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Clinical Application Analysis of Orthopedic Robot-Assisted Treatment for Lumbar Spondylolisthesis

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Abstract

Objective: To explore the clinical efficacy of orthopedic robot-assisted treatment for lumbar spondylolisthesis, focusing on the analysis of key indicators such as intraoperative blood loss, postoperative complications, and accuracy of nail placement, providing a reference basis for the widespread application of this technology. **Methods:** Retrospective analysis of clinical data of 25 patients with lumbar spondylolisthesis who underwent surgery with Tianji orthopedic robot assistance at Baise People's Hospital from June 2021 to December 2024, with an age of (59.72 ± 8.44) years, range: (45 - 80) years. Before surgery, all 25 patients had single-segment spondylolisthesis, 7 males, 18 females, L4/5 segment in 17 cases, L5/S1 in 7 cases, L3/4 in 1 case. Before surgery, 17 cases were grade I slippage, and 8 cases were grade II slippage. Through intraoperative and postoperative observation and follow-up, and statistical analysis of data such as intraoperative blood loss, postoperative complications, and nail placement accuracy to analyze the value of orthopedic robots in clinical applications. **Results:** The intraoperative blood loss under robot-assisted surgery was (209.60 ± 127.09) ml, the duration of surgery was (165.92 ± 16.08) min, the number of fluoroscopies during surgery was (2.24 ± 1.249) times, the postoperative hospital stay was (7.56 ± 1.83) days, the follow-up time after surgery was (9.52 ± 2.69) months, and the accuracy of nail placement was 96%. The visual analog scale (VAS) pain scores were 5.20 ±

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0.76 at one week after surgery and 2.20 ± 0.87 at the last follow-up, both lower than the preoperative score of 7.72 ± 1.14, with statistical significance ($p < 0.05$). The four observation indicators included in the Japanese Orthopedic Association for evaluation of the treatment score (JOA) were statistically higher than the preoperative scores. The accuracy of nail placement in patients was class A 90%, class B 6%, class C 4%, class D 0%, class E 0%, $x^2 = 307.6$, $p < 0.001$. It showed that orthopedic robot-assisted treatment of lumbar spondylolisthesis has good effects in controlling intraoperative blood loss and ensuring nail placement accuracy. **Conclusion:** Orthopedic robot-assisted treatment for lumbar spondylolisthesis has significant advantages and important reference value in clinical applications.

Keywords

Orthopedic Robots, Lumbar Spondylolisthesis, Postoperative Indicators, Application Analysis

1. Introduction

With the aging of he population, lumbar spondylolisthesis has gradually become one of the common diseases in orthopedics, seriously affecting the quality of life of patients. If not treated in time, severe cases may be accompanied by spinal stenosis and produce neurogenic claudication. Current treatments for lumbar spondylolisthesis are generally divided into conservative treatment and surgical treatment. Some patients may recover or improve with conservative treatment, but for those who do not show improvement or are ineffective after 3 - 6 months of conservative treatment, timely surgical intervention is required. There are various surgical procedures for treating lumbar spondylolisthesis, with the earliest surgical method of Wiltse's laminectomy proposed by the French physician Pierre Wiltse in the 20th century. In traditional open surgery for treating lumbar spondylolisthesis, including posterior lumbar fusion, lumbar interbody fusion, and minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF), there are issues such as large trauma and significant blood loss. In terms of pedicle screw placement, traditional procedures rely on multiple intraoperative X-ray fluoroscopy to confirm the screw position and direction before manually inserting the screws, resulting in high radiation exposure, long screw placement time, and high error rate. In recent years, with continuous breakthroughs in artificial intelligence and the benefit of faster development in the field of medicine, orthopedic robots have also been born. The accuracy and safety of pedicle screw placement in robotic-assisted surgery for lumbar spondylolisthesis are significantly improved compared to conventional fluoroscopy-guided manual screw placement. With the widespread popularity of artificial intelligence, robotic technology is becoming increasingly sophisticated and can not only provide a clear three-dimensional view but also perform rotational, bending, and other surgical maneuvers. Several studies have shown significant advantages in conducting surgical treatment for

degenerative lumbar diseases with robot assistance in various surgical evaluation indicators. The emergence of robotic-assisted surgery provides new opportunities for the treatment of lumbar spondylolisthesis and contributes to the trend of minimally invasive orthopedics. This study aims to evaluate the clinical efficacy and practical application value of using this technology in the treatment of lumbar spondylolisthesis by analyzing indicators such as intraoperative blood loss, postoperative complications, and screw placement accuracy [1]-[9].

