Robot-guided versus freehand fluoroscopy-guided minimally invasive transforaminal lumbar interbody fusion: a single-institution, observational, case-control study

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OBJECTIVE The use of robotics in spinal surgery has gained popularity because of its promising accuracy and safety. ROSA is a commonly used surgical robot system for spinal surgery. The aim of this study was to compare outcomes between robot-guided and freehand fluoroscopy-guided instrumentation in minimally invasive surgery (MIS)—transforaminal lumbar interbody fusion (TLIF).

METHODS This retrospective consecutive series reviewed 224 patients who underwent MIS-TLIF from March 2019 to April 2020 at a single institution. All patients were diagnosed with degenerative pathologies. Of those, 75 patients underwent robot-guided MIS-TLIF, and 149 patients underwent freehand fluoroscopy-guided MIS-TLIF. The incidences of pedicle breach, intraoperative outcomes, postoperative outcomes, and short-term pain control were compared.

RESULTS The patients who underwent robot-guided surgery had a lower incidence of pedicle breach (0.27% vs 1.75%, $p = 0.04$) and less operative blood loss (313.7 ± 214.1 mL vs 431.6 ± 529.8 mL, $p = 0.019$). Nonsignificant differences were observed in operative duration (280.7 ± 98.1 minutes vs 251.4 ± 112.0 minutes, $p = 0.056$), hospital stay (6.6 ± 3.4 days vs 7.3 ± 4.4 days, $p = 0.19$), complications (intraoperative, 1.3% vs 1.3%, $p = 0.45$; postoperative surgery-related, 4.0% vs 4.0%, $p = 0.99$), and short-term pain control (postoperative day 1, 2.1 ± 1.2 vs 1.8 ± 1.2 , $p = 0.144$; postoperative day 30, 1.2 ± 0.5 vs 1.3 ± 0.7 , $p = 0.610$). A shorter operative duration for 4-level spinal surgery was found in the robot-guided surgery group (388.7 ± 107.3 minutes vs 544.0 ± 128.5 minutes, $p = 0.047$).

CONCLUSIONS This retrospective review revealed that patients who underwent robot-guided MIS-TLIF experienced less operative blood loss. They also benefited from a shorter operative duration with higher-level (> 3 levels) spinal surgery. The postoperative outcomes were similar for both robot-guided and freehand fluoroscopy-guided procedures.

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KEYWORDS robot; pedicle screw; TLIF; transforaminal lumbar interbody fusion

TRANSFORAMINAL lumbar interbody fusion (TLIF) is an adapted technique for spinal fusion that can be performed as a minimally invasive surgery (MIS).¹⁻³ The paraspinous (Wiltse) technique has been commonly applied in MIS-TLIF to approach the unilateral facet joint with a small incision.^{4,5} However, minimally invasive spine surgery is time consuming and dependent on technical skill; a longer operative duration and steep learning

curve are typically required.⁶⁻⁸ Given the small surgical window, common complications include durotomy, neural injury, and hardware misposition.⁹ Moreover, to place the pedicle screw precisely, real-time fluoroscopy is usually necessary. Furthermore, excessive radiation exposure is a major concern.^{3,10,11} Hence, the application of surgical robotics can facilitate the workflow of minimally invasive spinal surgery. Robotics can help the surgeon navigate and

ABBREVIATIONS EBL = estimated blood loss; FG = fluoroscopy-guided; MIS = minimally invasive surgery; NRS = numeric rating scale; RG = robot-guided; TLIF = transforaminal lumbar interbody fusion.

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access major anatomical structures precisely based on 3D imaging with a minimally invasive approach. Additionally, the use of surgical robotics for pedicle screw placement is safe and accurate and limits the exposure of surgical staff to intraoperative radiation.^{12,13} However, only a few large-scale studies have compared robot-guided (RG) techniques with conventional fluoroscopy-guided (FG) techniques for TLIF.¹⁴ In this study, we compared intraoperative and postoperative parameters between RG and conventional MIS-TLIF procedures.

