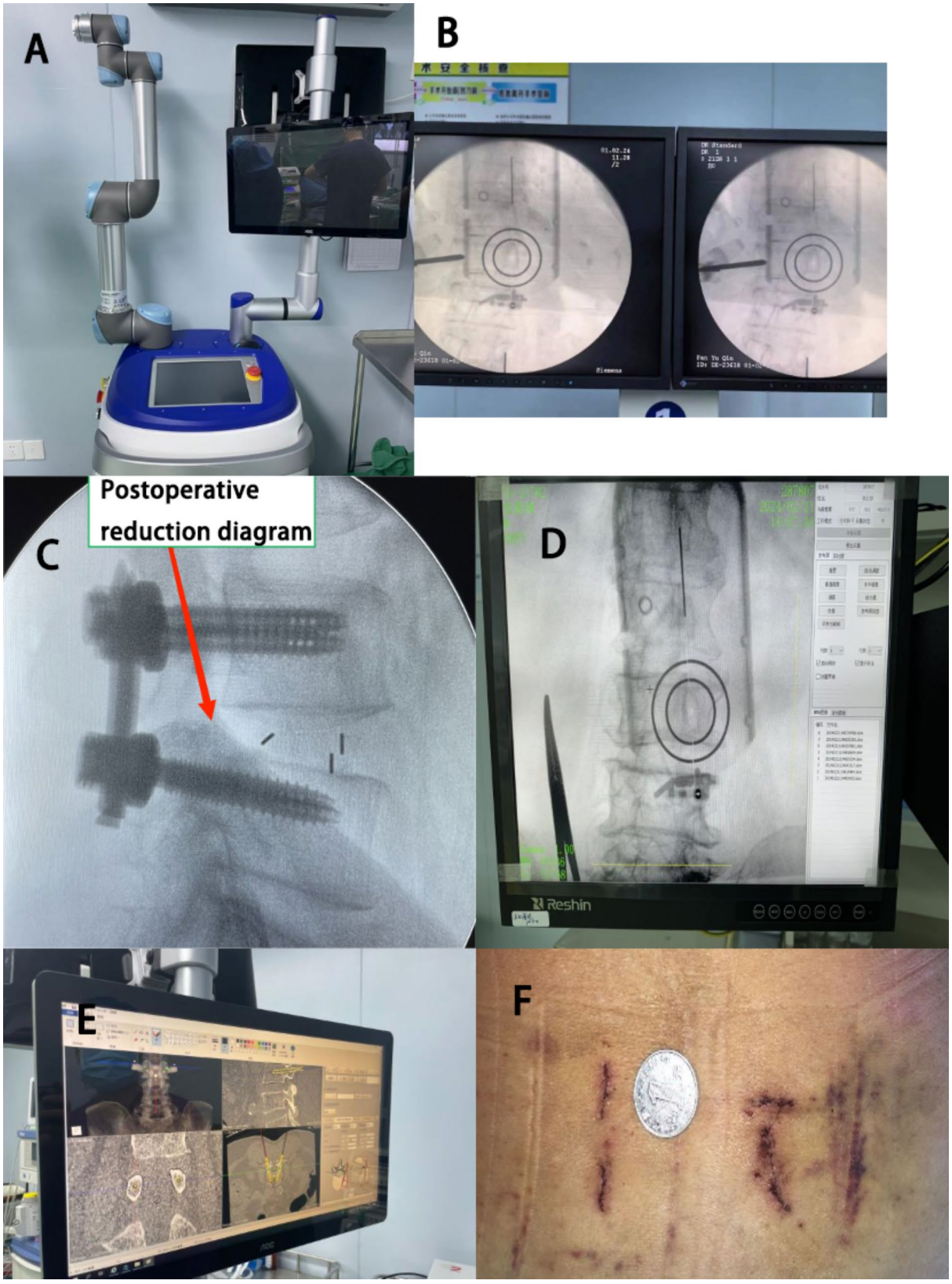

Fig. 2 Representative images of robot structure, system display, intraoperative reduction, and postoperative incisions. Captions: (**A**, **B**) The structure and working interface of the double-ring robot are shown in this figure; (**C**, **D**) intraoperative reduction is shown in this figure; (**E**, **F**) robot-simulated screw placement and incision size are shown in this figure