2. Materials and Methods

2.1. General Information

25 patients diagnosed with grade I and II lumbar spondylolisthesis who underwent orthopedic robotic-assisted surgery at Baise People's Hospital from June 2021 to December 2024 were included in this study. Detailed information including age, gender, disease duration, intraoperative blood loss, postoperative length of stay, and degree of lumbar spondylolisthesis (e.g. Meyerding classification) was recorded. Among them, there were 7 male and 18 female patients, with an average age of 59.72 ± 8.44 years and an age range of 45 to 80 years; with an average disease duration of over 6 months.

2.2. Inclusion Criteria and Exclusion Criteria

Inclusion criteria: 1) Patients complain of obvious lower back pain accompanied by leg pain, underwent multi-layer helical CT scan and digital X-ray examination to confirm the presence of single-segment lumbar spondylolisthesis; 2) Patients with unsatisfactory therapeutic effect of non-surgical methods; 3) Patients with Meyerding classification of grade I and II spondylolisthesis; 4) Main diagnosis is grade I and II lumbar spondylolisthesis.

Exclusion criteria: 1) Primary diseases such as lumbar vertebral fractures, infections, tumor metastases; 2) Patients inclined towards traditional surgical methods; 3) Patients who are intolerant of surgery.

2.3. Surgical Method

The patient was placed in the prone position before surgery, routine disinfection and draping of the surgical area, installation of positioning receiver on the body surface, collection of data through three-dimensional C-arm scanning, precise positioning assisted by robot, planning of entry points and screw paths, connecting the robot's universal arm after planning the pathway, executing the screw entry command program, robot arm running to the left body surface positioning point of the screw placement site, connecting the screw sleeve on the robot arm, incising the skin, subcutaneous tissue, deep fascia, drilling with an electric drill along the direction set by the robot to insert a Kirschner wire, creating a guide wire channel, connecting the guide wire after removing the Kirschner wire, inserting the guide wire smoothly into the corresponding vertebra on the right side using the same method, due to the decompression requirement, extending the left body surface

incision through, progressively expanding the working channel, dissecting the longissimus and multifidus muscles to the facet joints, installing the working base and free arm, installing the quadrant channel, connecting the light source of the working channel, repositioning the working channel using three-dimensional C-arm to ensure correct positioning between surgical segments, cleaning the soft tissue, exposing the facet joints and lamina, excising the ligamentum flavum, performing laminectomy for decompression, exploring the nerve roots in the spinal canal, fully decompressing the nerves, relaxing, irrigating, trialing the fusion cage, implanting autograft bone, allograft bone, and bone substitute into the decompression space, selecting the appropriate fusion cage for final implantation after washing, exiting the minimally invasive channel, installing the next-level expanding channel along the right guide wire, tapping along the guide wire, installing pedicle screws, connecting rods on the right side, confirming solid fixation, repeating the same method along the left guide wire, installing the expanding channel, tapping along the guide wire, installing pedicle screws, connecting rods on the left side, intraoperative three-dimensional C-arm scan confirming the good position of the internal fixators, applying hemostatic agents and hemostatic gauze for sufficient hemostasis, leaving a drainage tube at the decompression site on the left lumbar spine, suturing and dressing the incision, completion of the surgery, postoperative transfer to the ward for continued monitoring and treatment.

3. Research Indicators and Methods

3.1. Intraoperative Blood Loss

Use intraoperative suction devices to collect and measure the actual amount of blood loss during the patient's surgery, record it in milliliters, and use it as an evaluation indicator for statistical analysis.

3.2. Postoperative Complications

Observe and record the various complications that occur around one week after the surgery in patients, such as infection, spinal cord edema, nerve injury, and loosening of internal fixation, and calculate the incidence rate of complications.

