World Neurosurgery: X 23 (2024) 100390

Contents lists available at ScienceDirect

World Neurosurgery: X

journal homepage: www.journals.elsevier.com/world-neurosurgery-x

Robotic endoscopic transforaminal lumbar interbody fusion: A single institution case series

B.F. Saway [a,*], C. Cunningham [a], M. Pereira [a], M. Sowlat [a], S.S. Elawady [a], G. Porto [a], J. Barley [a], Nathan Nordmann [b], B. Frankel [b]

[a] Medical University of South Carolina, Department of Neurosurgery, Charleston, SC, 29425, USA
[b] Southern Illinois University, School of Medicine, Division of Neurosurgery, Springfield, IL, 62702, USA

ARTICLE INFO

Keywords:
Endoscopic
Robotic
TLIF
Spine
MIS

ABSTRACT

Background: Robotic-assisted, endoscopic transforaminal lumbar interbody fusion (RE-TLIF) is a promising, minimally invasive surgical option for degenerative lumbar spondylosis/spondylolisthesis; however, outcomes data and efficacy are limited, especially in multilevel disease. Here, we present the first reported series of patients that underwent either single or multilevel RE-TLIF.

Methods: A retrospective review was performed on 23 consecutive patients who underwent a single level or multilevel RE-TLIF by a single surgeon. Variables included demographics, perioperative results, pain scores, and functional outcome scores.

Results: Eighteen patients (78.3 %) underwent single level RE-TLIF and 5 patients (21.7 %) underwent multilevel RE-TLIF. The median reduction of visual analog scale (VAS) for low back pain (LBP) of all subjects was 6 (IQR = 4.5, 6.5) with no significant difference between single level and multilevel RE-TLIF ($p = 0.565$). The median reduction of VAS for leg pain of all subjects 7 (IQR = 6, 8) with no significant difference between single level and multilevel RE-TLIF ($p = 0.702$). Median blood loss was 25 cc (IQR = 25, 25) and 50 cc (IQR = 25, 100) for single and multilevel RE-TLIF, respectively ($p = 0.025$), whereas median length of stay was 1 (IQR = 1, 1; mean = 1.0 ± 00.18) days and 1 (IQR = 1, 2; mean = 1.4 ± 00.54) days, respectively ($p = 0.042$). One major complication was observed requiring reoperation for demineralized bone matrix migration resulting in an L5 radiculopathy.

Conclusions: Single and multi-level RE-TLIF appears to be a safe and efficacious approach with comparable outcomes to open and other minimally invasive approaches. Additionally, we observed favorable accuracy in robot-assisted pedicle screw, endoscope, and interbody device placement.

1. Introduction

Lumbar spondylosis and spondylolisthesis are a common and significant cause of disability, with a world-wide annual incidence of approximately 266 million people.[1] Clinical presentation includes a variety of symptoms including but not limited to low back pain, radiculopathy, paresthesias, weakness, neurogenic claudication, and in severe cases, bowel/bladder incontinence.[1,2] Surgical intervention is reserved for failure of non-operative management, which can result in significant improvement in pain and function in this population.[3]

Open transforaminal lumbar interbody fusion (TLIF) is one of several operative treatment approaches for these conditions allowing for central decompression and interbody fusion.[4–6] Although good outcomes have been reported using this approach, relatively longer incisions and considerable muscle dissection are required, resulting in an increase in hospital length of stay (LOS) (2.9–19.1 days), elevated estimated blood loss (EBL) (267.5–1438 mL), and postoperative complications.[4,7–14] Advancements in technology, instrumentation, and microsurgical/endoscopic techniques have allowed for the development of various minimally invasive decompressive and fusion procedures such as minimally invasive-TLIF (MIS-TLIF) approaches.[12,15–17] These modalities have led to a decrease in morbidity presumably through a reduction of soft tissue injury.[18–20] Several studies have compared outcomes, safety and efficacy, between open- and MIS-TLIF procedures. These studies report comparable decompression and fusion rates and lower peri- and post-operative complications with MIS-TLIF. However, the existing literature remains inconclusive.[5,18,20–33]

More recently, the addition of robotic-assisted pedicle screw placement and the widespread use of endoscopic spine approaches have

* Corresponding author.
E-mail address: saway@musc.edu (B.F. Saway).

https://doi.org/10.1016/j.wnsx.2024.100390
Received 6 December 2023; Accepted 29 April 2024
Available online 1 May 2024

Abbreviation

TLIF	Transforaminal Lumbar Interbody Fusion
EBL	Estimated Blood Loss
MIS	Minimally Invasive Spine
MIS-TLIF	Minimally Invasive Transforaminal Lumbar Interbody Fusion
RE-TLIF	Robotically Assisted Transforaminal Lumbar Interbody Fusion
PE-TLIF	Percutaneous Endoscopic Transforaminal Lumbar Interbody Fusion
VAS	Visual Analog Scale
LOS	Length of Stay
MRI	Magnetic Resonance Imaging
CT	Computed Tomography
SAP	Superior Articulating Process
CSF	Cerebral Spinal Fluid
DBM	Demineralized Bone Matrix

further contributed to promising outcomes.[34] Robotic-assisted, endoscopic TLIF (RE-TLIF) is a further evolution of the percutaneous endoscopic TLIF (PE-TLIF) technique that seeks to combine the MIS benefits of spinal endoscopy with highly accurate robotic targeting of pedicle screws, endoscopes, and interbody devices. Using this combined technique, Chang et al has shown lower EBL, decreased postoperative pain, shorter LOS, and decreased rates of paraspinal muscle atrophy. However, this study only addresses single level procedures at L4-5, necessitating additional studies that include multi-level disease as well as other regions of the lumbar spine..[35]

This paper aims to review and expand on the existing literature. Additionally, through this single-institution, single operator, case series, we aim to demonstrate the feasibility as well as the short-term efficacy and clinical outcomes in patients undergoing single and multilevel RE-TLIF.

2. Material and methods

2.1. Study population

After obtaining IRB approval, a retrospective chart review (2021–2023) of patients undergoing RE-TLIF by a single neurosurgeon at our institution was performed. Demographics, clinical, surgical, and radiographic characteristics were reviewed and analyzed.

2.2. Clinical data collection and outcomes

All patients were clinically assessed by the surgeon pre- and post-operatively. All patients received both dynamic radiographs of the lumbar spine as well as magnetic resonance imaging (MRI) of the lumbar spine upon consultation with the senior author. Indications for surgery included the presence of foraminal or lateral recess stenosis or spondylolisthesis (mobile or immobile) with associated lower extremity radicular pain with or without low back pain and failure of non-operative care. All recorded clinical parameters assessed were documented in the electronic health record. Primary clinical outcomes included Visual Analog Scale (VAS) score for back and leg, functional outcome (Modified MacNab Score), and post-operative complications.[12,36,37] Intra-operative parameters included operative time, the number of lumbar levels operated on, and EBL. Post-operative parameters included hospital length of stay (LOS) and need for re-operation.

2.3. Radiographical data collection and outcomes

All patients received pre-operative MRI and Mazor computed tomography (CT) protocol of the lumbar spine at the pre-operative visit. All imaging was retrospectively reviewed by two independent authors, both neurosurgeons. The presence of spondylolisthesis was graded as none, Grade I (less than 25 %), Grade II (25–50 %), Grade III (50–75 %), or Grade IV (>75 %). All patients underwent hardware assessment via intraoperative fluoroscopy or intraoperative CT evaluation with an O-arm spin at the end of the procedure. Additionally, standing lumbar x-rays were completed post-operatively to evaluate hardware placement.

