Research Article

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Journal of **Comparative Effectiveness Research**

# Robot-assisted minimally invasive transforaminal lumbar interbody fusion versus open transforaminal lumbar interbody fusion: a retrospective matched-control analysis for clinical and quality-of-life outcomes

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**Aim:** To compare the screw accuracy and clinical outcomes between robot-assisted minimally invasive transforaminal lumbar interbody fusion (RA MIS-TLIF) and open TLIF in the treatment of one-level lumbar degenerative disease. **Materials & methods:** From May 2018 to December 2019, a consecutive series of patients undergoing robot-assisted minimally invasive one-level lumbar fusion procedures were retrospectively compared with matched controls who underwent one-level open TLIF procedures for clinical and quality-of-life outcomes. **Results:** A total of 52 patients underwent RA MIS-TLIF procedures (robot-assisted [RA] group) and 52 matched controls received freehand open TLIF procedures (open [OP] group). The RA group had more grade A screws with 96.2% one-time success rate of screw placement ($p < 0.05$). Besides, the RA group experienced less intraoperative blood loss and shorter length of hospital stay, while the OP group had shorter operative duration and cumulative radiation time ($p < 0.001$). What is more, the average VAS score for low back pain and ODI score in the RA group were lower than that in the OP group 1 month after operation ($p < 0.05$). **Conclusion:** The use of real-time, image-guided robot system may further expand the advantages of MIS-TLIF technique in terms of accuracy and safety.

First draft submitted: 22 March 2021; Accepted for publication: 19 April 2021; Published online: 28 April 2021

**Keywords:** comparative effectiveness research • lumbar disc disease • minimally invasive surgical procedures • pedicle screw • robot

Reflecting the increasing size of elderly population, the spine surgeons are faced with a constant rise in the prevalence of lumbar degenerative disease, which brings a heavy burden on not only patients but also healthcare providers [1]. Since Harms *et al.* introduced the open transforaminal lumbar interbody fusion (TLIF) in 1982, it has become a popular and effective technique for lumbar fusion in the treatment of lumbar degenerative disease [2,3]. However, the open TLIF procedure is highly invasive and often requires a long midline incision with extensive paraspinal muscle detachment, which may lead to more soft tissue injury and longer hospital stay [4].

With the advances in minimally invasive spine surgery, Foley *et al.* introduced minimally invasive TLIF (MIS-TLIF) approach in 2002, which subsequently showed several advantages such as less intraoperative blood loss, shorter recovery time and fewer complications with comparable outcomes [5–8]. Latest review suggested that 79% of MIS-TLIF publications inserted pedicle screws in a percutaneous approach [9]. Given the indirect visual access of entry point for pedicle screw placement, the risk of screw malposition and perforation may increase in conventional

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MIS-TLIF procedure [10,11]. Therefore, technology such as robotic assistance and navigation seems to be gaining popularity in pedicle screw placement among spine surgeons [12,13].

Several studies had reported that robotic systems could increase the accuracy of pedicle screw instrumentation and decrease blood loss and radiation exposure to surgeon during spine surgery [14,15]. Thus, the robotic system could be particularly suitable for minimally invasive surgical procedures. However, the sample volume and follow-up data of previous clinical reports were limited [16–19]. Hence, additional evidence such as long-term follow-up was still needed to evaluate the value of robotic assistance in clinical practice. The purpose of this study was to investigate the screw accuracy and clinical outcomes of robot-assisted (RA) MIS-TLIF (RA MIS-TLIF) in the treatment of one-level lumbar degenerative disease.

In this study, we reported our clinical experience with the TiRobot system in one-level MIS-TLIF procedure and compared the result with matched historical cohort treated with the open TLIF technique. Meanwhile, as a completely new surgical tool, the learning curve of the TiRobot system in performing MIS-TLIF was also concerned in our study.

## Materials & methods

### Subjects

This is a retrospective cohort study with matched control. The study was approved by the Institutional Review Board (approved no.: KY2020-153) and all participants had received detailed information and given written informed consent. A total of 52 consecutive patients who underwent one-level RA MIS-TLIF between May 2018 and December 2019 were included as the RA group. Inclusion criteria were as follow: >18 years of age, patient complied with study; lumbar degenerative disease required one-level lumbar fusion, after failure of conservative treatment; a minimum of 12 months follow-up after operation. Patients were excluded according to these criteria: lumbar degenerative disease with infection, tumor, tuberculosis and fracture; history of spinal surgery on intended level; severe pre-operative comorbidities; incomplete data for reviewing the case.

A series of matched cases underwent one-level open TLIF between January 2017 to April 2018 were included as the open (OP) group, which were based on age, sex, BMI, primary diagnosis, operated level and comorbidities using the American Society of Anesthesiologists Physical Status Classification System (ASA grade) [20]. All operations were performed by one surgical team led by a well-trained senior surgeon with >20 years of clinical experience.