Methods

Patient Selection

Patient information was obtained with the approval of the IRB of Taipei Medical University. We retrospectively reviewed the medical records of patients with degenerative spinal pathology who underwent minimally invasive paraspinal surgery with the Wiltse approach for TLIF from March 2019 to April 2020. Patients were excluded if they 1) were younger than 18 years, 2) underwent revision of the instrumentation from prior spinal surgery, 3) had a preexisting lumbar spinal neoplasm, 4) underwent surgery with the midline approach, or 5) had insufficient (< 30 days) follow-up results. Patients were able to choose between two options for pedicle screw placement (RG or FG). Operations were performed by 5 spine specialists involved in the study. The collected patient data included age, sex, BMI, and Charlson Comorbidity Index score.

Surgical Technique for Freehand FG MIS-TLIF

The surgical procedure for the minimally invasive, Wiltse, posterolateral spinal approach for TLIF has been described in the literature.^{4,15–17} The patient was placed prone under general anesthesia. Decompression was performed on the side that was considered the most symptomatic. A paramedian incision was made approximately 2.5 cm to 3 cm away from the spinous process. After the fascia was opened, blunt dissection of paraspinal muscles was performed. The facet joint and transverse process were palpated. A dilator pin was placed on the facet joint parallel to the superior endplate of the intervertebral disc under fluoroscopic guidance. Next, sequential tubular dissection was performed using the MAST QUADRANT (Medtronic) retractor system. The soft tissue overlying the facet joint and lamina was removed. After identification of perifacet bony structures, unilateral laminectomy and inferior facetectomy were performed for adequate nerve root decompression. After discectomy and endplate preparation, an interbody cage with bone fragments was inserted into the disc space. Subsequently, pedicular screws were inserted freehand with fluoroscopic guidance. The anatomical landmarks, including the transverse process and facet joint, were exposed. The entry point of the pedicle screw was defined at the confluence of the transverse process and pars interarticularis. The posterior cortex of the entry point was opened with an awl or burr. A curved pedicle probe was used to drill into cancellous bone. The mediolateral inclination of the probe typically ranged from 5° to 10° in the upper lumbar spine and 10° to 15° in the lower lumbar spine. The probe was advanced

slowly to the anterior third of the vertebral body parallel to the superior endplate without cranial or caudal angulation in the sagittal plane. The superoinferior trajectory was maintained under fluoroscopic guidance. The pedicle track was palpated with a ball-tipped sensor to confirm that it was completely interosseous and that the trajectory could be repositioned once the pedicle breach was encountered. Subsequently, the pedicle track was tapped along the same trajectory as the probe, and the screw was then inserted. The ipsilateral screws were connected using a rod. The same surgical approach for foraminotomy was performed on the contralateral side, when needed. Percutaneous pedicle screws were placed via fluoroscopic guidance when decompression was not necessary. The pedicles were inspected using orthogonal anteroposterior radiographs. A small skin incision was made laterally to the pedicle. Blunt dissection of subcutaneous tissue, fascia, and muscles was performed using scissors. A cannulated bone biopsy needle was placed at the midpoint of the lateral border of the pedicle. The needle was hammered through the posterior cortex in the appropriate direction. A lateral radiograph was obtained to confirm the trajectory when the needle reached the medial border of the pedicle. If the tip of the needle had not passed through the posterior part of the vertebral body, the needle was repositioned. After the needle tip reached the anterior third of the vertebral body, a K-wire was placed via the cannulated needle. The needle was removed, and the K-wire was left in place. A cannulated screw with the appropriate length and diameter was placed along the K-wire. The positions of the screws were confirmed using fluoroscopy, and any malpositioning was revised immediately.