3.3. Nail Placement Accuracy

The accuracy of nail placement in patients was evaluated through postoperative imaging examinations (such as X-rays, CT scans, etc.) to determine whether the nail was correctly positioned at the predetermined vertebral location and to calculate the accuracy rate of nail placement. According to the Gertzbein-Robbins classification, pedicle screws are divided into four categories: A, B, C, and D, with the highest accuracy requirements for Type A screws. Specifically, Type A screws are located within the pedicle; Type B screws penetrate the pedicle cortex by ≤ 2 mm; Type C screws penetrate the pedicle cortex by > 2 - 4 mm; Type D screws penetrate the pedicle cortex by > 4 - 6 mm; Type E screws penetrate the pedicle

cortex by > 6 mm. Among these classifications, Type A is considered accurately placed, and the accuracy rate of nail placement is calculated as the number of Type A screws divided by the total number of screws. The total nail placement time (from the robot starting to scan the lumbar spine images to the completion of the last screw insertion) is also recorded, and the average value is calculated to determine the time required for placing a single screw, which is calculated as the total nail placement time divided by the total number of screws. This is used to assess the accuracy of postoperative nail placement.

3.4. Evaluation Criteria

The postoperative scores of back pain and leg pain were calculated using the Visual Analogue Scale (VAS), as well as the JOA score (Japanese Orthopedic Association assessment score) which includes subjective symptoms, clinical signs, degree of daily activity restriction, and bladder function at preoperatively, one week postoperatively, and at the final follow-up.

3.5. Postoperative Treatment Methods

A drainage tube is placed intraoperatively, covering it with sterile dressings and fixing it with a biofilm. Postoperatively, cephalosporin is given to prevent wound infection, along with gastric mucosal protection, pain relief, prevention of electrolyte imbalance, and prophylactic anticoagulation therapy. Depending on the actual amount of fluid drained by the drainage tube, it may be removed within 72 hours. Instructing patients to wear protective equipment for ambulation and to exercise their lower back muscles.

3.6. Statistical Methods

Using SPSS 27.0 (SPSS Inc., USA) for statistical analysis, the quantitative data indicators are represented by ± S to present the specific situation and trend of each indicator. The chi-square test was used for R × C contingency table data, with $p < 0.05$ indicating statistically significant differences.

4. Results

In this study, 25 patients completed the surgery successfully, with a surgery duration of 135 to 192 minutes. The average surgery duration for patients was (165.92 ± 16.08) minutes. The average intraoperative blood loss was (209.60 ± 127.09) mL, ranging from 20 to 500 mL. The number of intraoperative fluoroscopies ranged from 1 to 4 times, with an average of (2.24 ± 1.249) times. The postoperative hospital stay ranged from 4 to 11 days, with an average of (7.56 ± 1.83) days. The postoperative follow-up time ranged from 6 to 14 months, with an average of (11.12 ± 3.249) months. The incidence of postoperative complications in patients was 8%. Among them, 2 cases had spinal cord edema after surgery. After diagnosis, dehydration treatment was given to the patients, with intravenous administration of mannitol to reduce edema, resulting in relief of symptoms without

other abnormal manifestations. There were no cases of infection, nerve injury, or loosening of internal fixation. According to statistics, a total of 100 pedicle screws were inserted in the 25 patients during the surgery. Postoperative X-ray and CT scan evaluation using A and B screws as standards showed an accuracy rate of 96% in screw placement. Ninety A screws, six B screws, four C screws, zero D screws, and zero E screws were inserted, with a total screw placement duration of 1290 minutes and an average screw placement duration of 12.9 minutes. The accuracy rates of A and B screws were 90% and 6%, respectively.

The VAS scores before surgery, one week after surgery, and at the last follow-up visit showed significant improvement in both back pain and leg pain. The preoperative back pain score was 7.72 ± 1.14, decreased to 5.20 ± 0.76 one week postoperatively, and further decreased to 2.20 ± 0.87 at the last follow-up, with an F value of 180.3300 and a p-value of 0.0000, indicating a significant time effect. The leg pain score followed a similar trend, with a preoperative score of 8.00 ± 0.82, dropping to 5.32 ± 0.99 one week postoperatively, and decreasing to 2.16 ± 0.94 at the last follow-up, with an F value of 252.7200 and a p-value of 0.0000. These results suggest that surgery has a significant effect on pain relief, with patients experiencing noticeable pain reduction postoperatively, and the variance in assessment showing homogeneity. Detailed results are shown in Table 1. The JOA scores indicated significant improvement in patients' subjective symptoms, clinical signs, and daily activities. The preoperative subjective symptom score was 1.72 ± 1.24, significantly increasing to 4.96 ± 0.79 one week postoperatively, and reaching 8.04 ± 0.89 at the last follow-up, with an F value of 253.6000 and a p-value of 0.0000, indicating the statistical significance of subjective symptom improvement. The clinical sign score increased from 1.64 ± 0.49 preoperatively to 3.56 ± 0.51 one week postoperatively, and was 5.00 ± 0.82 at the last follow-up, with an F value of 181.7500 and a p-value of 0.0000, demonstrating clinical sign improvement. The score for daily activity limitation increased significantly from 4.24 ± 1.23 preoperatively to 8.36 ± 1.15 one week postoperatively, and reached 11.56 ± 1.36 at the last follow-up, with an F value of 215.5700 and a p-value of 0.0000. These results indicate that surgery not only effectively relieves pain, but also significantly improves patients' daily function and quality of life. Overall, surgical intervention plays an important role in the overall symptom and functional recovery of patients. Detailed results are shown in Table 2.