### RA MIS-TLIF procedure

Operations were performed under general anesthesia with patients placed in prone position on the Jackson carbon fiber operation table (Mizuho OSI, AS, USA). The TiRobot system (TINAVI, China) was composed of an optical tracking system, a flexible robot arm and a controlling workstation for screw trajectory planning (Figure 1). The general work flow of RA MIS-TLIF procedure was summarized in Figure 2 and 3. To avoid additional incision for tracker anchoring, the patient tracker was securely attached as close as possible to the skin and surgical area by multiple incise drapes and tapes (Figure 3D). The reference fiducial marker array and tracker on robot arm were matched in the surgical field via lateral and anteroposterior fluoroscopy. Subsequently, a set of images containing reference marker were obtained by intraoperative 3D C-arm scanning, and transferred to workstation of TiRobot system to construct 3D spinal segment model (Figure 3A & B). Registration was automatically achieved in this process. On working station, the length, diameter and position of pedicle screw were planned by surgeon (Figure 3C). Then four K-wires were percutaneously inserted with robotic assistance. During the placement of K-wires, the TiRobot system could provide real-time monitoring and adjustment. Once the position of K-wires was confirmed by lateral and anteroposterior fluoroscopy, the robot was removed from surgical field.

On the basis of the neurological symptoms, two cannulated screws were placed percutaneously along the K-wires into the asymptomatic side pedicles. Screw trajectories of symptomatic side pedicles were prepared. The remaining two screws should be placed after performing decompression and interbody fusion procedure, otherwise the tails of the screws would interfere with the instruments in the following process.

According to clinical indication, bilateral or unilateral decompression was conducted via paramedian incision and Wiltse approach between ipsilateral two screws. After transforaminal interbody fusion with cage augmented by autologous bone graft, the remaining two screws were placed along the previous trajectories in pedicles. Postoperative computed tomography (CT) scan was performed in all cases 3 days after surgery to verify the position of implants (Figure 3J & K).

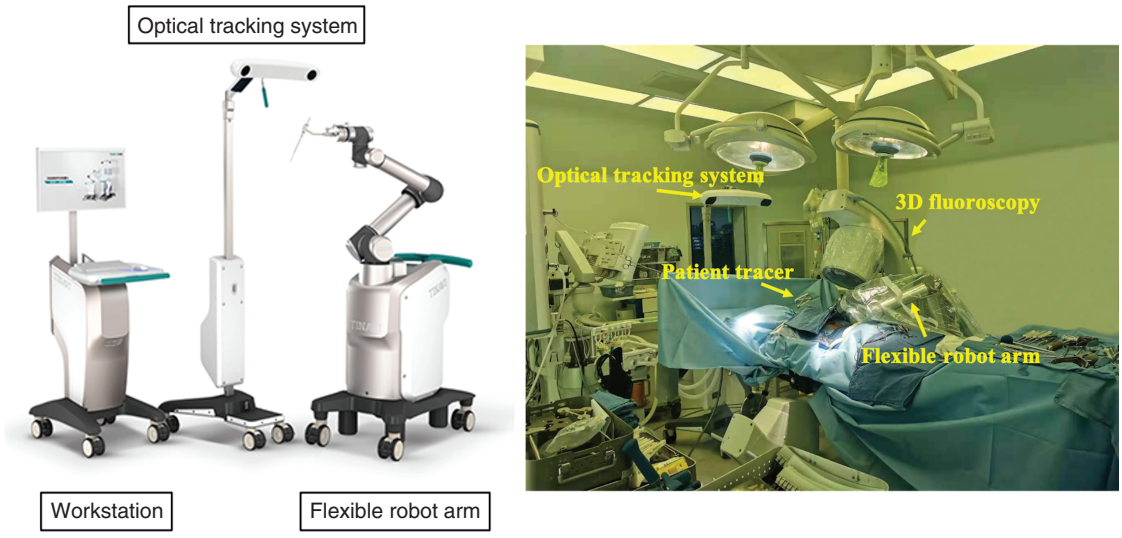


**Figure 1. The composition of TiRobot system: a flexible robot arm, an optical tracking system and a surgical planning workstation.**