2.4. Operative technique

Prior to surgical intervention, all subjects underwent a Mazor robotic protocol CT scan. Operative planning was performed using the Mazor Robot software (Medtronic, Minneapolis, MN, USA) for pedicle screw and interbody graft placement, as well as endoscope trajectory and incision location. Operating room set-up is demonstrated in Fig. 1. Subsequent workflow is as follows. The patient is positioned prone on an open-Jackson table (Mizuho, Union City, CA, USA) following induction of general endotracheal anesthesia and the application of neuromonitoring electrodes, and baseline neurophysiologic data is obtained. After prepping and draping, an iliac pin is placed and connected to the Mazor robot. Depending on patient variables such as degree of lumbar lordosis, number of levels being treated, and iliac crest height, either multiple percutaneous or two 'Wiltse' paramedian incisions are used for screw placement and interbody work. Pedicle screws are placed using robotic guidance in standard fashion. Following screw placement, transforaminal interbody work is conducted by working between previously placed screws. Using the pre-planned trajectories for interbody graft placement, robotic guidance is used to guide the endoscope toward Kambin's triangle without the need for fluoroscopy (Fig. 2). The ideal trajectory is selected to facilitate visualization of the disc space, traversing and exiting nerve root, and the superior aspect of the caudal vertebral body being addressed. After this entry point is targeted robotically, a standard transforaminal approach is used to enter the disc

Fig. 1. This intraoperative photograph demonstrates the operating room setup with the Mazor Robot and endoscope monitor display at the foot of the bed. This allows for visualization of both the endoscope and navigation display in tandem. The optical camera for the Medtronic Stealth Navigation is placed above the anesthesia curtain, which is not shown in this picture.

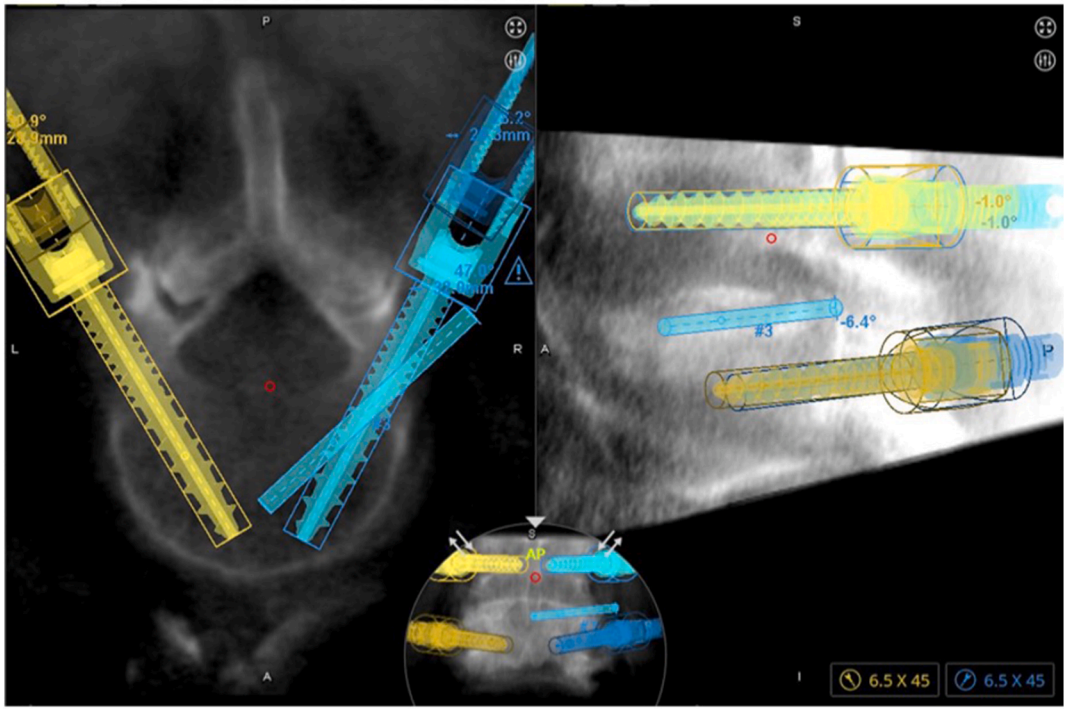

Fig. 2. Pre-operative robotic plan depicting the trajectories of L4 and L5 pedicle screws as swell as trajectory for the L4-5 endoscopic interbody placed under robotic guidance.

space using serial dilation and crown-reaming of the superior articular process (SAP) as previously described.[12] Sequential dilaters are placed through the robotic end effector and held securely in place by the arm. Navigation is used to confirm both the trajectory and location of these devices until, lastly, the endoscope (Joimax GmbH, Karlsruhe, Germany) is inserted through the robotic end effector. The disc space preparation begins through the endoscope center channel using rongeurs, and curettes under direct visualization. Subsequently, a slightly larger port is transitioned to for the placement of drills, endplate shavers and wire brushes to finish preparing the disc space to receive a vertical and horizontally expandable interbody device (FlareHawk Accelus, Palm Beach, FL, USA). The expanded interbody device is then filled with demineralized bone matrix putty. For additional operative levels, these steps are repeated. Lastly, rods are placed percutaneously and secured within the poly-axial screw heads with caps, and finally tightened. A final intra-operative fluoroscopic or O-arm (Medtronic, Minneapolis, MN, USA) image is acquired to confirm hardware placement. Upon closure, neuromonitoring obtains a final data acquisition and reports if final data remains consistent or changed from baseline data.

2.5. Statistical analysis

Continuous variables were reported as median along with the interquartile range and analyzed using Mann Whitney U/Wilcoxon Rank sum test. Categorical variables were reported as percentage and analyzed using Pearson's Chi squared test. p value less than 0.05 was considered significant. All statistical analyses were performed by JAMOVI open-source R based statistical software version 1.6.

3. Results

3.1. Baseline characteristics

In this series, 23 patients (11 male and 12 female) with a median age of 60 years were treated with RE-TLIF. 18 of these patients (78.3 %) underwent a single-level operation and 5 (21.7 %) underwent multi-level operations (2-level ($n = 4$); 3-level ($n = 1$)). 13 patients (56.5 %) had spondylolisthesis, with 11 (47.8 %) having Grade I spondylolisthesis, and 2 (8.7 %) having Grade II spondylolisthesis). While Grade III and IV spondylolisthesis were not excluded from this series, the low prevalence of higher-grade pathology as compared to Grade I and II is the reason for the absence in this small case series. No patients in this series had severe central stenosis at the operated levels. Median pre-operative VAS back- and leg pain was 8 (IQR = 7, 8.5) and 8 (IQR = 8, 9), respectively. There was no significant difference in median age ($p = 0.086$), sex ($p = 0.912$), or pre-operative VAS back- ($p = 0.121$) and leg pain ($p = 0.937$) between patients undergoing single-vs. multi-level RE-TLIF (Table 1).

Table 1
Pre-operative data.

	All	1-Level	>1-Level	*p*-value
n	23	18 (78.3 %)	5 (21.7 %)	
Age in years, Median (IQR)	60 (49, 73)	56 (44.25, 70)	77 (60, 77)	0.086
Sex	11 Male, 12 Female	8 Male, 10 Female	3 Male, 2 Female	00.912
Spondylolisthesis Grade				
None	10 (43.5 %)	7 (38.9 %)	3 (60.0 %)	
I	11 (47.8 %)	10 (55.6 %)	1 (20.0 %)	
II	2 (8.7 %)	1 (5.6 %)	1 (20.0 %)	
Pre-Operative VAS Back Pain, Median (IQR)	8 (7, 8.5)	8 (7.25,8.75)	6 (6, 8)	0.121
Pre-Operative VAS Leg Pain, Median (IQR)	8 (8, 9)	8 (8, 9)	8 (7, 10)	0.937

Spondylolisthesis grade is the lumbar level with the highest spondylolisthesis grade in each subject.

3.2. Intra-operative results

A total of 29 lumbosacral levels were treated (L2/3 ($n = 2$, 6.9 %); L3/4 ($n = 2$, 6.9 %); L4/5 ($n = 17$, 58.6 %); and L5/S1 ($n = 8$, 27.6 %)). 18 patients underwent a single-level operation (L2/3 $n = 2$, 11.1 %); L4/5 ($n = 12$, 66.6 %); and L5/S1 ($n = 4$, 22.2 %)). 5 patients underwent a multi-level operation ($n = 3$ (60.0 %) at L4-L5-S1 lumbosacral levels; $n = 1$ (20.0 %) at L3-L4-L5 lumbar levels, and $n = 1$ (20.0 %) at the L3-L4-L5-S1 lumbosacral levels.