Table 1 Comparison of basic information of observation and control groups

	Observation group ($n=17$)	Control group ($n=15$)	*P* Value
Number of patients	15	17	
Gender			0.982
Male	8	9	
Female	7	8	
Age range	35–58	37–56	
Average age	50.3 ± 2.7	48.5 ± 2.6	0.065
Slip type			0.946
Degenerative spondylolisthesis	9	10	
Spondylolisthesis caused by isthmic spondylolisthesis	6	7	
Affected segment			0.999
L2/3	1	1	
L3/4	1	1	
L4/5	7	8	
L5/S1	6	7	
Slip degree			0.538
Grade I spondylolisthesis	11	14	
Grade II spondylolisthesis	4	3	
Disease duration	1–12	1–15	
Average disease duration	2.5 ± 1.3	2.4 ± 1.1	0.817
Complications			
Hypertension	3	4	0.810
Diabetes	2	1	0.471

Table 2 Comparison of perioperative indicators between the two groups of patients (mean ± SD)

Group	Case	Surgery Time (min)	Intraoperative Blood Loss (mL)	Postoperative Drainage Volume (mL)	Hospital Stay (d)
Observation group	17	162.6 ± 18.3	87.8 ± 10.8	63.7 ± 20.7	8.2 ± 1.2
Control group	15	104.2 ± 15.9	206.5 ± 25.1	258.1 ± 34.6	11.6 ± 1.5
t value		13.437	23.902	26.622	9.814
P value		<0.001	<0.001	<0.001	<0.001

Immediate intervention was provided upon detection of any complications.

Follow up

Follow-up evaluations included wound healing, pain levels, and spinal function at 1 week, 1 month, 3 months, and 6 months after surgery. Imaging examinations were performed if needed to assess structural changes at the surgical site. A comprehensive follow-up plan and detailed observation indicators ensured a thorough understanding of the patient's recovery, prompt detection and management of complications, and delivery of optimal medical care.

1.5 Statistical methods

Data processing was carried out using SPSS version 22.0 statistical software. Measurement data were expressed as mean ± standard deviation (SD). The chi-square test was used to compare the count data among the groups. Inter-group comparisons were performed using the student's t-test. Countable data were expressed as percentages, and inter-group comparisons were conducted using the Chi-square test. A p-value of less than 0.05 was considered statistically significant.

Results

Comparison of patient characteristics

A total of 32 patients with lumbar spondylolisthesis were included in this study. This study compared perioperative indicators between the observation group and the control group in lumbar spondylolisthesis surgery. Although the operation time was longer in the observation group compared to the control group, the observation group demonstrated significantly better outcomes in terms of intraoperative blood loss, postoperative drainage volume, and length of hospitalization. These differences were statistically significant ($P<0.05$). The details are listed in Table 2 and presented in Fig. 3A, B and C, and 3D.

Low back and leg pain scores

Before surgery, pain levels were similar between the two groups. However, postoperatively, the observation group experienced significantly greater pain relief compared to the control group(2.9 ± 0.9 VS 3.8 ± 1.2, $P<0.01$), with this