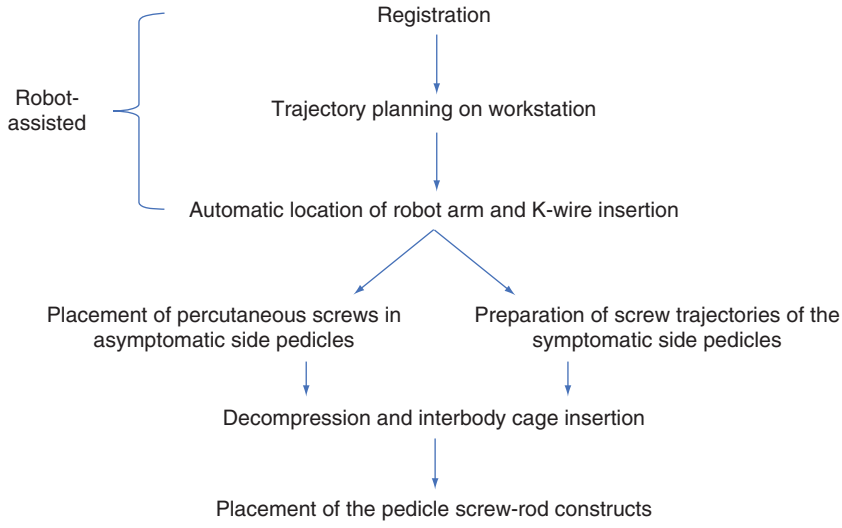


**Figure 2. The general work flow of robot-assisted minimally invasive transforaminal lumbar interbody fusion surgery.**

## Open TLIF procedure

In the conventional open group, patients were placed on the radio-transparent operating table in prone position after general anesthesia. Open TLIF procedure was performed through a midline incision on the back as described in previous studies [8]. Intraoperative C-arm fluoroscopy were used after pedicle screw placement to confirm the screw position.

## Accuracy measurement of screw position

The position of each pedicle screw was evaluated with Gertzbein-Robbins grading system on postoperative computed tomography images obtained from first time follow-up. Grade A screws were within pedicle; Grade B screws encroached on pedicle wall by <2 mm; Grade C screws breached pedicle wall by 2–4 mm; Grade D screws breached pedicle wall by 4–6 mm; Grade E screws breached pedicle wall by >6 mm. Grade A or B screws were considered as clinically acceptable [21]. These measurements were conducted by two separate spine surgeons who did not participate in the operation in a blinded fashion. Each of spine surgeons had at least 10 years of clinical

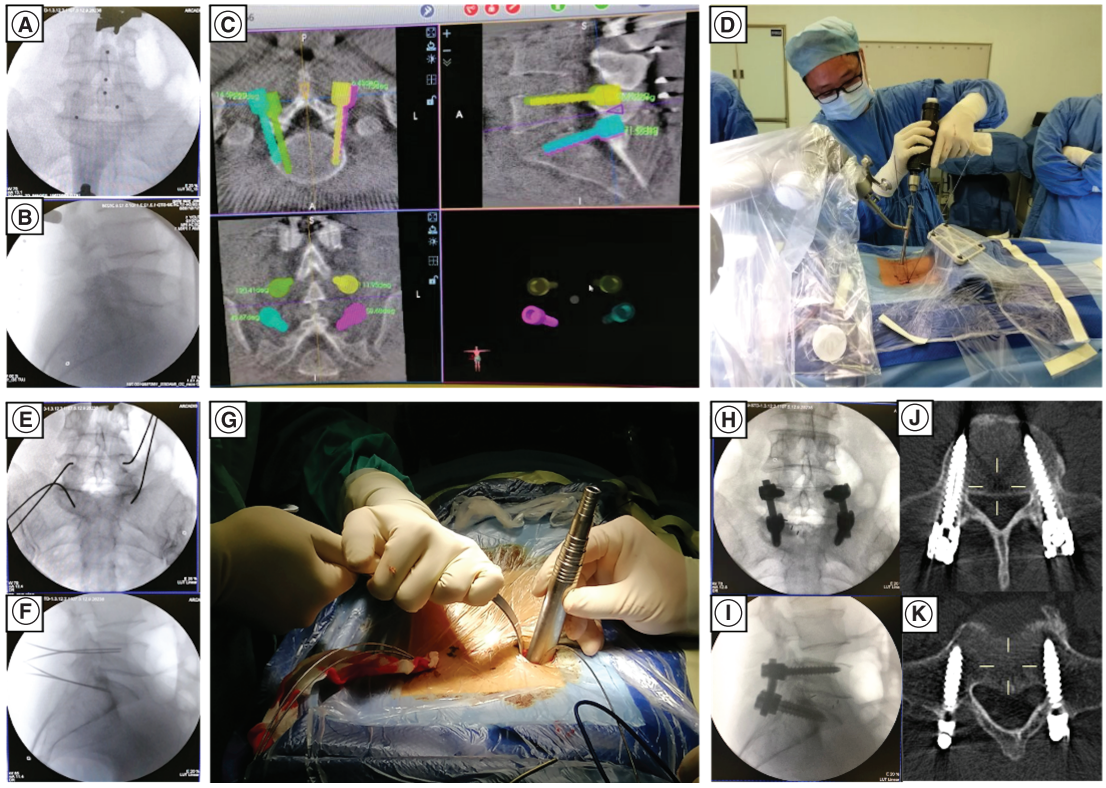


**Figure 3. The general steps of robot-assisted minimally invasive transforaminal lumbar interbody fusion surgery.** Registration **(A–B)**; trajectory planning **(C)**; automatic location and manual K-wire insertion **(D)**; confirmation of K-wire position **(E–F)**; performance of minimally invasive transforaminal lumbar interbody fusion procedure **(G)**; fluoroscopy for screw position verification **(H–I)**; evaluation of screw grade by postoperative computed tomography scan **(J–K)**.