Surgical Technique for RG MIS-TLIF

The 4 surgical steps are shown in Fig. 1. The entire procedure was performed under general anesthesia. The patient was positioned prone on a radiolucent table with the O-arm intraoperative imaging system (Medtronic). An optic camera was placed on the patient's lower-left side. After disinfection and draping, a reference pin was inserted percutaneously on the right posterior iliac wing. The reference pin and robot arm were then coregistered by the optic camera. The RG surgery comprised 4 stages, as follows.

1) Registration

The main purpose of this step was to map the 3D geometry of the spine into the 3D geometry of the robotics (Fig. 1A). To perform this step, a 3D registration pattern (32 metal balls), which was attached to the robotic arm, was placed on top of the level of the spine (operation level). The O-arm then scanned the 3D registration pattern and the spine image together, and the scanned images were uploaded to the robotic arm.

2) Planning

The trajectory of each screw was planned using ROSA software (Zimmer Biomet) (Fig. 1B). The entry site was on the lateral border of the superior articular process and a horizontal line that bisected the transverse process.¹⁸ The

FIG. 1. Surgical steps for ROSA surgery. **A:** Registration (mapping the 3D geometry of the spine into the 3D geometry of the robotics). **B:** Planning (selecting different entry sites via ROSA software). **C:** Pin insertion (using robotic guidance to reduce malpositioning). **D:** Confirmation (justification of pin insertion by O-arm).

target point was on the anterior third of the vertebral body. The path was proposed along the pedicle while maintaining orientation parallel to the superior endplate.

3) Pin Insertion With Robotic Guidance

In this step, avoiding “ripping”¹⁹ or “skiving”²⁰ effects during drilling was crucial because even with robotic guidance and trocars to guide the angle and position of the entry point, the drill can still move slightly without triggering the movement-tracking system. Hence, a tension-free technique was critical in this step; any tension related to soft tissue or slippage of the drill-bone surface could have led to malpositioning of the drill. After drilling to the vertebral body through the pedicle with robotic guidance, a K-wire was placed (Fig. 1C).

4) Confirmation

After completion of pin insertion, an O-arm scan was used to confirm the position of the pins (Fig. 1D). The accuracy measurement of the K-wire was defined according to the Gertzbein-Robbins scale.²¹ Malposition was defined as Gertzbein-Robbins grade C, D, or E. If malpositioning of the guidewire was found, the wire was necessarily

removed and the pedicle screw was placed with freehand fluoroscopy guidance.

Next, an initial dilator was placed through the K-wire, close to the inferior endplate of the intervertebral disc, which was expected for discectomy and interbody fusion. The subsequent tubular retractor was erected on the inferior facet joint, orthogonal toward the intervertebral disc. After decompression and fusion, cannulated screws with the appropriate length and diameter were placed along the reamed pedicle tracks. The ipsilateral screws were connected using a rod.

Outcome Measurement

Intraoperative outcomes included operative duration, estimated blood loss (EBL), and complications. We obtained numeric rating scale (NRS) pain scores on the day of surgery, postoperative day 1, and at the 1-month follow-up visit to assess short-term outcomes. Postoperative complications included medical- and procedure-related complications.

Pedicle screw breach was evaluated by 2 independent inspectors (M.C.L. and W.L.L.) using orthogonal postero-anterior and lateral plane radiography.^{22,23} Lateral breach

TABLE 1. Comparison of patient demographics and outcomes between freehand FG and RG MIS-TLIF