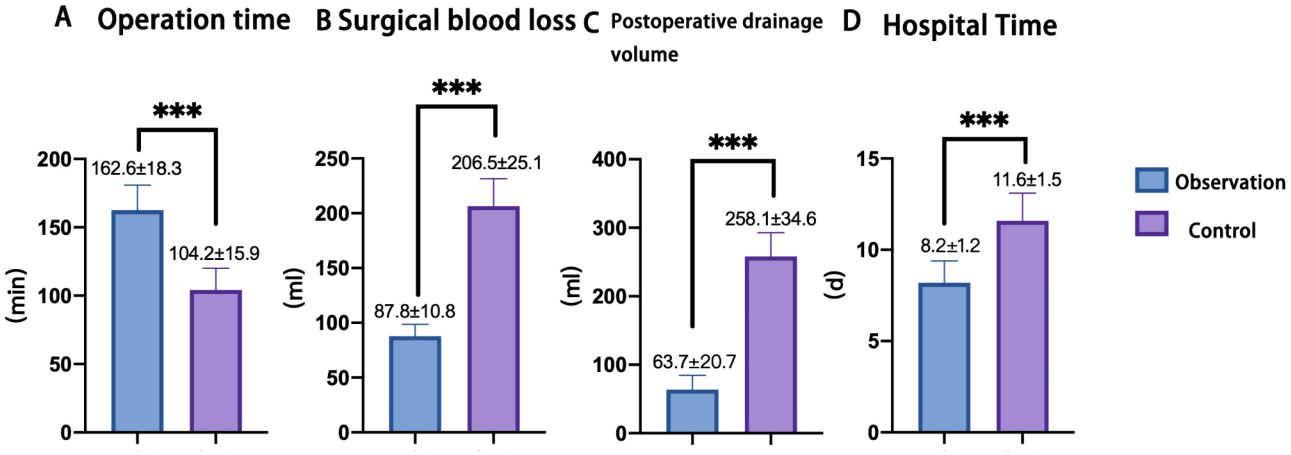

Fig. 3 Comparison of surgical indicators between the two groups. Captions: **(A)** Comparison of surgical duration between the two groups; **(B)** Comparison of intraoperative blood loss, **(C)** Comparison of postoperative drainage volume, **(D)** Comparison of hospital stay. *** $P<0.001$

Table 3 Comparison of VAS scores of low back and leg pain between the two groups of patients before and after surgery (mean ± SD)

Group	Case	Preoperative	1 week after surgery	1 month after surgery	3 months after surgery	6 months after surgery
Observation group	17	6.2 ± 0.6	2.9 ± 0.9	2.3 ± 0.5	1.7 ± 0.6	1.5 ± 0.4
Control group	15	6.0 ± 0.5	3.8 ± 1.2	2.8 ± 1.0	2.2 ± 0.7	1.9 ± 0.7
t value		1.429	3.323	2.464	3.010	2.738
P value		0.156	0.002	0.017	0.004	0.008

advantage sustained from 1 week to 6 months after surgery. This improvement may be attributed to differences in surgical methods, techniques, or postoperative rehabilitation measures. Data supporting these findings are presented in Table 3; Fig. 4A.

Evaluation of spinal function

Prior to surgery, spinal function impairment was comparable between the two groups. After surgery, the observation group showed significantly better spinal function recovery compared to the control group(23.1 ± 2.6 VS 29.2 ± 3.4, $P<0.001$), with this benefit lasting from 1 week to 6 months postoperatively. This difference may be related to variations in surgical methods, techniques, or postoperative rehabilitation strategies. Refer to Table 4; Fig. 4B for detailed results.

Perioperative complications

In the observation group, one patient (5.88%) experienced an incision infection on the first postoperative day. After 2 weeks of treatment with sensitive antibiotics, the infection was controlled and resolved, with no additional complications reported.

In the control group, one patient (6.66%) developed an intraspinal hematoma. The patient received intravenous methylprednisolone (2 g) to reduce inflammation and nerve edema, followed by emergency surgery to evacuate the hematoma. Additional rehabilitation treatments, including nerve nutrition, acupuncture, and electrical stimulation, led to full recovery within 2 weeks. There was no significant difference in the incidence of surgical complications between the two groups ($P>0.05$). The acceptance rate of screw placement in the robot-assisted group was higher than that in the control group (97.06% vs. 93.33%, $p=0.32$), but no significant difference was found statistically, which may be related to the small number of samples included. (Table 5) In both groups of patients, we did not observe loosening of screws and cages, and all patients achieved intervertebral fusion.