Overall, median operative-time was 132 min (IQR = 114.5, 211.5), while the median EBL was 25 cc (IQR = 25.00, 25.00). There was a significantly longer median operative-time in the multi-vs. single-level cohort, 248 min (IQR = 248.00, 300.00) vs. 129.5 min (IQR = 107.75, 165.75), respectively ($p = 0.025$). Additionally, there was a significantly higher median EBL in the multi-vs. single-level cohort, 50 cc (IQR = 25.00, 100.00) vs. 25 cc (IQR = 25.00, 25.00), respectively ($p = 0.004$) (Table 2).

3.3. Post-operative results

Overall, median and mean LOS was 1 (IQR = 1, 1) and 1.08 ± 00.32 days, respectively. There was a statistically higher LOS observed in the multi-vs. single-level cohort, 1 (IQR = 1, 2; mean = 1.4 ± 00.54) vs. 1 (IQR = 1, 1; mean = 1.0 ± 00.18) days, respectively ($p = 0.042$).

Median final follow-up was 7 (IQR = 6, 12) months; there was no significant difference in time to final follow up visit observed between the single- and multi-level cohort ($p = 0.665$). Overall, median 6-month follow-up VAS back- and leg pain was 2 (IQR = 1, 2.5) and 1 (IQR = 0, 1.5), respectively. This was significantly decreased from median pre-operative VAS back- and leg pain values of 8 (IQR = 7, 8.5) ($p = 0.000025$) (Fig. 3) and 8 (IQR = 8, 9) ($p = 0.000026$) (Fig. 4), respectively. The median change from pre-to 6-month postoperative follow-up VAS back- and leg pain was 6 (IQR = 4.5, 6.5), and 7 (IQR = 6, 8), respectively (Table 2). There was no lasting observed increase in VAS back- or leg pain reported by any patients in this series.

When comparing post-operative results of patients that underwent single-level vs multi-level RE-TLIF, the median 6-month follow-up VAS back- and leg pain for all patients that underwent a single-level operation was 2 (IQR = 1, 2.5) and 1 (IQR = 0, 1.5), respectively. For those undergoing multi-level operations, the median 6-month follow-up VAS back- and leg pain was 1 (IQR = 1, 1) and 1 (IQR = 1, 1), respectively. There was no statistical difference seen between the median 6-month follow-up VAS back- ($p = 0.236$) and leg pain ($p = 0.813$) in these two cohorts. For those that underwent a single-level operation, the median change from pre-operative to 6-month follow-up VAS back- and leg pain was 6 (IQR = 4.5, 6.5) and 7 (IQR = 6, 8), respectively. For those that underwent a multi-level operation, the median change from pre-operative to 6-month follow-up VAS back- and leg pain was 5 (IQR = 5, 6) and 8 (IQR = 6, 9), respectively. Again, there was a significant difference observed between the median change from pre-operative to 6-month follow-up VAS back- ($p = 0.590$) and leg pain ($p = 0.730$) in these two cohorts (Figs. 5 and 6).

At final follow up, no patient was observed to have a Modified MacNab score of 1 (Poor). 2 (8.70 %) patients had a Modified MacNab score of 2 (Fair), 8 (34.8 %) had a score of 3 (Good), and 13 (56.5 %) had a score of 4 (Excellent). The Modified McNab score breakdown of the 18 patients that underwent a single-level operation was as follows: 2 patients (11.1 %) had a score of 2, 6 (33.3 %) had a score of 3, and 10 (55.6 %) had a score of 4. The Modified McNab score breakdown of the 5 patients that underwent a multi-level operation was as follows: 2 patients (40.0 %) had a score of 3, and 3 (60.0 %) had a score of 4. The distribution of these scores compared between the single-level and multi-level cohort were not significantly different ($p = 0.734$) (Fig. 7).

Table 2
Intra- and post-operative data.

Variable	All Cases ($n = 23$)	1-Level ($n = 18$)	>1-Level ($n = 5$)	*p*-value
Operative Time (minutes), Median (IQR)	132 (114.5, 211.5)	129.5 (107.5, 165.5)	248 (248, 300)	0.025*
Blood Loss (cc), Median (IQR)	25 (25, 25)	25 (25, 25)	50 (25, 100)	0.004*
Length of Stay, Median (IQR)	1 (1, 1)	1 (1, 1)	1 (1, 2)	0.042*
Follow Up (months) Median (IQR)	7 (6, 12)	7.5 (6, 12)	7 (6, 8)	0.665
Post-Operative VAS Back Pain at 6 months, Median (IQR)	2 (1, 2.5)	2 (1, 2.75)	1 (1, 1)	0.236
Post-Operative VAS Leg Pain at 6 months, Median (IQR)	1 (0, 1.5)	1 (0, 1.5)	1 (1, 1)	0.813
VAS Back Pain Change, Median (IQR)	6 (4.5, 6.5)	6 (4.5, 6.5)	5 (5, 6)	0.590
VAS Leg Pain Change, Median (IQR)	7 (6, 8)	7 (6, 8)	8 (6, 9)	0.730
Modified MacNab Score				00.734
1 (Poor)	0 (0 %)	0 (0 %)	0(0 %)	
2 (Fair)	2 (8.7 %)	2 (11.1 %)	0 (0 %)	
3 (Good)	8 (34.8 %)	6 (33.3 %)	2 (40.0 %)	
4 (Excellent)	13 (56.5 %)	10 (55.6 %)	3 (60.0 %)	

3.4. Complications

There were no intraoperative complications such as durotomy, cerebrospinal (CSF) leak, or misplaced pedicle screws as confirmed with intraoperative and post-operative imaging (see Fig. 8). Additionally, there were no blood transfusions required. There were 4 (17.4 %) instances of post-operative radiculitis that improved by 1-month follow-up. One patient had a lower extremity DVT at post-operative day 10. There was one re-operation required due to migration of demineralized bone matrix (DBM) causing radiculopathy. This was treated by percutaneous endoscopic washout of the DBM.

4. Discussion

Compared to open procedures, MIS-TLIF is associated with less EBL, tissue damage, and faster recovery.[38] Attempts at further minimizing this procedure have been reported using endoscopic approaches with promising results.[35,39–41] In this series we aim to broaden the evolution of the endoscopic TLIF technique with the introduction of robotic assistance for endoscope, pedicle screw, and interbody device placement. Additionally, we provide the first study describing clinical outcomes of patients undergoing L5-S1 as well as multilevel, interbody fusion via the RE-TLIF approach.

Current metanalyses assessing clinical outcomes of patients undergoing MIS-TLIF report postoperative VAS back pain to range from 2.3 to 4.2 and postoperative VAS leg pain range of 00.79–1.8 [38,39]. When comparing MIS-TLIF to open TLIF, MIS VAS scores trend lower during the post-operative period up to 1 year; however, long term follow-up demonstrates that these differences become insignificant after one year follow-up.[38,41,42] A single-institution case series of 26 patients that underwent single level RE-TLIF with Grade 1 spondylolisthesis reported a mean post-operative VAS of leg pain of 1.1 (5.4 preoperatively) and VAS of LBP to be 1.3 (6.7 preoperatively). When comparing the VAS data reported here to that of open TLIF and MIS-TLIF, we find our clinical findings at 6-months to have similar improvements in VAS leg- and back pain. However, the small sample size and operator differences found in this series make a direct comparison of this case series to previously published data difficult.