experience. If divergence occurred, two surgeons would discuss and re-evaluate the controversial CT scan again after an interval of 5 days to reach the final consensus.

## Clinical outcomes measurements

The one-time success rate of RA pedicle screw placement referred to the ratio of the number of pedicle screws successfully inserted in one attempt to the total screw number with robotic assistance. Operative duration, cumulative radiation time, intraoperative blood loss, length of hospital stay, adverse events and revisions were recorded. To evaluate clinical outcomes, self-rating Visual Analog Scale (VAS) was recorded to assess the severity of pain in low back and leg, and Oswestry Disability Index (ODI) was used to quantify disability of patients. All the evaluation were performed pre-operatively and at 1-, 6- and 12-months postoperative follow-up. The overall patient-reported outcomes were compared with their minimal clinically important difference (MCID). If the magnitude of the treatment effect ≥MCID, we could consider that the treatment substantially improved clinical outcomes. The reference MCIDs used in this study were three for VAS scores and 15 for ODI scores [22,23].

Radiological assessment consisted of lumbar plain radiograph in anteroposterior, lateral and flexion-extension view, CT scans and MRI. Solid fusion at 12 months was evaluated based on flexion-extension radiographs with following criteria: visible bridging trabecular bone in the intervertebral space; less than 5 degrees of angulation on flexion-extension view; less than 3 mm of translation on flexion-extension view [24]; no cage migration; no screw loosening. If plain x-ray did not show a clear fusion, then the patients were evaluated by CT scan. The fusion criteria used the protocol of Williams *et al.* [25]: no lucency at the margins; no visible fracture of the cage or vertebrae; no cystic changes within the endplates adjacent to the cage; no any linear defects (fracture) through the intervertebral new bone formation within or surrounding the cage; no subsidence or dislocation of the cage and bridging bone surrounding or within the cage. The radiological fusion criteria were evaluated by two blinded

Table 1. Patient demographics in two groups.

| Characteristics | RA group (n = 52) | OP group (n = 52) | p-value |
|---|---|---|---|
| – Age (years) | 57.98 ± 12.63 | 58.08 ± 9.87 | 0.966 |
| – Sex (M/F) | 32/20 | 31/21 | 0.841 |
| – Mean BMI (kg/m$^2$) | 24.86 ± 3.82 | 23.71 ± 2.68 | 0.079 |
| Primary diagnosis | | | 0.812 |
| – Symptomatic lumbar disc herniation | 37 | 34 | |
| – Symptomatic lumbar spinal canal stenosis | 8 | 10 | |
| – Symptomatic lumbar spondylolisthesis | 7 | 8 | |
| ASA grade | | | 0.695 |
| – Grade 1 | 0 | 0 | |
| – Grade 2 | 28 | 25 | |
| – Grade 3 | 24 | 27 | |
| – Grade 4 | 0 | 0 | |
| Level of fusion | | | 0.716 |
| – L3–L4 | 7 | 9 | |
| – L4–L5 | 28 | 24 | |
| – L5–S1 | 17 | 19 | |
| – Mean follow-up time (months) | 15.81 ± 3.33 | 16.62 ± 3.38 | 0.222 |

Grade 1: a normal healthy patient; Grade 2: a patient with mild systemic disease; Grade 3: a patient with severe systemic disease; Grade 4: a patient with severe systemic disease that is a constant threat to life. There was no significant difference in these baseline parameters between two groups.
ASA Grade: The American Society of Anesthesiologists Physical Status Classification System; F: Female; L: Level; M: Male; OP group: Open group; RA group: Robot-assisted group.

investigators (one senior surgeon and one junior surgeon). When they had different fusion results, they discussed and reached a consensus.

### Learning curve evaluation

The learning curve of RA MIS-TLIF was evaluated through scatter plot and logarithmic curve fitting regression analysis. The fitting equation was $y = aln(x) + b$, in which x was the number of operation cases and y was the operative duration or robot usage time. Scatter plot (operation number vs operative duration and robot usage time) could demonstrate the trend of operative time fluctuating with the number of operation cases.