Discussion

Lumbar spondylolisthesis results in complex alterations in spinal canal morphology, involving several abnormal changes in lumbar structures. These changes include intervertebral disc degeneration, increased protrusion, loss of intervertebral height, significant sagittalization of articular processes, and compensatory hyperplasia of articular process joints, surrounding joint capsules, and yellow ligaments. Such alterations impact lumbar spine stability and may compress nerve tissues, leading to severe symptoms like irritation or compression of the dura mater sac, cauda equina, and sacral nerves. Therefore, timely diagnosis and treatment are essential for managing lumbar spondylolisthesis [7]. The lumbar spine, bearing the body's heaviest load and frequently involved in various activities, is prone to degeneration due to its complex anatomy. Structures such as articular process joints, joint capsules, and yellow ligaments

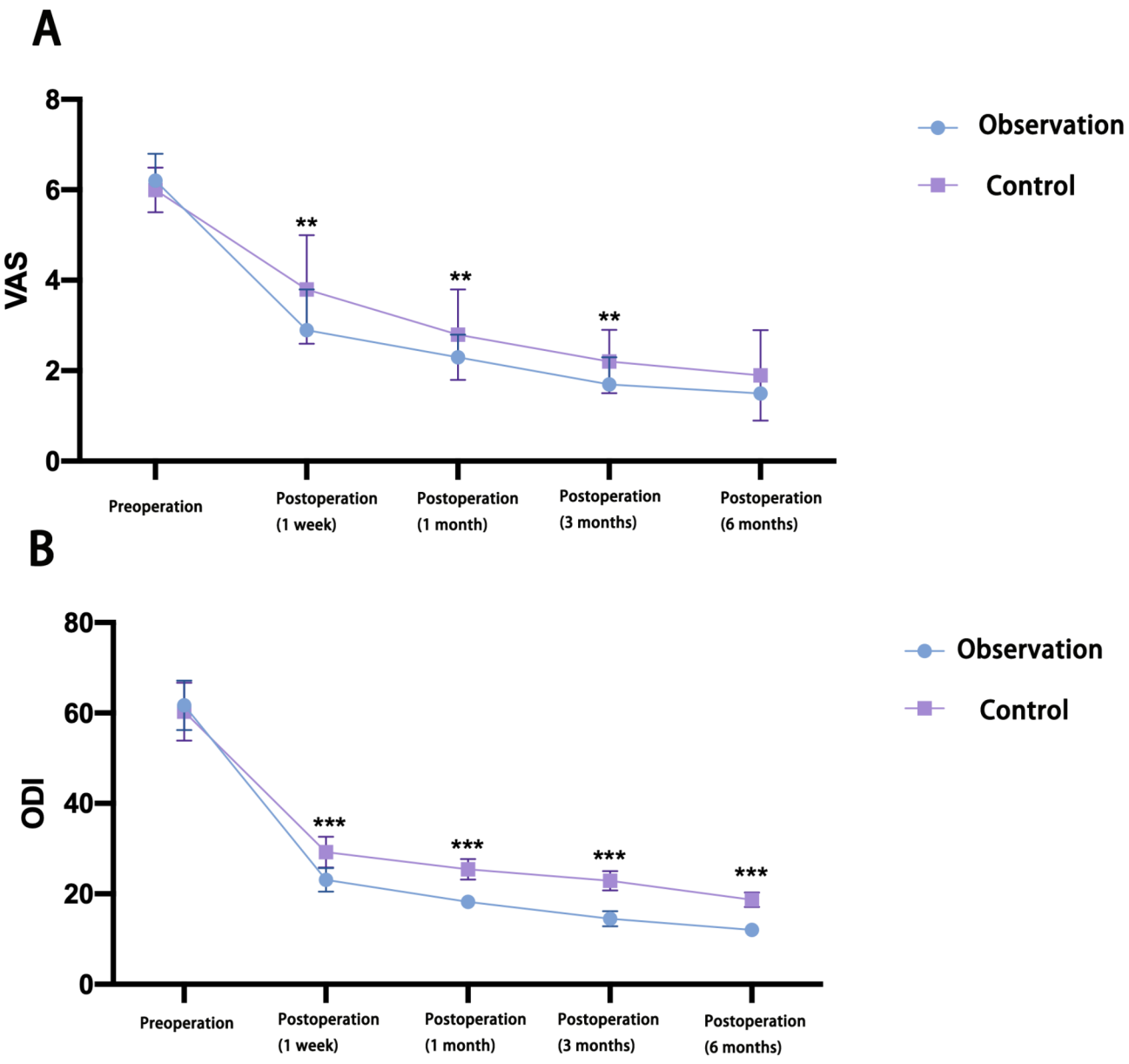

Fig. 4 Comparison of VAS scores between. Captions: Comparison of VAS scores of low back and leg pain before and after surgery **(A)** and ODI of spinal function before and after surgery **(B)** between the two groups of patients. ** $P<0.01$, *** $P<0.001$