Operative times reported in the existing literature demonstrate wide ranges in both conventional open TLIF and MIS-TLIF. For example, Qin

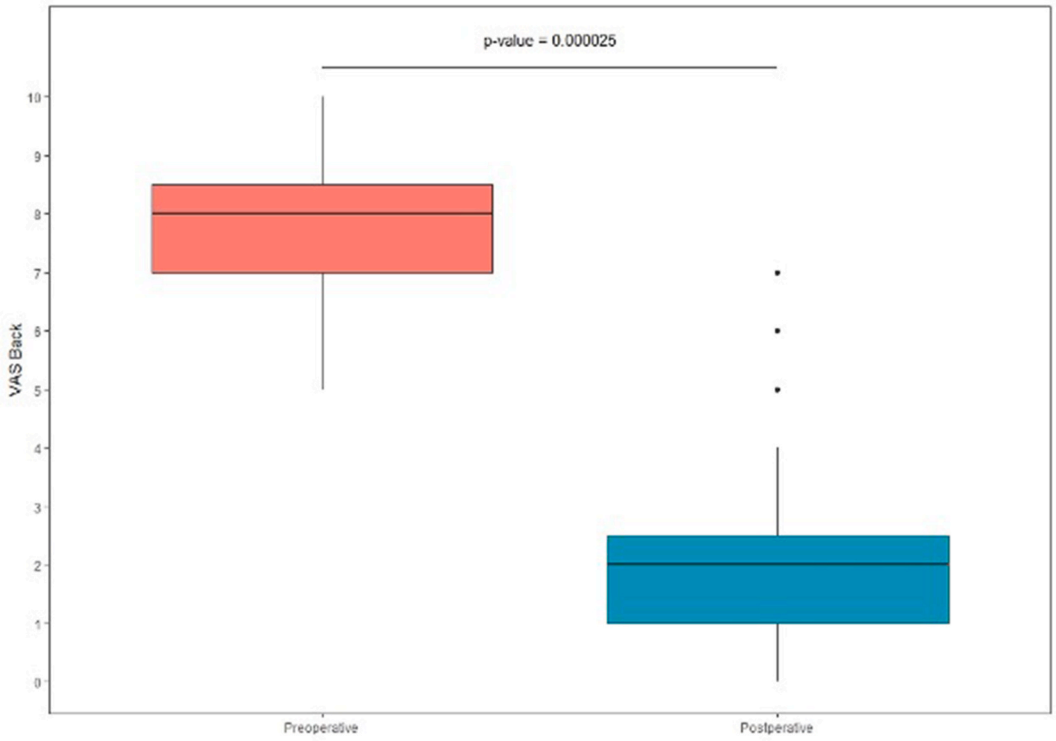

Fig. 3. Comparison of pre-operative vs post-operative VAS back pain score of all patients in this series.

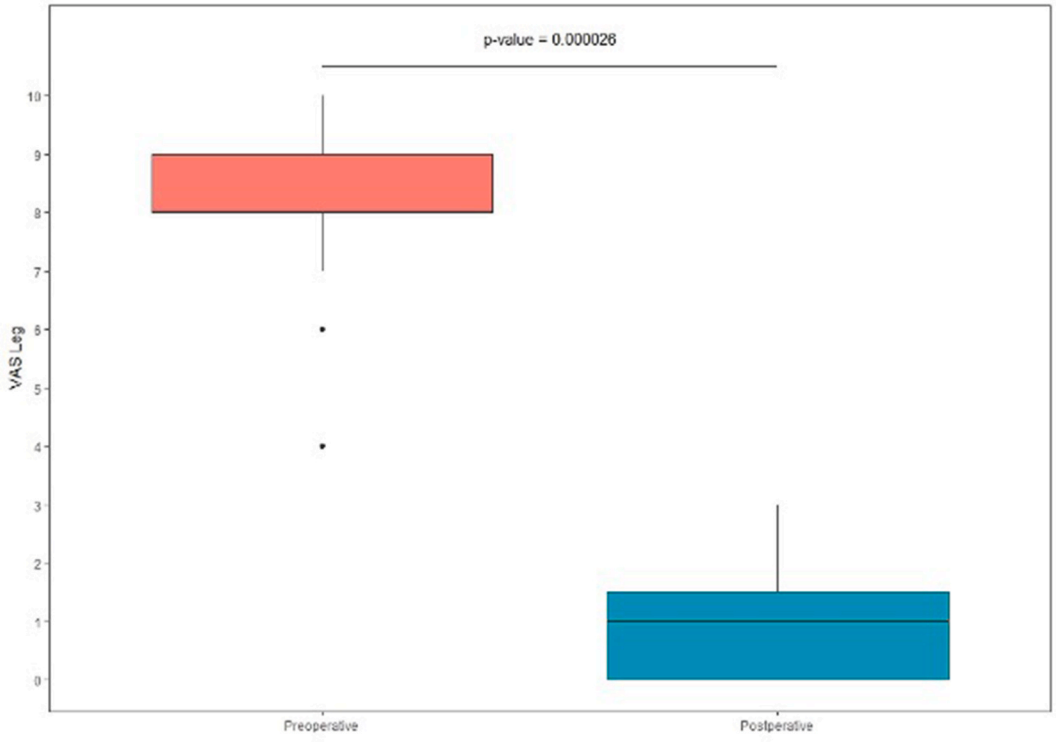

Fig. 4. Comparison of pre-operative vs post-operative VAS leg pain score of all patients in this series.

et al, reported a statistically significant difference between open TLIF (113 min) and MIS-TLIF (143 min), while Chen et al, reported no statistically significant difference.[38,42] Additionally, a systematic review by Zhu et al, found that percutaneous endoscopic TLIF (155 min) significantly reduced operative time as compared to MIS-TLIF (181 min).[39] Furthermore, a case series of single-level fusions demonstrated RE-TLIF (208 min) to have significantly longer operative times relative to MIS-TLIF (161 min).[35] Here, we report a median operative time of 132 min for all subjects in this series. When stratifying by number of levels performed, the median operative time for a single-level and multi-level

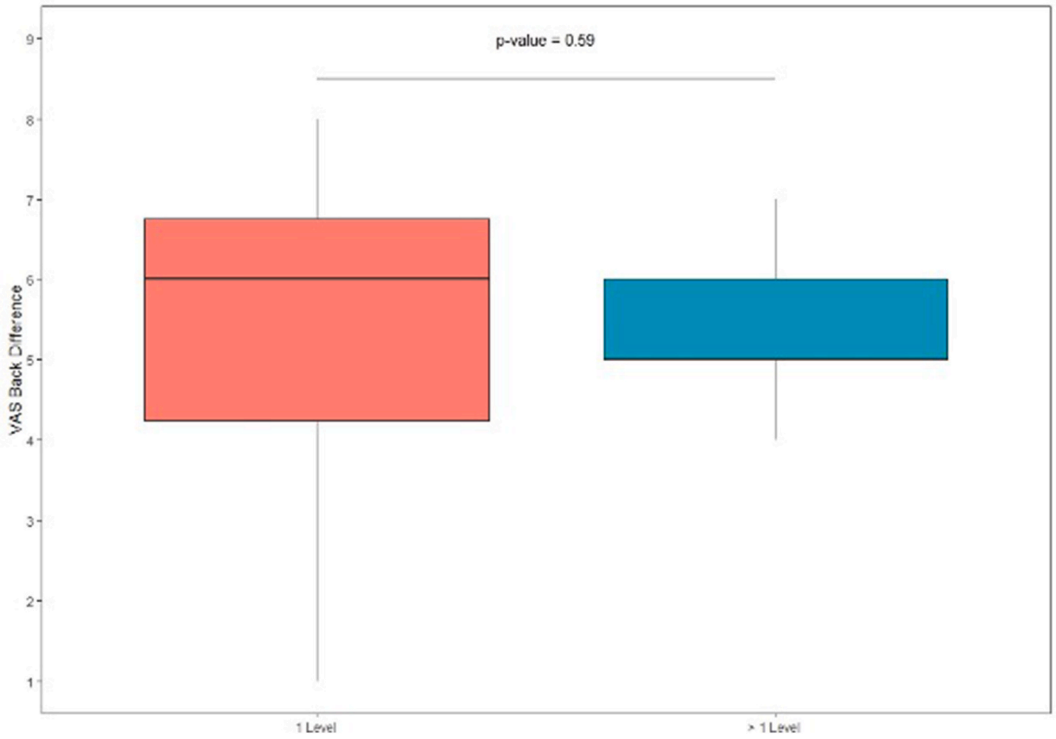

Fig. 5. Comparison of the post-operative change in VAS back pain score between patients that underwent 1 level RE-TLIF and multilevel RE-TLIF.