	FG (n = 149)	RG (n = 75)	p Value
Mean age, yrs	62.7 ± 12.61	65.38 ± 10.02	0.095
Sex, n			0.67
F	85	45	
M	64	30	
Mean BMI, kg/m ²	26.1 ± 4.0	25.8 ± 3.9	0.55
Mean CCI score	2.47 ± 1.5	2.41 ± 1.4	0.79
Mean hospital stay, days	7.3 ± 4.4	6.6 ± 3.4	0.19
Total no. of screws*	682	364	
2 levels	112/448	46/184	
3 levels	31/186	26/156	
4 levels	6/48	3/24	
Mean op duration, mins			
Total	251.4 ± 112.0	280.7 ± 98.1	0.056
2 levels	215.6 ± 76.0	235.8 ± 65.9	0.098
3 levels	324.4 ± 101.5	347.7 ± 99.8	0.507
4 levels	544.0 ± 128.5	388.7 ± 107.3	0.047
Mean EBL, mL			
Total	431.6 ± 529.8	313.7 ± 214.1	0.019
2 levels	289.7 ± 268.3	211.1 ± 119.1	0.012
3 levels	770.0 ± 863.1	473.8 ± 226.6	0.037
4 levels	1333.3 ± 320.4	500.0 ± 327.9	0.023
Complications, no. of pts (%)			
Intraop	2 (1.3)	1 (1.3)	0.45
Postop, medical-related	4 (2.7)	3 (4.0)	0.59
Postop, op-related	6 (4.0)	3 (4.0)	0.99
Pedicle screw breach			
Total no. of screws (%)	12/682 (1.75)	1/364 (0.27)	0.04
Medial	3	0	
Lateral	9	1	
Mean NRS pain score			
Preop	5.4 ± 1	5.6 ± 1	0.187
Postop day 1	1.8 ± 1.2	2.1 ± 1.2	0.144
1-month follow-up	1.3 ± 0.7	1.2 ± 0.5	0.610

CCI = Charlson Comorbidity Index; pts = patients.

Mean values are presented as the mean ± SD.

* Values represent the number of patients/number of screws.

was defined as the tip of the screw failing to cross the medial pedicle wall in the posteroanterior view. Medial breach was defined as the tip of the screw crossing the midline of the vertebral body. When the 2 inspectors disagreed on the existence of a pedicle breach, a third reviewer (C.M.L.) made the final decision.

Statistical Analysis

Data were analyzed using GraphPad version 9.1.2 (GraphPad Software). Descriptive analysis for each group (FG and RG) is shown as the mean ± SD for continuous variables. We used the Wilcoxon matched-pairs test for continuous data, Fisher's exact test for dichotomous data, and chi-square analyses for categorical data with > 1 response.

FIG. 2. Boxplots showing a comparison of the operative duration between freehand FG and RG pedicle screw implantation in MIS-TLIF for all procedures (A) and 2- (B), 3- (C), and 4-level (D) procedures. ns = not significant. * $p < 0.05$.

Results

Patient demographic data are shown in Table 1. A total of 224 patients underwent MIS-TLIF surgery during the study period. Pedicle screw placement was performed with RG surgery in 75 patients and freehand FG surgery in 149 patients. For the vertebral segments of fixation, 158 patients underwent 2-level surgery (FG/RG = 112/46), 57 patients underwent 3-level surgery (FG/RG = 31/26), and 9 patients underwent 4-level surgery (FG/RG = 6/3).

Among the outcomes studied, patients who underwent FG pedicle screw placement in MIS-TLIF surgery had a slightly shorter operative duration (251.4 ± 112.0 minutes vs 280.7 ± 98.1 minutes, $p = 0.056$; Fig. 2A). Subgroup analysis revealed no significant difference in the operative duration between the FG and RG groups for patients who underwent 2-level (215.6 ± 76.0 minutes vs 235.8 ± 65.9 minutes, $p = 0.098$; Fig. 2B) or 3-level (324.4 ± 101.5 minutes vs 347.7 ± 99.8 minutes, $p = 0.507$; Fig. 2C) fixation. However, the operative duration was significantly longer in the FG group for patients who underwent 4-level fixation than for those in the RG group (544.0 ± 128.5 minutes vs 388.7 ± 107.3 minutes, $p = 0.047$; Fig. 2D). We also found a significantly lower EBL in the RG group (FG vs

RG: 431.6 ± 529.8 mL vs 313.7 ± 214.1 mL, $p = 0.019$; Fig. 3A). Moreover, EBL was significantly lower for every subgroup of the RG group (FG vs RG 2-level fixation: 289.7 ± 268.3 mL vs 211.1 ± 119.1 mL, $p = 0.012$; 3-level fixation: 770.0 ± 863.1 mL vs 473.8 ± 226.6 mL, $p = 0.037$; 4-level fixation: 1333.3 ± 320.4 mL vs 500.0 ± 327.9 mL, $p = 0.023$) (Fig. 3B–D).