Table 4 Comparison of ODI between groups before and after surgery (mean ± SD)

Group	Case	Preoperative	1 week after surgery	1 month after surgery	3 months after surgery	6 months after surgery
Observation group	17	61.7 ± 5.5	23.1 ± 2.6	18.2 ± 1.5	14.5 ± 1.7	12.0 ± 1.4
Control group	15	60.3 ± 6.4	29.2 ± 3.4	25.4 ± 2.3	22.9 ± 2.1	18.7 ± 1.6
t value		0.921	7.896	14.494	17.241	17.499
P value		0.367	<0.001	<0.001	<0.001	<0.001

Table 5 Comparison of the accuracy of interposition screws between the two groups

Group	Number of screws	Grade A	Grade B	Grade C	Grade D	Grade E	Acceptable Screws	Unacceptable Screws
Observation Group	68	40	24	2	2	0	66(97.06%)	2(2.94%)
Control Group	60	30	20	6	2	2	56(93.33%)	4(6.67%)
X^2	0.99							
P	0.32							

may undergo compensatory growth, making this area susceptible to damage. Lumbar spondylolisthesis most commonly affects the L4/5 segment, followed by the L5/S1 and L3/4 segments [8]. In younger individuals, spondylolysis can cause lumbar instability and is often associated with disc herniation. Early-stage disc herniation typically involves minimal disc degeneration, with the nucleus pulposus, annulus fibrosus, and cartilage plate maintaining relative integrity and elasticity. Despite this, disc herniation can occur, often involving a large herniated disc tissue with its annulus fibrosus and cartilage plate entering the spinal canal. Fractures of the posterior vertebral body may also cause severe nerve compression. Due to their physical activity, young patients may struggle with long-term conservative treatments, making surgical options necessary [9]. Degenerative lumbar spondylolisthesis, prevalent in young and middle-aged patients, is often accompanied by spinal stenosis. This condition can result from disc water loss, yellow ligament hyperplasia, and articular process hypertrophy. These changes reduce the spinal canal's inner diameter and cause intervertebral foramen stenosis, compressing nerve roots and the spinal cord. The disease is characterized by a long course and severe degeneration, with conservative treatment providing only short-term relief and a high recurrence rate. Therefore, surgical intervention remains the long-term solution [10]. Traditional open intervertebral fusion surgeries, such as TLIF and PLIF, are standard treatments for lumbar spondylolisthesis. While effective in decompression and surgical outcomes, these methods are associated with greater trauma, intraoperative bleeding, and longer postoperative recovery. Although they relieve symptoms and improve quality of life in the short term, long-term complications can affect overall patient satisfaction [11]. Recent advancements in minimally invasive surgical techniques, particularly those using spinal endoscopy, have led to the development of microscope-assisted minimally invasive channel transforaminal interbody fusion. This technology allows effective decompression while minimizing damage to the multifidus muscle and posterior ligament complex, facilitating faster patient recovery. During surgery, minimal removal of the affected facet joint or lamina is required, preserving the contralateral facet joint and lamina, thereby adhering to the minimally invasive approach [12]. Studies [13] have shown that microscope-assisted minimally invasive TLIF is versatile and effective for various lumbar disc herniation conditions. The technology enhances tissue structure visibility, improving surgical accuracy and safety. Due to minimal surgical trauma and low blood loss, patients experience faster recovery and return to normal life more quickly. While this technique shows clear short-term benefits, its long-term efficacy may be limited, with potential issues such as intervertebral disc height loss, endplate inflammation, and recurrence of herniation. Thus, it may not fully restore spinal stability on its own [14]. To enhance long-term outcomes and reduce recurrence, researchers have combined percutaneous pedicle screw fixation with microscope-assisted minimally invasive decompression intervertebral fusion. This innovative approach integrates advanced technologies to provide a more precise, minimally invasive, and durable treatment option. It improves safety and effectiveness, aids faster recovery, and minimizes postoperative recurrence. The results have demonstrated significant therapeutic benefits, including pain relief and improved nerve compression symptoms, along with long-term efficacy in reducing recurrence and enhancing spinal stability [15]. Full microscope intervertebral fusion offers surgeons a magnified view of the surgical field, allowing precise lesion localization and operation. This minimally invasive technique reduces tissue damage, lowers surgical risks, and enhances safety. Meta-analysis results indicate that microscope-assisted TLIF significantly reduces intraoperative blood loss, hospitalization time, ambulation time, and low back pain VAS scores compared to traditional TLIF and MIS-TLIF. The complication rates and operative times were similar [16]. This approach leads to improved postoperative VAS scores and Japanese Orthopaedic Association (JOA) scores, indicating better pain relief, neurological function, and quality of life. The low complication rate associated with this technique further reduces postoperative risk, hospital stay, and financial burden. Moreover, it has a higher interbody fusion rate, crucial for long-term surgical success and patient recovery [17]. Despite some complications associated with microscopic fusion for spinal stenosis, their incidence was comparable to traditional open surgery. This suggests that microscopic fusion is as safe as traditional methods, with additional benefits in postoperative recovery and rehabilitation [18].