### Statistical analysis

The SPSS 25.0 software was used for the statistical analysis and the G*Power 3.1 software was applied in *post hoc* power analysis for each statistically significant outcome. Shapiro–Wilk test was used for normal distribution determination. Measurement data was expressed by $x \pm s$. Student's t-tests were used for measurement data outcome comparison. Paired-sample t-tests and repeated measure ANOVA were used to compare the changes between preoperative and postoperative outcomes measurements. The pairwise comparisons were then conducted through multiple paired t-tests with a Bonferroni correction. Differences of enumeration data were compared using chi-square tests. The learning curve of RA MIS-TLIF procedure was evaluated by logarithmic curve fitting regression analysis. The statistical significance level was set at $p < 0.05$.

## Results

The demographic characteristics of both groups were listed in Table 1. RA group consisted of 52 patients (32 males and 20 females) while OP group had 52 patients (31 males and 21 females). The average age was 58.03 ± 11.28 years, ranging from 18 to 88 years. The mean BMI was 24.28 ± 3.33 kg/m$^2$. No significant differences were found between these two groups in terms of age, sex, BMI, primary diagnosis, operated level and ASA grade ($p > 0.05$). The mean follow-up time was 16.21 months (range: 12–23 months).

### Accuracy of screw position

Accuracy measurements of screw position were summarized in Table 2. In the RA group, the one-time success rate of screw placement was 96.2% (200/208). Moreover, the rate of 'perfect' screw (Grade A) was also superior

**Table 2. Accuracy measurements of the pedicle screw fixation.**

| Variables | RA group(n, [%]) | OP group(n, [%]) | p-value |
|---|---|---|---|
| Total | 208 | 208 | |
| Screw grade | | | <0.001 |
| – A† | 192 (92.3) | 161 (77.4) | |
| – B | 13 (6.3) | 40 (19.2) | |
| – C | 3 (1.4) | 6 (2.9) | |
| – D | 0 (0.0) | 1 (0.5) | |
| – E | 0 (0.0) | 0 (0.0) | |
| – A + B | 205 (98.6) | 201 (96.6) | 0.338 |

Gertzbein and Robbins Grading System: Grade A, screw is completely within the pedicle; Grade B, pedicle cortical breach <2 mm; Grade C, pedicle cortical breach <4 mm; Grade D, pedicle cortical breach <6 mm; Grade E, pedicle cortical breach >6 mm.
†Means statistical difference between two groups ($p < 0.05$).
OP group: Open group; RA group: Robot-assisted group.

**Table 3. Comparison of surgical outcomes between two groups.**

| Surgical outcomes | RA group | OP group | p-value |
|---|---|---|---|
| Operative time (min) | 169.67 ± 26.92 | 135.48 ± 43.77 | <0.001 |
| Intraoperative blood loss (ml) | 91.52 ± 25.87 | 261.1 ± 48.42 | <0.001 |
| Length of hospital stay (day) | 6.9 ± 1.7 | 10.5 ± 2.1 | <0.001 |
| Radiation time (min) | 1.26 ± 0.24 | 0.54 ± 0.20 | <0.001 |
| Perioperative complication | 0 | 1 | |
| Revision | 0 | 0 | |

OP group: Open group; RA: Robot-assisted.

**Table 4. Visual Analog Scale and Oswestry Disability Index scores between robot-assisted and open group.**

| Variables | RA group | OP group | p-value |
|---|---|---|---|
| VAS scores for low back pain | | | 0.136 |
| – Pre-operative | 5.37 ± 1.27 | 5.46 ± 1.02 | |
| – 1 m after surgery† | 2.64 ± 0.66 | 3.10 ± 0.70 | |
| – 6 m after surgery | 1.96 ± 0.52 | 2.08 ± 0.59 | |
| – 12 m after surgery | 0.54 ± 0.50 | 0.69 ± 0.47 | |
| VAS scores for leg pain | | | 0.830 |
| – Pre-operative | 5.90 ± 1.19 | 6.08 ± 1.23 | |
| – 1 m after surgery | 2.40 ± 0.72 | 2.62 ± 0.69 | |
| – 6 m after surgery | 1.56 ± 0.61 | 1.69 ± 0.67 | |
| – 12 m after surgery | 1.02 ± 0.58 | 1.06 ± 0.64 | |
| ODI scores (%) | | | 0.210 |
| – Pre-operative | 41.69 ± 3.49 | 42.08 ± 3.22 | |
| – 1 m after surgery† | 22.21 ± 3.54 | 23.85 ± 2.55 | |
| – 6 m after surgery | 15.92 ± 1.58 | 16.23 ± 1.79 | |
| – 12 m after surgery | 12.48 ± 1.66 | 12.67 ± 1.76 | |

†Means statistical difference between two groups ($p < 0.001$).
m: Month; ODI: Oswestry Disability Index; OP group: Open group; RA: Robot-assisted; VAS: Visual Analog Scale.

to that in the OP group (92.3 vs 77.4%; $p < 0.001$). No significant difference was noted in the rate of 'clinically acceptable' (Grade A or B) screw placement between groups (98.6 vs 96.6%; $p = 0.338$).