In terms of the intraoperative and postoperative complication rates, no significant difference was found between the FG and RG groups (intraoperative, 1.3% vs 1.3%, $p = 0.45$; postoperative medical-related, 2.7% vs 4.0%, $p = 0.59$; postoperative procedure-related, 4.0% vs 4.0%, $p = 0.99$). In the FG group, intraoperative iatrogenic durotomy occurred in 2 patients, screw malposition was found in 2 patients after surgery, and CSF leakage following wound infection occurred in 2 patients. In the RG group, malpositioning of the K-wire occurred in 1 patient, intraoperative durotomy during decompression occurred in 1 patient (with subsequent postoperative CSF leakage), and wound infection occurred in 2 patients. No significant difference in the duration of the hospital stay was found between the FG and RG groups (7.3 ± 4.4 days vs 6.6 ± 3.4 days, $p = 0.19$). Neither group had mortality within 30 days after surgery. Short-term pain control was also similar in both the FG and RG groups (postoperative day 1, 1.8 ± 1.2 vs 2.1 ± 1.2 , $p = 0.144$; postoperative day 30, 1.3 ± 0.7 vs 1.2 ± 0.5 , $p = 0.610$).

The accuracy of RG K-wire implantation was 99.85%. Among the 364 K-wires implanted, only 1 showed malpositioning (Gertzbein-Robbins grade C) and was revised under freehand fluoroscopic guidance. In terms of the accuracy of pedicle screw instrumentation, 12 screws exhibited pedicle breach (lateral/medial = 9/3) in the FG group and 1 screw exhibited lateral breach in the RG group (1.75% vs 0.27% , $p = 0.04$).

Discussion

This is the largest study to compare screw placement guided by a floor-mounted surgical robot with that of freehand placement guided by fluoroscopy for MIS-TLIF. In this retrospective case-control study, we identified advantages of a surgical robot, including more precise screw placement, reduction of intraoperative blood loss, and a shorter operative duration in complex spinal surgery. No significant differences were found in operative duration in 2- and 3-level surgery, complications, hospital stay, and short-term pain control for RG surgery compared with the freehand procedure. We propose that the use of a surgical robot not only provides reliable safety but also aids users in performing minimally invasive spinal surgery.

Accuracy of RG Pedicle Screw Placement

Pedicle screws are routinely used to maintain spinal stability in spinal fusion. To place the pedicle screw during a freehand minimally invasive procedure, real-time fluoroscopy is always needed for optimal instrumentation. The incidence of pedicle perforation during freehand screw placement is 15%,²⁴ whereas RG placement of pedicle screws provides an optimal accuracy of 85% to 100%.¹⁴ Many studies have reported the application of

FIG. 3. Boxplots showing a comparison of EBL between freehand FG and RG pedicle screw implantation in MIS-TLIF for all procedures (A) and 2- (B), 3- (C), and 4-level (D) procedures. * $p < 0.05$.

patient-mounted robots (Mazor Surgical Technologies). Lonjon et al.²⁹ conducted a prospective study to investigate the safety and accuracy of the same robot device as that used in our institution. They found higher accuracy with the robot (97.3%, Gertzbein-Robbins grades A and B) compared with the freehand technique (92%). Our results showed that robotic guidance provided higher accuracy than freehand fluoroscopic guidance. We believe that the floor-mounted base and rigid arm of our device ensured that the planned trajectory was maintained. Additionally, dynamic tracking ensured that the movement of the robot arm was synchronized to the patient's movement, preventing trajectory deviation during pedicle drilling. The results also suggested that the floor-mounted robot for pedicle screw implantation provided accuracy similar to that of the patient-mounted robot reported in the literature.