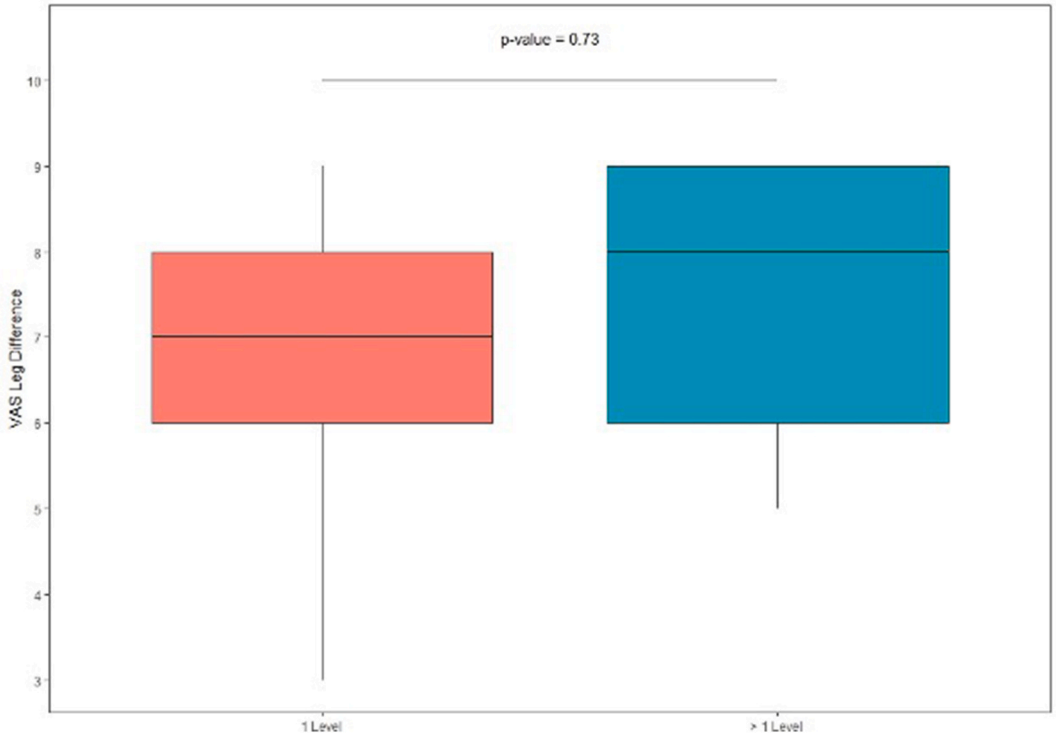

Fig. 6. Comparison of the post-operative change in VAS leg pain score between patients that underwent 1 level RE-TLIF and multilevel RE-TLIF.

RE-TLIF was 129.5 and 248 min, respectively. While our operative time for a single-level fusion is comparable to previously reported open and MIS approaches, the introduction of multiple levels was found to significantly increase operative times in this series ($p = 0.025$). It is important to note that for this combined operative technique, expected operative times must be contextualized by the surgical team's experience with both robotic- and endoscope spine surgery, as each have their own associated learning curve. At the time of this series, the lead surgeon had performed 12 years and >1000 endoscopic spine surgeries. However, the addition of robotic spine surgery was relatively novel for this center, and the combination of these two modalities presented a new workflow for the team, and its own associated learning curve. It is

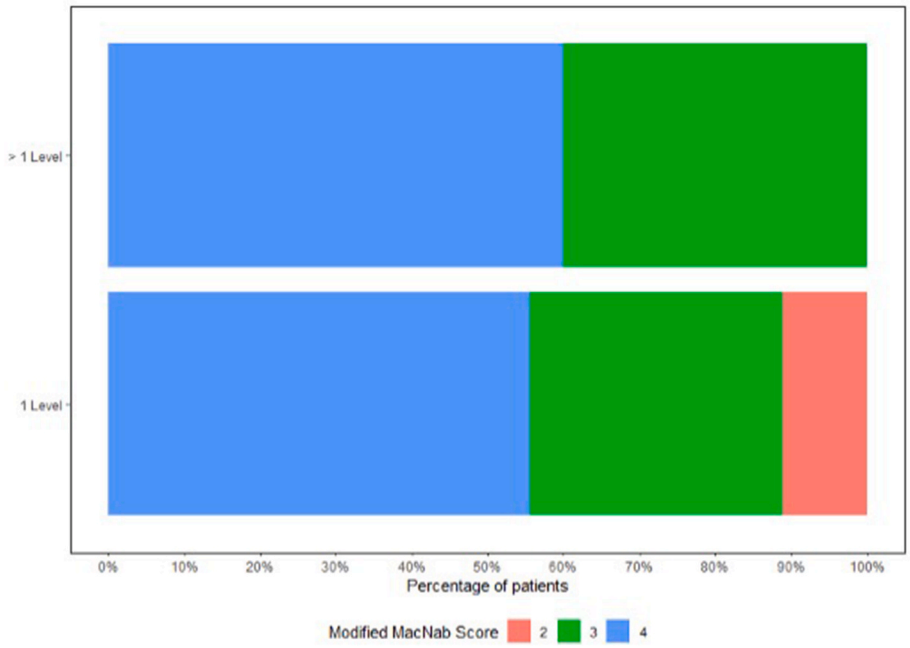

Fig. 7. Distribution of Modified MacNab Score of patients that underwent 1 level vs > 1 level Robotic Endoscopic TLIF.

expected that operative times will reflect these independent and combined learning curves and will depend on surgeon familiarity with these different technologies. In this series we observed a variability in operative times ranging from 95 to 334 min with longer outlier cases occurring earlier on. This was likely attributed to a learning curve as the surgical team was gaining familiarity with the new operative workflow. We expect that operative times will continue to decrease and level off with further experience.

Multiple studies have shown a significantly decrease in EBL of 100–500 mL in MIS- as compared to open TLIF. For instance, one meta-analyses reported a mean EBL for MIS-TLIF to be approximately 248 mL as compared to open TLIF of 568 mL.[14,38,42,43] Endoscopic TLIF EBL has a reported range of 25–190 mL with an average of 101 mL.[39,40] Chang et al reported on single-level RE-TLIF with an average EBL of 25 mL.[35] While the median and mean EBL in our series was 25 mL and 42.4 mL respectively, this includes single and multi-level fusion cases and demonstrates low blood loss and safety associated with this approach.

The median hospital LOS in our series was 1 day. While some studies show no difference in hospital LOS between open and MIS techniques, most report a shorter LOS by 1–3 days for MIS-TLIF.[43] In a meta-analysis review Hammad et al, reported hospital LOS for open TLIF ranging from 2.9 to 19.1 days with an average of 6.92 days. Alternatively, ranges from 2 to 13.7 days with an average of 5.05 days for MIS-TLIF are reported in a 26 study meta-analysis.[14] While there is less data, endoscopic TLIF LOS reports range from 1.1 to 6.7 days with an average of 3.7 days.[39,40] In a 48-patient case-series, Cui et al, reported 7.3 days as the average hospital LOS for robotic-assisted MIS-TLIF.[44] In general MIS techniques have been shown to require a longer average operative times, but require smaller incisions with less EBL, perhaps translating to less operative trauma and as a result, quicker recovery and shorter LOS.[42] Our data with RE-TLIF appears to mirror these findings.