## Clinical outcomes

The results of clinical outcomes were listed in Table 3 and Table 4. Patients in the RA group showed less intraoperative blood loss than those in the OP group (92 vs 261 ml; $p < 0.001$). Also, patients undergoing RA fusion had significantly shorter length of stay compared with length of hospital stay in the OP group (6.9 vs 10.5 day; $p < 0.001$). Conversely, the operative duration (169.67 vs 135.48 min; $p < 0.001$) and radiation time (1.26 vs 0.54 min; $p < 0.001$) in the RA group were longer than those in the OP group with statistical significance.

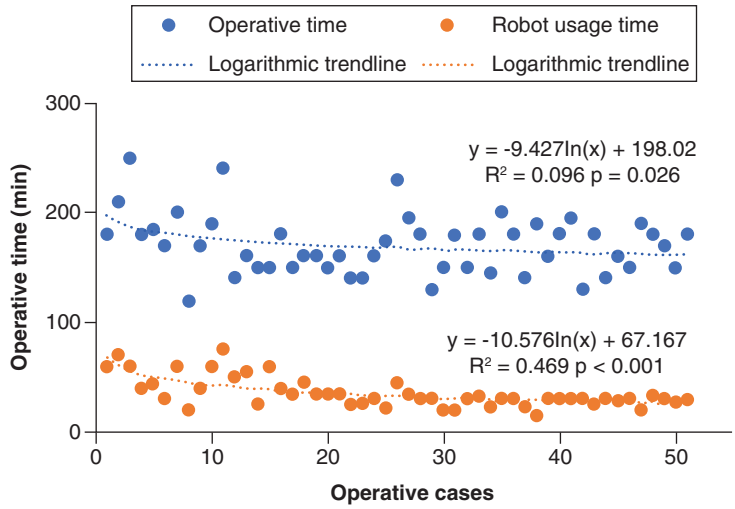


**Figure 4. Curve fitting using logarithmic regression between operative time and number of operation cases.**

In respect to patient-reported outcomes, the results of repeated measure ANOVA test demonstrated that both two groups showed improvement in average ODI score and VAS scores for low back/leg pain after operation (time effect, $p < 0.001$). Patients in the RA group showed lower average ODI score and VAS score for back pain than those in the OP group 1 month postoperatively ($p < 0.001$). However, there were no significant group–time interactions which indicated the comparable clinical outcomes achieved by RA technique or OP technique ($p = 0.136$ for VAS back pain interaction; $p = 0.830$ for VAS leg pain interaction; $p = 0.210$ for ODI score interaction) (Table 4). Follow-up at 6 and 12 months after operation showed no significant differences in ODI score and VAS score for back pain between groups. Also, there was no significant difference in VAS score for leg pain between these two groups. As for the bony fusion rate, two groups showed comparable fusion at 12 months postoperative follow-up without statistical significance (RA: 94.2% [49/52] vs OP: 92.3% [48/52]; $p > 0.05$]. Dural tear occurred in one case in the OP group and no revision was needed in both groups. The *post hoc* power analysis of each statistically significant outcome showed that all the actual power (1-β) were more than 0.9.

### Learning curve

To evaluate the learning curve for the real-time image-guided robot, we used a scatter plot showing operation number versus operative duration and robot usage time (Figure 4). The learning curve of the first 20 cases fluctuated significantly. After 20 cases, the robot usage time was significantly shortened, and the curve tended to be stable. However, the learning curve for overall operative duration showed more fluctuant pattern compared with that of robot usage time. Through logarithmic curve fitting regression analysis, we found that both the overall operative time ($y = -9.427\ln[x] + 198.02$, $R^2 = 0.096$; $p = 0.026$) and the robot usage time ($y = -10.576\ln[x] + 67.167$, $R^2 = 0.469$; $p < 0.001$) decreased significantly with the increase of operation cases, which exhibited a stable trend after 20 cases.