Microscope-assisted minimally invasive fusion technology has demonstrated numerous advantages in treating conditions such as lumbar spondylolisthesis. These benefits include minimal invasiveness, reduced tissue damage, and accelerated recovery. However, its technical implementation requires exceptional skill and the surgical process can be time-consuming, involving a relatively steep learning curve. Robot-assisted surgery lacks reliable tactile feedback. In addition, the robot is large, bulky, and expensive to purchase, which makes it difficult to promote robot-assisted surgery [19]. Robotic surgery has not seen any special complications. Besides the meticulous operation under the microscope, precise screw placement and the duration of intraoperative X-ray fluoroscopy exposure are critical factors influencing the smooth execution of the surgery. To enhance screw placement accuracy, researchers have explored

using an O-arm machine for intraoperative navigation. The combination of the O-arm and a microscope has been shown to improve screw placement precision [20]. Additionally, the introduction of orthopedic robot navigation systems has yielded impressive results. These systems enhance pedicle screw placement accuracy through high-precision positioning and navigation, thereby minimizing operational errors. This aligns with findings from our study. Robotic navigation systems also significantly reduce the risk of X-ray radiation exposure during surgery, benefiting both medical staff and patients [21]. Compared to traditional fluoroscopic positioning, robot-assisted percutaneous pedicle screw placement offers higher accuracy, lower error rates, and improved surgical outcomes. This technology is both minimally invasive and effective, providing a new and competitive approach to screw placement in spinal surgery [22]. The use of robotic navigation allows for more precise positioning and placement of pedicle screws, improving the procedure's accuracy and safety. In 2 review papers, the authors believed that the accuracy of robot-assisted nail placement was higher than that of traditional methods [19, 23]. In this study, the acceptance rate of screw placement in the robot-assisted group was higher than that in the control group (97.06% vs. 93.33%, $p=0.32$), but no significant difference was found statistically, which may be related to the small number of samples included. This result is similar to the results of Cui et al. (87/92 vs. 85/100, $P=0.025$) [24] Moreover, it reduces the likelihood of screw breakage [25]. Although this technology was associated with a longer average operation time, which was about 50 min longer than traditional methods, this duration remains within a clinically acceptable range. This observation is consistent with findings reported by Yarbrough et al. [26]. Considering the enhanced accuracy and safety provided by robotic navigation, this extended duration is justified. With ongoing advancements in technology, improved team efficiency, and better equipment, the operation time is expected to decrease further in the future [27].