The procedure-related complications reported in this series were comparable to previous reports. Zaifei et al, reported complication rates of 17.5 % and 9.2 % for open TLIF and MIS-TLIF, respectively. Hammad et al, found rates of 14.2 % and 11.3 % for open TLIF and MIS-TLIF, respectively.[14,42] Complication rates in an endoscopic TLIF metanalyses ranges from 8.6 to 14.9 % with an average of 12.3 %.[41] In our case series we observed several complications including 4 (17 %) temporary post-operative lower extremity radiculitis, 1 (4.3 %) DVT, and 1 (4.3 %) reoperation for a L5/S1 demineralized bone matrix migration causing nerve root irritation. There were no instances of dural tears/CSF leaks, often reported in open approaches.[39] Furthermore, there was 100 % accuracy in pedicle screw placement in our series, which was determined by post-operative x-ray. Intraoperative navigation and robotically placed pedicle screws have decreased the rate of errant pedicle screw placement.[45,46] Ringel et al, described a 93 % accuracy rate of screw placement utilizing robotics compared to 85 % with the freehand convention technique.[47] When reviewing MIS-TLIF screw placement without intraoperative navigation, Shafi et al, found the accuracy rate to be 88 %.[48] Endoscopic TLIF accuracy rates without the use of robotic assistance have been recorded as high as 95.9 %.[49] Here we demonstrate that the introduction of robotic guidance not only provides high pedicle screw placement accuracy but also allows for excellent accuracy when using the robot to target Kambins triangle (without the use of fluoroscopy) for endoscopy and placing the interbody device. All of this can be performed while still allowing for a comparable operative time (132 min in this series) to previous published MIS-TLIF series.

To the best of our knowledge there has been an absence of reported cases of multilevel RE-TLIF in the literature. In this series, 5 patients underwent a multilevel RE-TLIF: 4 of these patients had a 2-level fusion and 1 patient, a 3-level fusion. Similar to the single-level cohort, the multilevel cohort had a significant reduction in mean VAS back pain and leg scores. When comparing the mean change in VAS back and leg scores between the two cohorts, there was no significant difference observed. Moreover, all patients in the multi-level cohort resulted in a Modified MacNab score of 3 or higher. Although a small cohort of patients, this provides the first reported data to support multi-level RE-TLIF.

The current findings provide crucial data to support the introduction of intraoperative robotic assistance to the endoscopic TLIF procedure. The ability to pre-plan the endoscope, interbody device, and pedicle screw trajectories and subsequent robotic assisted placement has the potential to improve efficiency in the operating room while simultaneously minimizing radiation exposure by the operating team. Once the associated learning curve of the robot is overcome, and an efficient workflow is established, the time added from the introduction of the robot can possibly be obviated by the reduction in fluoroscopic time needed without the robot. Moreover, as demonstrated by the pedicle screw accuracy presented in this series, the high accuracy afforded by

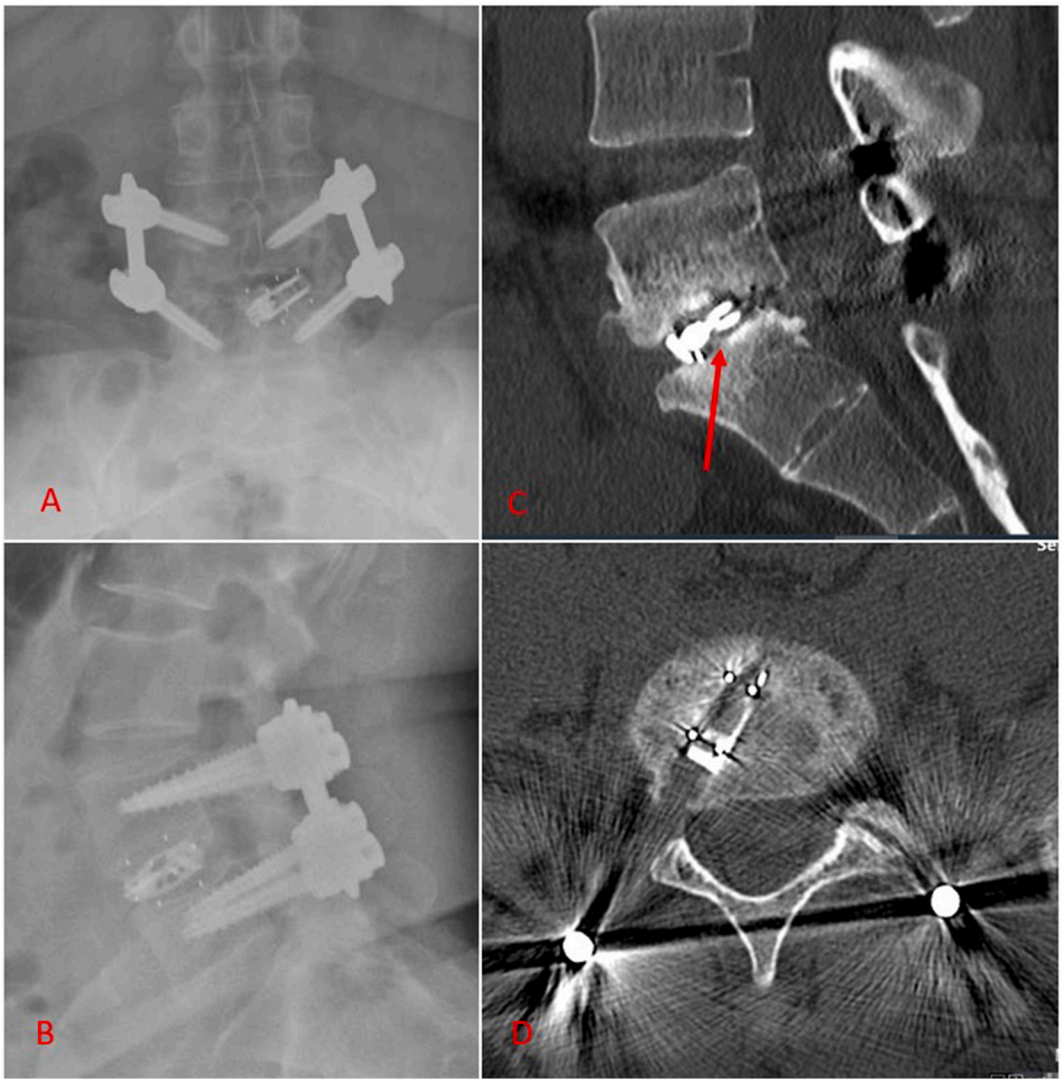

Fig. 8. The anterior-posterior (A) and lateral (B) post-operative X-Rays in a patient that underwent a single level robotic endoscopic TLIF. The sagittal (C) and axial (D) post-operative CT scan at 5 months of a patient that underwent the same procedure at L5-S1 demonstrating appropriate placement of interbody with the beginning of bony ingrowth of the interbody (red arrow).

the robotic assistance is a valuable addition to the procedure. As technology progresses, it can be assumed that the accuracy and efficiency of the robotic assistance will further increase. While it is crucial that surgeons not be reliant on technology introduced in the operating room and be capable of addressing surgical issues when technology fails, we believe the addition of robotic assistive technology to the endoscopic TLIF procedure provides value that is demonstrated in the results of this series.

There are several limitations to this study that must be addressed. Primarily, overall fusion rate evaluated by computed tomography was not calculated. While patients had an overall improvement in VAS scores at their follow-up visit, the degree of fusion and pseudoarthrosis rates were not calculated at this time frame. All patients did undergo post-operative lumbar radiographs at the 1-month visit, and there was no device migration or screw failure observed. Nevertheless, without long term imaging, the rate of long-term radiographic arthrodesis rates cannot be calculated for this series. The lack of high-grade (Grade III and IV) spondylolisthesis in this series is another limitation as its efficacy in this higher-grade pathology remains unclear and should be examined in future studies. Additionally, the mean follow-up time for this series was 8.4 months. While the greatest reported difference in clinical outcome between open and MIS-TLIF occurred in the immediate postoperative period with no significant difference in long-term clinical outcomes, the long-term clinical follow up is a component of this procedure that must be assessed in future studies.[43] While the objective of this report was to demonstrate the safety and initial efficacy of this intervention in a small cohort to promote future investigations, it is important to note that the small sample size and the retrospective nature of this study limit the conclusions that can be drawn. The external validity of the clinical results observed as well as the comparisons made to historical values reported in the literature must be taken in the context of the single surgeon, retrospective nature of this case series. Furthermore, because this is a single-surgeon case series comparing current results to historical ones, there is no internal control group for comparison, therefore limiting any conclusion on non-inferiority. It will be essential for further studies to assess the reproducibility of these promising results at other institutions. Future exploration should focus on multi-institutional, prospective, randomized clinical trials comparing the intraoperative and postoperative clinical efficacy of RE-TLIF versus various other MIS-TLIF approaches and open-TLIF to further evaluate any differences in outcomes following these treatment modalities. Additionally, future studies must focus on cost-effectiveness analyses to determine whether the utility of this new technology is justified.