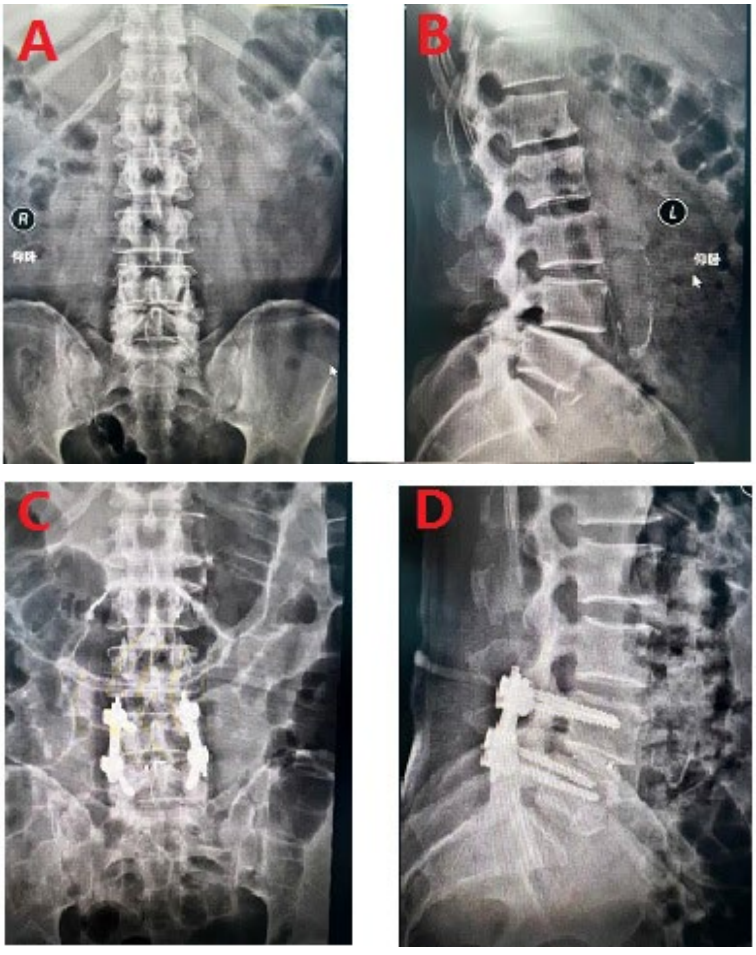
Table 1. Comparison of VAS scores before surgery, one week after surgery, and at the last follow-up visit (n = 25, score, ±S).

	Symptom	Preoperative	1 week postoperative	Last follow-up	F-value	p-value	χ^2 value	P value	Result Evaluation
VAS Score	Low back pain	7.72 ± 1.14	5.20 ± 0.76	2.20 ± 0.87	180.3300	0.0000	4.13	0.127	Variance is homogeneous
	Leg pain	8.00 ± 0.82	5.32 ± 0.99	2.16 ± 0.94	252.7200	0.0000	0.87	0.648	Variance is homogeneous

Table 2. Comparison of preoperative, postoperative one week, and final follow-up joa scores (n = 25, points, ±S).

	Symptoms	Preoperative	Postoperative Week 1	Final Follow-up	F-value	p-value	χ^2 value	p-value	Result Evaluation
joa Score	Subjective Symptoms	1.72 ± 1.24	4.96 ± 0.79	8.04 ± 0.89	253.6000	0.0000	5.3700	0.0680	Equal variance
	Clinical Signs	1.64 ± 0.49	3.56 ± 0.51	5.00 ± 0.82	181.7500	0.0000	8.3000	0.0160	Unequal variance
	Limitation of Daily Activities	4.24 ± 1.23	8.36 ± 1.15	11.56 ± 1.36	215.5700	0.0000	0.6800	0.7130	Equal variance
	Bladder Function	−1.72 ± 1.24	-	-	-	-	-	-	-

A typical case is a 61-year-old male patient who was admitted to the hospital for lower back pain accompanied by leg pain and numbness for 6 months. The preoperative diagnosis was L4 vertebral body grade I anterior spondylolisthesis. After undergoing surgery with orthopedic robot-assisted treatment, the symptoms of lower back pain and leg numbness disappeared. Preoperative and postoperative vertebral imaging and intraoperative data for the patient are shown in **Figures 1(A)-(H)**.