## Discussion

Compared with conventional open TLIF, MIS-TLIF was believed to have several advantages due to its minimally invasive principles such as minimizing soft tissue damage, performing bilateral decompression through unilateral approach and keeping stabilization of the posterior spinal segment [9]. With the advancement of robotic technology, spine surgeons could perform the operation in a more accurate and precise robot-assisted manner [26]. The TiRobot system that we used was a multi-indication, real-time, image-guided orthopaedic surgical robot approved by China in 2016. So far, several literature have been published to evaluate the accuracy and clinical outcomes with utilization of orthopaedic robot in posterior cervical surgery and thoracolumbar surgery [14,27–29]. At present, there is an increasing number of studies focusing on the combination of robot with MIS-TLIF technique in the treatment of lumbar degenerative disease [16–19,26,30]. These studies showed better or non-inferior screw accuracy and perioperative outcomes compared with freehand or fluoroscopy-guided techniques. However, the 12 months follow-up data such as VAS score or ODI scores were absent in these studies. Therefore, this study compared the

accuracy and clinical outcomes between RA MIS-TLIF and open TLIF technique to discover the potential value of robotic assistance in minimally invasive spinal surgery with a minimum 1-year follow-up.

In this retrospective cohort study, patients in the RA MIS-TLIF group had high one-time success rate of screw placement as well as higher screw accuracy, which was in accordance with some previous literature using RA techniques [18,27,31,32]. Roser *et al.* found a 99% accuracy rate of lumbosacral pedicle instrumentation using the SpineAssist robot compared with 98% utilizing fluoroscopy guided, and 92% using navigation techniques [33]. Schizas *et al.* reported a 95% accuracy rate versus 92% for robot-assisted versus fluoroscopic-guided lumbosacral pedicle screw instrumentation [34]. Kantelhardt *et al.* similarly showed 95% accuracy versus 92% using SpineAssist and conventional fluoroscopy, respectively [32]. We proposed several factors which might contribute to the high accuracy of RA technique. First was that the 3D intraoperative image obtained from circumferential C-arm fluoroscopy could provide more detailed and multidimensional information to the robotic system, which enabled spine surgeon to plan the trajectory for optimal screw placement on the workstation. After determining the angle and direction of the screw trajectories, the screws could be placed precisely on the basis of preplanned trajectory. Through robotic guidance, spine surgeon could minimize the risk of percutaneous screw malposition. Second, with real-time monitoring from sensitive optical tracking system and the flexible robotic arm, spine surgeon could stick to the predetermined screw trajectory, even when the position of patient changed due to respiratory movement [35]. Another factor was that the strenuous and challenging surgical procedures could lead to physical and psychological fatigue of the surgeon, which might further influence the accuracy of screw placement [26]. Whereas, the robotic assistance could reduce manual errors and perform repetitive work without fatigue [36]. What is more, the high one-time success rate of pedicle screw placement suggested that the RA technique could not only increase the pullout strength of screws, but also save time for readjustment of the screw position, leading to less damage to the pedicle, facet joint and soft tissue [37,38]. Given that intraoperative screw revision could affect the integrity of screw trajectory, the high one-time success rate of screw insertion was often appreciated due to higher pullout strength and lower risk of internal fixation failure [39,40]. For long-term outcome, one review showed lower revision rate after robot-assisted spinal surgery ($p < 0.01$, odds ratio 8.1) [39]. Hence, we demonstrated the evidence that the utilization of RA technique in MIS surgery could augment its accuracy and precision, and finally benefit patient's long-term outcome.

In aspect of clinical outcomes, RA group had lower intraoperative blood loss and shorter hospital stay relative to those in the OP group. Also, we found that the RA group showed statistically better VAS score for back pain and ODI score at 1 month postoperative follow-up without complication and revision. This could be attributed to smaller incision, higher accuracy and less tissue damage, which indicated a faster and better back pain recovery from RA MIS-TLIF surgery. What is more, we calculated the mean difference in VAS and ODI at 1-year follow-up and then evaluated whether the mean differences exceeded the MCID. The VAS for back pain decreased by 4.83 in RA group and 4.77 in OP group, which were higher than the MCID of three points. For leg pain, the mean improvement was 4.89 in RA group and 5.02 in OP group, which were also higher than the MCID. The mean improvement in ODI was 29.21 in RA group and 29.40 in OP group. This was nearly twice as high as the MCID of 15 points. All of these suggested that RA MIS-TLIF technique could improve fast recovery of patients and help to cut down the hospitalization cost due to shorter hospital stay, which was in line with previous studies [41,42]. In general, RA MIS-TLIF could acquire satisfying and comparable clinical outcomes for at least 1 year, with a faster recovery from back pain due to less tissue damage.

In terms of less trauma, we attributed this to the excellent combination of MIS and RA techniques, where the MIS ensured less soft tissue injury and RA guaranteed less hard tissue damage by providing precise guidance for decompression via accurate K-wire insertion. In our clinical practice, we tended to perform percutaneous pedicle screw placement at asymptomatic side and prepare the screw canal at symptomatic side first, followed by decompression and interbody cage insertion and finally placement of pedicle screw. The former prepared screw canal could indicate the position of the superior and inferior pedicles and help surgeon to determine the osteotomy level of the superior and inferior facet joints, which could provide maximum protection of the posterior spinal structures. In this short cohort, there was neither complication nor revision happened in the RA group, which required further follow-up to evaluate long-term prognosis.