Robotics Offers Greater Bleeding Control in Paramedian MIS-TLIF

The major causes of bleeding during paramedian spinal fusion are dissection of intramuscular vasculature before surgical corridor placement, disruption of the venous plexus during osteotomy and discectomy, and pedicle tapping for screw placement. In our practice, we

typically place the pedicle screw after decompression and cage placement. This workflow is commonly adopted worldwide.²⁵ Because intraoperative bleeding is limited in minimally invasive procedures, continuous oozing from the decompression site during screw placement cannot be ignored. Thus, computer-aided navigation guidance has become popular in spinal fixation to facilitate the surgical workflow and reduce complications. Fan et al. retrospectively reviewed the common technologies for pedicle screw placement, including robotic guidance, navigation templates, O-arm navigation, and fluoroscopic guidance.²⁶ They found significantly less blood loss during procedures with these technologies in comparison with the freehand technique. Our results also suggested that bleeding can be controlled under robotic guidance. We believe that the application of robotics can help surgeons localize the decompression site and track percutaneous pedicles instead of relying on extended periosteal dissection to expose the facet joint and transverse process during freehand procedures.

Robotics Can Facilitate Workflow During Minimally Invasive Spine Surgery

The success of minimally invasive procedures depends on the surgeon's experience. Mastery in this regard is inherently difficult and has a long learning curve.^{8,27} Moreover, a longer operative duration is typically required, particularly in complex cases. Performing bilateral tubular decompression, as well as screw placement, in severe spinal stenosis with bilateral lateral recess or foraminal stenosis is challenging. The surgical window for performing decompression and placing pedicle screws is not the same in most cases. To increase exposure of the surgical field, the operator must localize the surgical segment and ensure that the working channel is correctly oriented to Kambin's triangle. To place pedicle screws, the operator must translate and angle the retractor to gain pedicle access. Repetitive adjustment of the position of the surgical corridor and confirmation of retractor orientation are typically required, particularly in multisegment or complex spinal surgery. This often demands finesse and is time-consuming work. In our study, the operative duration of RG MIS-TLIF was no different from that of freehand surgery for 2- and 3-level fixation, and the time-saving effect observed for 4-level fixation with robotic guidance is encouraging. The use of robotics can help surgeons to not only place screws efficiently but also mount retractors effectively. However, the results in the literature are inconsistent. A systematic review revealed that an extended operative duration has been reported for most procedures performed under the guidance of patient-mounted robotics.²⁸ Lonjon et al. reported the preliminary results of a prospective comparative study between floor-mounted robotic guidance and freehand pedicle screw implantation in TLIF surgery, and an extended operative duration was also reported.²⁹ Another study group retrospectively compared the outcomes of floor-mounted robotic guidance and freehand, conventional, open short-segment lumbar fusion. They found a similar operative duration between the freehand and RG groups.³⁰ Although it takes almost 2 hours to operate the robot, guidewires can be placed quickly one after another without checking the orientation of pedicle

tapping under real-time fluoroscopy, which is a necessity during freehand procedures. Moreover, with robotic guidance, the operator can design the ideal trajectory for placement of the corridor to perform decompression. We believe that RG pedicle screw placement can be beneficial in select cases, particularly in complex or long-segment spinal surgery.

Study Limitations

In our case series, we did not collect information regarding radiation exposure during the operation or the duration of screw placement in the freehand group because this was a retrospective review. Our evaluation did not involve measuring the accuracy of 3D imaging in the freehand group. Further prospective investigation is necessary.

Conclusions

Our retrospective review found that RG MIS-TLIF is a safe and accurate alternative to conventional freehand techniques. Moreover, robotics can improve efficiency in complex cases.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

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