This study evaluated the feasibility of an economical and widely applicable robotic system for MIS-TLIF surgery. By utilizing C-arm machines for navigation with two-dimensional images, the overall cost of the robotic system was significantly reduced. Spine surgeons prefer real-time fluoroscopic images over intraoperative virtual images. Additional features of this system include: (1) the elimination of traditional fiducial markers during navigation, and (2) the ability to verify the safety of the screw path through perspective images projected along the path once positioning is completed. However, the robotic system has potential limitations. Although image registration was successful in our initial and actual experiments, challenges may arise in cases of severe osteoporosis. Osteoporotic patients may present with anatomical features, such as pedicles, that are difficult to identify on X-ray images, making contour-based matching challenging. In such cases, manual screw placement or open surgery may be necessary. Future research will focus on predicting osteoporosis using bone mineral density (BMD) and CT values, and defining criteria for registration difficulties or failures due to osteoporosis. Pathological changes in the vertebral body can alter its anatomical landmarks, complicating X-ray recognition. For instance, abnormalities in the pedicles may affect standard morphological recognition. In such situations, we will rely on clearer anatomical structures visible on X-rays, such as spinous processes, transverse processes, or superior articular surfaces, for contour matching and positioning. Breathing movements can cause slight vertebral displacement, particularly in the lower thoracic and lumbar regions. Studies indicate that the maximum vertebral displacement during breathing is 1.3 mm. Our tests showed an angular deviation of about 10 degrees and a lateral displacement of approximately 0.4 mm. Reducing respiratory tidal volume during surgery can minimize these breathing-induced deviations. Additionally, soft tissue, ridges, and slopes on the vertebral body surface can cause instrument deflection and trajectory changes during drilling and screw fixation. Selecting an optimal bone entry point that avoids these anatomical variations may help reduce surgical errors. Our early model experiments showed an overall deviation within 1 mm. Considering additional errors from breathing and drilling, we estimate the final deviation to be around 1.6 mm. All pedicle screws placed with the robotic system in our animal experiments were accurately positioned.

Recent advancements in spinal surgery have introduced dual-loop robotic navigation combined with microscopic minimally invasive fusion technology as a cutting-edge treatment method. Practical applications have led to several key observations: First, robotic navigation technology significantly reduces intraoperative bleeding and postoperative drainage while shortening hospitalization times. This is due to the high precision of robotic systems, which accurately position and operate during surgery, thereby minimizing unnecessary tissue damage and improving surgical outcomes. Second, in treating lumbar spondylolisthesis, especially when faced with intervertebral foramen stenosis and loss of intervertebral space height, the combination of robotic navigation with microscopic minimally invasive techniques provides distinct advantages. The transarticular process approach enables safer and more convenient contralateral decompression, enhancing surgical safety. For procedures involving the L4/5 and L5/S1 segments, which have large intervertebral head tilt angles, dual-loop robotic navigation helps by aligning the microscope with the endplate, improving

operational ease. Ensuring that the intervertebral space is perpendicular to the ground further optimizes the surgical field of view and convenience. In lumbar intervertebral foramen enlargement and plasty, this technology focuses on removing most of the bone from the upper articular process to expose Kambin's triangle and create a safe channel for cage implantation. Special attention is given to avoiding damage to the exiting nerve root and keeping the working area close to the lower part of the intervertebral foramen. Microscopic decompression emphasizes treating the exiting nerve roots, where complete decompression of the contralateral nerve root can be challenging due to the small incision and tunnel size. However, by exposing the lateral edge of the contralateral dural sac and intervertebral disc, and using tools such as gun pliers, ultrasonic osteotome, and power drills, the surgeon ensures thorough decompression and sufficient space for the nerve root to avoid re-entrapment.

Summary

In summary, dual-loop robotic navigation combined with microscopic minimally invasive fusion technology offered significant advantages in treating lumbar spondylolisthesis of grades I and II. It enhanced surgical accuracy and safety, reduced postoperative recovery burdens, and improved patient outcomes and quality of life. Further research and clinical application of this technology are recommended to extend its benefits to a broader patient population.

Author contributions

X.P. Gu and W.H. Ma designed this study. S.O. Zhang wrote the main manuscript text. Y.T. Liu, J.L. Qi and Y.Q. Gu prepared Figs. 1, 2, 3 and 4; Tables 1, 2, 3 and 4. All authors reviewed the manuscript.

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Data availability

All raw data can be obtained by contacting the corresponding author.

Declarations

Ethics approval and consent to participate

This study was conducted after review by the Ethics Committee of Zhoushan Gu Hechuan Orthopedic Hospital.

Consent for publication

Not Applicable.

Competing interests

The authors declare no competing interests.

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