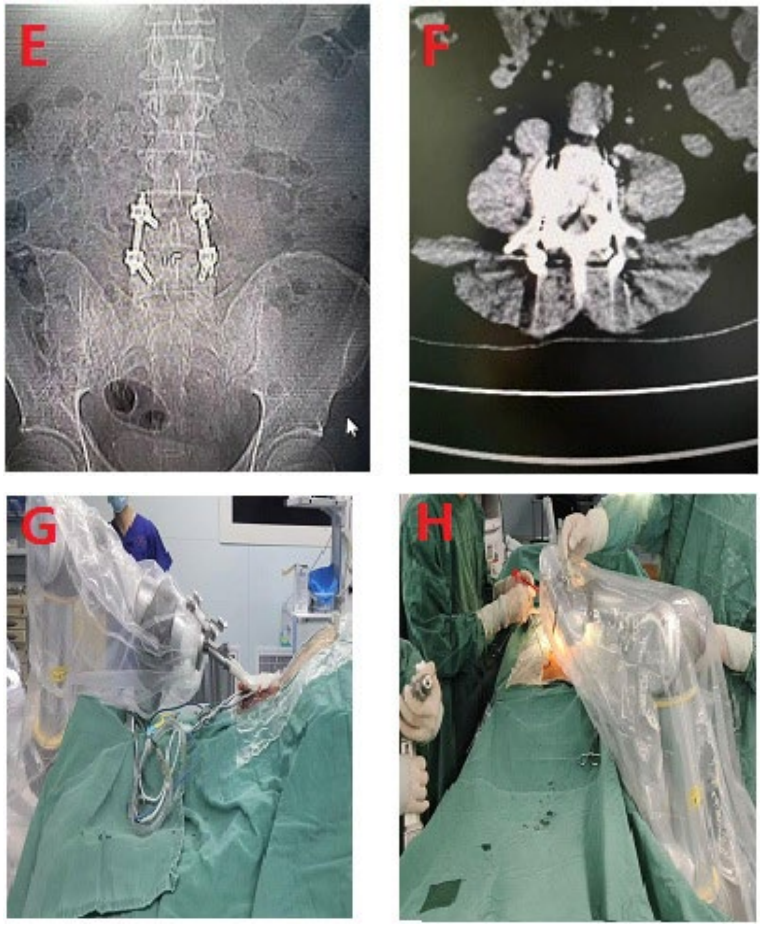


Figure 1. (A)-(B): Preoperative X-ray reveals Grade I anterior spondylolisthesis of the L4 vertebra. (C)-(D): Postoperative X-ray review shows significant improvement in the L4 vertebra spondylolisthesis, with satisfactory restoration of the L4-L5 intervertebral space height. (E)-(F): Follow-up CT scan at 8 months postoperatively shows that the screws are positioned within the pedicle, classified as Type A according to the Gertzbein Robbins grading system. (G)-(H): The surgeon treats lumbar spondylolisthesis using orthopedic robotic assistance.

5. Discussion

Research has shown that the etiology of lumbar spondylolisthesis is rather complex, and it is generally believed to be associated with degenerative changes in the lumbar spine, lumbar instability, loss of facet joint function, and other factors [10]. Patients often complain of lower back pain accompanied by leg pain and numbness when seeking medical attention for lumbar spondylolisthesis. Non-surgical methods are preferred when choosing treatment for lumbar spondylolisthesis. Physicians need to develop a comprehensive treatment plan for patients, including pain management, education, supervised exercises, self-care, and physical activities. Patients must strictly adhere to the plan to enhance treatment effectiveness [11]. In traditional surgical methods, procedures like traditional posterior decompression fusion internal fixation surgery may disrupt the bony stability of