5. Conclusions

Here we present a single-surgeon, case series demonstrating the clinical outcomes of patients that undergo single and multilevel RE-TLIF. This surgical approach appears to be a safe, and efficacious approach with a high pedicle screw placement accuracy rate and low morbidity.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

B.F. Saway: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Cunningham:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Pereira:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Sowlat:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S.S. Elawady:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G. Porto:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J. Barley:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nathan Nordmann:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B. Frankel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

None.

References

1. Ravindra VM, Senglaub SS, Rattani A, et al. DegenerativeLumbar spine disease: estimating global incidence and worldwide volume. *Global Spine J*. 2018;8(8):784–794. https://doi.org/10.1177/2192568218770769.
2. Wong AP, Smith ZA, Stadler JA, et al. Minimally invasive transforaminal lumbar interbody fusion (MI-TLIF): surgical technique, long-term 4-year prospective outcomes, and complications compared with an open TLIF cohort. *Neurosurg Clin N Am*. 2014;25(2):279–304. https://doi.org/10.1016/j.nec.2013.12.007.
3. Weinstein JN, Lurie JD, Tosteson TD, et al. Surgical versus nonsurgical treatment for lumbar degenerative spondylolisthesis. *N Engl J Med*. 2007;356(22):2257–2270. https://doi.org/10.1056/nejmoa070302.
4. Chen YC, Zhang L, Li EN, et al. An updated meta-analysis of clinical outcomes comparing minimally invasive with open transforaminal lumbar interbody fusion in patients with degenerative lumbar diseases. *Medicine*. 2019;98(43), e17420. https://doi.org/10.1097/md.0000000000017420.
5. Serban D, Calina N, Tender G. Standard versus minimally invasive transforaminal lumbar interbody fusion: a prospective randomized study. *BioMed Res Int*. 2017;2017:1–5. https://doi.org/10.1155/2017/7236970.
6. Harms J, Rolinger H. [A one-stager procedure in operative treatment of spondylolistheses: dorsal traction-reposition and anterior fusion (author's transl)]. *Z Orthop Ihre Grenzgeb*. 1982;120(3):343–347. https://doi.org/10.1055/s-2008-1051624.
7. Mehta VA, McGirt MJ, Garcés Ambrossi GL, et al. Trans-foraminal versus posterior lumbar interbody fusion: comparison of surgical morbidity. *Neurol Res*. 2011;33(1):38–42. https://doi.org/10.1179/016164110x12681290831289.
8. Gejo R, Matsui H, Kawaguchi Y, Ishihara H, Tsuji H. Serial changes in trunk muscle performance after posterior lumbar surgery. *Spine*. 1999;24(10):1023–1028. https://doi.org/10.1097/00007632-199905150-00017.
9. Moskowitz A. Transforaminal lumbar interbody fusion. *Orthop Clin North Am*. 2002;33(2):359–366. https://doi.org/10.1016/s0030-5898(01)00008-6.
10. Rantanen J, Hurme M, Falck B, et al. The lumbar multifidus muscle five years after surgery for a lumbar intervertebral disc herniation. *Spine*. 1993;18(5):568–574. https://doi.org/10.1097/00007632-199304000-00008.
11. Kalanithi PS, Patil CG, Boakye M. National complication rates and disposition after posterior lumbar fusion for acquired spondylolisthesis. *Spine*. 2009;34(18):1963–1969. https://doi.org/10.1097/brs.0b013e3181ae2243.
12. Porto GBF, Cisewski SE, Wolgamott L, Frankel BM. Clinical outcomes for patients with lateral lumbar radiculopathy treated by percutaneous endoscopic transforaminal discectomy versus tubular microdiscectomy: a retrospective review. *Clin Neurol Neurosurg*. 2021;208:106848. https://doi.org/10.1016/j.clineuro.2021.106848.
13. Hong JY, Kim WS, Park J, Kim CH, Jang HD. Comparison of minimally invasive and open TLIF outcomes with more than seven years of follow-up. *N Am Spine Soc J*. 2022;11:100131. https://doi.org/10.1016/j.xnsj.2022.100131.
14. Hammad A, Wirries A, Ardeshiri A, Nikiforov O, Geiger F. Open versus minimally invasive TLIF: literature review and meta-analysis. *J Orthop Surg Res*. 2019;14(1). https://doi.org/10.1186/s13018-019-1266-y.
15. Foley KT, Holly LT, Schwender JD. Minimally invasive lumbar fusion. *Spine*. 2003;28(supplement):S26–S35. https://doi.org/10.1097/01.brs.0000076895.52418.5e.
16. Tan LA, Rivera J, Tan XA, Le VP, Khoo LT, Berven SH. Clinical and radiographic outcomes after minimally invasive transforaminal lumbar interbody fusion—early experience using a biplanar expandable cage for lumbar spondylolisthesis. *Int J Spine Surg*. 2020;14(s3):S39–S44. https://doi.org/10.14444/7125.
17. Dahdaleh NS, Nixon AT, Lawton CD, Wong AP, Smith ZA, Fessler RG. Outcome following unilateral versus bilateral instrumentation in patients undergoing minimally invasive transforaminal lumbar interbody fusion: a single-center randomized prospective study. *Neurosurg Focus*. 2013;35(2):E13. https://doi.org/10.3171/2013.5.focus13171.
18. Tsutsumimoto T, Shimogata M, Ohta H, Misawa H. Mini-open versus conventional open posterior lumbar interbody fusion for the treatment of lumbar degenerative spondylolisthesis: comparison of paraspinal muscle damage and slip reduction. *Spine*. 2009;34(18):1923–1928. https://doi.org/10.1097/brs.0b013e3181a9d28e.
19. Rodríguez-Vela J, Lobo-Escolar A, Joven E, Muñoz-Marín J, Herrera A, Velilla J. Clinical outcomes of minimally invasive versus open approach for one-level transforaminal lumbar interbody fusion at the 3- to 4-year follow-up. *Eur Spine J*. 2013;22(12):2857–2863. https://doi.org/10.1007/s00586-013-2853-y.
20. Adogwa O, Parker SL, Bydon A, Cheng J, McGirt MJ. Comparative effectiveness of minimally invasive versus open transforaminal lumbar interbody fusion: 2-year assessment of narcotic use, return to work, disability, and quality of life. *J Spinal Disord Tech*. 2011;24(8):479–484. https://doi.org/10.1097/bsd.0b013e3182055cac.
21. Schizas C, Tzinieris N, Tsiridis E, Kosmopoulos V. Minimally invasive versus open transforaminal lumbar interbody fusion: evaluating initial experience. *Int Orthop*. 2008;33(6):1683–1688. https://doi.org/10.1007/s00264-008-0687-8.
22. Peng CWB, Yue WM, Poh SY, Yeo W, Tan SB. Clinical and radiological outcomes of minimally invasive versus open transforaminal lumbar interbody fusion. *Spine*. 2009;34(13):1385–1389. https://doi.org/10.1097/brs.0b013e3181a4e3be.
23. Wang J, Zhou Y, Zhang ZF, Li CQ, Zheng WJ, Liu J. Comparison of one-level minimally invasive and open transforaminal lumbar interbody fusion in degenerative and isthmic spondylolisthesis grades 1 and 2. *Eur Spine J*. 2010;19(10):1780–1784. https://doi.org/10.1007/s00586-010-1404-z.
24. Shunwu F, Xing Z, Fengdong Z, Xiangqian F. Minimally invasive transforaminal lumbar interbody fusion for the treatment of degenerative lumbar diseases. *Spine*. 2010;35(17):1615–1620. https://doi.org/10.1097/brs.0b013e3181c70fe3.
25. Lau D, Lee JG, Han SJ, Lu DC, Chou D. Complications and perioperative factors associated with learning the technique of minimally invasive transforaminal lumbar interbody fusion (TLIF). *J Clin Neurosci*. 2011;18(5):624–627. https://doi.org/10.1016/j.jocn.2010.09.004.
26. Park Y, Ha JW. Comparison of one-level posterior lumbar interbody fusion performed with a minimally invasive approach or a traditional open approach. *Spine*. 2007;32(5):537–543. https://doi.org/10.1097/01.brs.0000256473.49791.f4.
27. Kotani Y, Abumi K, Ito M, Sudo H, Abe Y, Minami A. Mid-term clinical results of minimally invasive decompression and posterolateral fusion with percutaneous pedicle screws versus conventional approach for degenerative spondylolisthesis with spinal stenosis. *Eur Spine J*. 2011;21(6):1171–1177. https://doi.org/10.1007/s00586-011-2114-x.
28. Kim DY, Lee SH, Chung SK, Lee HY. Comparison of multifidus muscle atrophy and trunk extension muscle strength: percutaneous versus open pedicle screw fixation. *Spine*. 2005;30(1):123–129. https://doi.org/10.1097/01.brs.0000148999.21492.53.
29. Arikat A, Allaoui M, Assaker R, Zairi F. Transforaminal lumbar interbody fusion: comparison between open and mini-open approaches with two years follow-up. *J Neurol Surg Part A Cent Eur Neurosurg*. 2013;74(03):131–135. https://doi.org/10.1055/s-0032-1330956.
30. Harris EB, Sayadipour A, Massey P, Duplantier NL, Anderson DG. Mini-open versus open decompression and fusion for lumbar degenerative spondylolisthesis with stenosis. *Am J Orthop (Belle Mead NJ)*. 2011;40(12):E257–E261.
31. Lee KH, Yue WM, Yeo W, Soeharno H, Tan SB. Clinical and radiological outcomes of open versus minimally invasive transforaminal lumbar interbody fusion. *Eur Spine J*. 2012;21(11):2265–2270. https://doi.org/10.1007/s00586-012-2281-4.
32. Burneikiene S, Roeca C, Nelson L, Mason A, Villavicencio A. Minimally invasive versus open transforaminal lumbar interbody fusion. *Surg Neurol Int*. 2010;1(1):12. https://doi.org/10.4103/2152-7806.63905.
33. Jin-tao Q, Yu T, Mei W, et al. Comparison of MIS vs. open PLIF/TLIF with regard to clinical improvement, fusion rate, and incidence of major complication: a meta-