However, the operation and radiation time were longer in the RA group. Some studies believed that the RA procedure could increase the operative duration [43,44], while some studies reported no significant difference in operative time between RA technique and freehand technique [31]. The increased operative duration can be attributed to the initial learning curve and the additional time for robot usage. In addition, the pre-operative robot

preparation and screw trajectory planning also increased the operative duration. Our learning curve experience showed that after 20 cases the robot usage time could reach a stable plateau, while the overall operative time was still fluctuated. This phenomenon might be attributed to different degree of lumbar degeneration and anatomical variances. Several studies suggested that the learning curve for robotic surgery might lie within the range of 20–50 cases, which was also observed in this study [45,46]. The overall operative duration and robot usage time showed a decreasing trend with the increase of cases. After achieving the initial learning curve with better understanding of the work flow of robot-assisted procedure, RA MIS-TLIF technique could be a reliable and effect alternative for treatment of lumbar degenerative disease.

As for higher radiation time, we selected freehand open TLIF procedure as control group rather than fluoroscopic-guided spinal fusion procedure. Generally speaking, freehand technique only required fluoroscopy for segment location and screw verification. During radiation, the medical team was outside the operating room with minimal radiation exposure. Hyun *et al.* reported that robot-assisted spinal surgery significantly reduced fluoroscopy time and radiation dose compared with fluoroscopic-guided surgery (3.5 vs 13.3 s/screw) [31]. However, our study showed radiation time was 18.9 s/screw, which was much higher than literature reported. We attributed this divergence to the different way of acquiring intraoperative image from two type of robots. The robot used in Hyun's study could merge pre-operative CT scan with intraoperative fluoroscopy images. In our study, the robot received an intraoperative image from a 1 min circumferential scan of C-arm fluoroscopy, during which the medical staffs were outside the odds ratio. Therefore, after exclusion of 60 s scan, the average radiation time for medical staff was adjusted to 3.9 s/screw, which suggested much lower radiation to medical staff with utilization of RA technique.

This study had several limitations such as single institution retrospective study with small sample size, and lacked comparison between RA MIS-TLIF and MIS-TLIF technique. Also, we limited the scope of study to one-level lumbar degenerative disease. Further study with randomized control, longer follow-up and larger number of prospective cases is still warranted for long-term evaluation of advantages for lumbar degenerative disease.

## Conclusion

The robotic assistance could ensure less intraoperative screw adjustment and guide more accurate decompression when performing MIS-TLIF. Due to higher accuracy and less trauma, RA MIS-TLIF may promote fast recovery after surgery and achieve comparable clinical outcomes. The use of real-time, image-guided robot system may further expand the advantages of MIS-TLIF technique in terms of accuracy and safety.

## Future perspective

In future, with more advanced technologies such as augmented reality and robot-assisted osteotomy, future generations of robot have great potential to further improve minimally invasive spine surgery for both patients and healthcare providers.

### Summary points

- This comparative study investigated the screw accuracy and clinical outcomes of robot-assisted minimally invasive transforaminal lumbar interbody fusion (RA MIS-TLIF) in the treatment of lumbar degenerative disease with at least 1-year follow-up.
- RA MIS-TLIF exhibited less intraoperative blood loss and shorter length of hospital stay but longer operative duration and cumulative radiation time.
- After 20 cases, the robot usage time was significantly shortened and reached a stable plateau.
- RA MIS-TLIF group had better Visual Analog Scale score for back pain and Oswestry Disability Index score at 1 month after operation.
- The patient-reported outcomes were similar in both RA MIS-TLIF and open TLIF technique at 1-year follow-up.
- RA MIS-TLIF may promote fast recovery. The use of real-time, image-guided robot system may further expand the advantages of MIS-TLIF technique in terms of accuracy and safety.

### Author contributions

X Chen, Q Song and Q Li designed the work. H Shen, Q Li, Z Chen and K Wang performed the surgery. X Chen, Q Song and Y Han performed the data acquisition. X Chen and Q Song analyzed and interpreted the patient data. X Chen and Q Song con-

tributed equally in writing the manuscript. H Shen and Q Li substantively revised it. All authors read and approved the final manuscript.

### Financial & competing interests disclosure

This work was supported by the Smart Medical Special Research Project of Shanghai Municipal Commission of Health and Family Planning (2018ZHYL0215). The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.

### Data sharing statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Ethical conduct of research

This retrospective cohort study was approved by the institutional review board of Renji Hospital Affiliated to Shanghai Jiaotong University School of Medicine (KY2020-153). Written informed consent was obtained for each participant.



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