the lumbar spine, necessitating the use of pedicle screw rod systems to reconstruct the stability of the operated segment, which increases the surgical trauma and can lead to complications such as incision infections and postoperative back pain [12]. Non-fusion decompression is considered a less invasive surgery. Various studies have indicated that the addition of fusion results in better decompression effects. Surgery offers several potential benefits and greater improvements for patients who have failed conservative treatment. The optimal technique has yet to be definitively determined [13]. Investigations have found that the incidence rate of L4/5 segment in lumbar spondylolisthesis is the highest, followed by L5/S1 and L3/4 segments, with single-segment lumbar spondylolisthesis having the highest incidence rate. Nowadays, digital orthopedics, as a new discipline of digital medicine, is based on orthopedics and assisted by computer imaging technology [14] [15]. The rapid development of medical technology has made minimally invasive orthopedics a mainstream trend. The emergence of orthopedic robots has made surgical treatment for lumbar spondylolisthesis more convenient and efficient [16]. According to relevant literature reports, the problem of high error rate in manual nail placement under robot assistance has been mitigated to a certain extent. The robot-assisted system exhibits high precision in lumbar spondylolisthesis surgery. Compared to traditional surgery, it can more accurately position the pedicle screw placement, effectively reducing the risk of screw misplacement through detailed preoperative planning and real-time navigation during surgery [17] [18]. Relevant data indicates that the accuracy rate of screw placement in the robot-assisted group can exceed 92%, higher than the screw placement rate in traditional surgery. This is crucial for stabilizing the slipped vertebrae, restoring the normal spinal sequence, and improving fusion rates. From the perspective of surgical trauma, robot-assisted surgery generally achieves smaller incisions, reducing damage to surrounding soft tissues. This significantly reduces postoperative pain for patients and shortens their hospital stay. Despite the many advantages of robot-assisted treatment for lumbar spondylolisthesis, the complexity of the technology cannot be ignored. Surgical teams need specialized training to proficiently operate the system, including the use of preoperative planning software, robot manipulation during surgery, and integration with traditional surgical techniques. In our practical experience, novice doctors often require multiple practice surgeries to become proficient in this technology, which to some extent, limits its rapid promotion in primary healthcare institutions [19] [20]. Additionally, the high cost of acquiring robot-assisted surgical equipment poses a financial challenge for many hospitals considering the introduction of this technology. The price of an advanced robot-assisted system is often in the range of millions or tens of millions. Furthermore, continuous investment is needed for regular maintenance of the equipment and software updates. This financial burden restricts the wider application of this technology. With the continuous development of technology, robot-assisted treatment for lumbar spondylolisthesis is expected to improve in the following aspects in the future. On the one hand, enhancing the flexibility and adapt-

ability of robots to better address the anatomical differences of different patients and apply to surgeries for different orthopedic diseases, achieving more personalized surgical planning. On the other hand, optimizing the interaction interface between the robot and the operating surgeon to make operations more intuitive and straightforward, reducing the learning curve and enabling more doctors to proficiently master this technology.

6. Conclusion

In conclusion, orthopedic robot-assisted treatment for lumbar spondylolisthesis has shown good clinical outcomes in terms of intraoperative blood loss, postoperative complications, and accuracy of nail placement. This technology can effectively reduce intraoperative blood loss, decrease the incidence of postoperative complications, and improve the accuracy of nail placement, demonstrating important value in the treatment of lumbar spondylolisthesis. However, it should be noted that this technology may have some limitations, such as high equipment costs and high training requirements. This study provides a comprehensive understanding of the efficacy of robot-assisted treatment for lumbar spondylolisthesis, postoperative indicators, and future development, which can serve as a reference for its further clinical application and research.

7. Limitations of the Study

Although this study analyzed the clinical efficacy of robotic-assisted surgery for lumbar spondylolisthesis, it has several limitations. Firstly, the sample size is small, comprising only 25 patients, which may affect the generalizability of the results. Secondly, the follow-up period is relatively short (an average of 9.52 months), which does not allow for a comprehensive assessment of long-term efficacy and potential postoperative complications. Additionally, there was no in-depth analysis of patients' underlying conditions and individual differences, which may influence the accuracy of the results. Lastly, the evaluation mainly relied on VAS and JOA scores, which may not fully reflect patients' quality of life. Therefore, future studies should consider increasing the sample size and extending the follow-up period to further validate the clinical advantages of this technology.

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Conflict of Interest Statement

The research team members declare that there are no conflicts of interest regarding the publication of this paper, and the order of authorship does not imply any conflicts.

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