analysis. *Eur Spine J*. 2015;24(5):1058–1065. https://doi.org/10.1007/s00586-015-3890-5.
34. Fan Y, Du JP, Liu JJ, et al. Accuracy of pedicle screw placement comparing robot-assisted technology and the free-hand with fluoroscopy-guided method in spine surgery: an updated meta-analysis. *Medicine*. 2018;97(22), e10970. https://doi.org/10.1097/md.0000000000010970.
35. Chang M, Wang L, Yuan S, Tian Y, Zhao Y, Liu X. Percutaneous endoscopic robot-assisted transforaminal lumbar interbody fusion (PE RA-TLIF) for lumbar spondylolisthesis: a technical note and two years clinical results. *Pain Physician*. 2022;25(1):E73–E86.
36. Macnab I. Negative disc exploration: an analysis of the causes of nerve-root involvement in sixty-eight patients. *J Bone Joint Surg*. 1971;53(5):891–903. https://doi.org/10.2106/00004623-197153050-00004.
37. Kim SK, Kang SS, Hong YH, Park SW, Lee SC. Clinical comparison of unilateral biportal endoscopic technique versus open microdiscectomy for single-level lumbar discectomy: a multicenter, retrospective analysis. *J Orthop Surg Res*. 2018;13(1). https://doi.org/10.1186/s13018-018-0725-1.
38. Qin R, Wu T, Liu H, Zhou B, Zhou P, Zhang X. Minimally invasive versus traditional open transforaminal lumbar interbody fusion for the treatment of low-grade degenerative spondylolisthesis: a retrospective study. *Sci Rep*. 2020;10(1). https://doi.org/10.1038/s41598-020-78984-x.
39. Zhu L, Cai T, Shan Y, Zhang W, Zhang L, Feng X. Comparison of clinical outcomes and complications between percutaneous endoscopic and minimally invasive transforaminal lumbar interbody fusion for degenerative lumbar disease: a systematic review and meta-analysis. *Pain Physician*. 2021;24(6):441–452.
40. Heo DH, Lee DC, Kim HS, Park CK, Chung H. Clinical results and complications of endoscopic lumbar interbody fusion for lumbar degenerative disease: a meta-analysis. *World Neurosurg*. 2021;145:396–404. https://doi.org/10.1016/j.wneu.2020.10.033.
41. Sik Goh T, Hwan Park S, Suk Kim D, Ryu S, Min Son S, Sub Lee J. Comparison of endoscopic spine surgery and minimally invasive transforaminal lumbar interbody fusion for degenerative lumbar disease: a meta-analysis. *J Clin Neurosci*. 2021;88:5–9. https://doi.org/10.1016/j.jocn.2021.03.030.
42. Chen Z, Wu W, Xiong H, et al. Systematic review and meta-analysis of the therapeutic effects of minimally invasive transforaminal interbody fusion on spondylolisthesis. *Ann Palliat Med*. 2021;10(9):9848–9858. https://doi.org/10.21037/apm-21-2137.
43. Kim CH, Easley K, Lee JS, et al. Comparison of minimally invasive versus open transforaminal interbody lumbar fusion. *Global Spine J*. 2020;10(2_suppl):143S–150S. https://doi.org/10.1177/2192568219882344.
44. Cui G, Han X, Wei Y, et al. Robot-assisted minimally invasive transforaminal lumbar interbody fusion in the treatment of lumbar spondylolisthesis. *Orthop Surg*. 2021;13(7):1960–1968. https://doi.org/10.1111/os.13044.
45. Kim HJ, Lee SH, Chang BS, et al. Monitoring the quality of robot-assisted pedicle screw fixation in the lumbar spine by using a cumulative summation test. *Spine*. 2015;40(2):87–94. https://doi.org/10.1097/brs.0000000000000680.
46. Li C, Li W, Gao S, et al. Comparison of accuracy and safety between robot-assisted and conventional fluoroscope assisted placement of pedicle screws in thoracolumbar spine: a meta-analysis. *Medicine*. 2021;100(38), e27282. https://doi.org/10.1097/md.0000000000027282.
47. Ringel F, Stüer C, Reinke A, et al. Accuracy of robot-assisted placement of lumbar and sacral pedicle screws: a prospective randomized comparison to conventional freehand screw implantation. *Spine*. 2012;37(8):E496–E501. https://doi.org/10.1097/brs.0b013e31824b7767.
48. Shafi KA, Pompeu YA, Vaishnav AS, et al. Does robot-assisted navigation influence pedicle screw selection and accuracy in minimally invasive spine surgery? *Neurosurg Focus*. 2022;52(1):E4. https://doi.org/10.3171/2021.10.focus21526.
49. Winder MJ, Gilhooly PM. Accuracy of minimally invasive percutaneous thoracolumbar pedicle screws using 2D fluoroscopy: a retrospective review through 3D CT analysis. *J Spine Surg*. 2017;3(2):193–203. https://doi.org/10.21037/jss.2017.06.05.