CLINICAL ARTICLE

Three-dimensional High-definition Exoscope in Minimally Invasive Transforaminal Lumbar Interbody Fusion: A Retrospective Cohort Study

Ya-Wei Yao, MD[1,2], Zhi-Peng Yao, MD[3], Ming Jiang, MD[3], Wen-Xiong Zhu, MD[3], Fang-qiang Zhu, MD[1], Cheng-Jie Xiong, PhD[1], Feng Xu, PhD[1]

[1]Orthopaedic Department, General Hospital of Central Theater Command of PLA, Wuhan, [2]Department of Orthopaedics, Chinese People's Liberation Army General Hospital (301 Hospital), Beijing and [3]Affiliated Dongguan Hospital, Southern Medical University (Dongguan People's Hospital), Dongguan, China

Objectives: The operative microscope (OM) has revolutionized the field of modern spine surgery, however, it remains limited by several drawbacks. Recently, the exoscope (EX) system has been designed to assistant spine surgery. It provides a three-dimensional (3D) high-definition (HD) operative experience and becomes an alternative to the OM. The aim of the study was to evaluate the clinical outcomes, advantages and limitations of EX-assisted minimally invasive transforaminal lumbar interbody fusion (EMIS-TLIF) and OM-assisted MIS-TLIF (OMIS-TLIF).

Methods: The clinical outcomes were assessed in 47 patients with lumbar degenerative diseases (LDD) who underwent MIS-TLIF assisted with the OM or EX between January 2019 and September 2020. A total of 22 were treated with EMIS-TLIF, and 25 received OMIS-TLIF. Perioperative parameters (including sex, age, number of fusion levels and body mass index), perioperative parameters (operation time, intraoperative blood loss, postoperative drainage, postoperative hospitalization stay, and duration of follow-up), visual analogue scale (VAS) of back pain, VAS of leg pain, Oswestry disability index (ODI) scores and clinical outcomes were assessed and compared. Image quality, handling of equipment, ergonomics, 3D glasses and educational usefulness were scored according to a questionnaire.

Results: Operation time in the OMIS-TLIF group (121.92 ± 16.92 min) was significantly increased compared with that in the EMIS-TLIF group (111.00 ± 19.87 min) ($P < 0.05$). The VAS of the back pain and ODI scores in the EMIS-TLIF group were significantly lower compared with the OMIS-TLIF group at 1 week postoperatively ($P < 0.05$). The good-excellent outcomes rate was 90.91% in the EMIS-TLIF group and 88.00% in the OMIS-TLIF group, and there was no significant difference. A total of 44 visits completed the questionnaire. The results of the questionnaire showed that the EX has exhibited advantages regarding handing of equipment, ergonomics and educational usefulness, and comparable image quality as compared with the OM, however, operating surgeons complained uncomfortable sensation when wearing 3D glasses.

Conclusions: The EMIS-TLIF was a safe and effective procedure in the management of LDD as compared with the OMIS-LIF. Meanwhile, EMIS-TLIF might resulted in a short operation time.

Key words: Exoscope; Lumbar degenerative diseases; Minimally invasive transforaminal interbody fusion; Three dimensional

Address for correspondence: Feng Xu, PhD, Orthopaedic Department, General Hospital of Central Theater Command of PLA, #627 Wuluo Road, Wuchang District, Wuhan, China 430070 Tel: +86-13397191978; Fax: +027-50772548; Chengjie Xiong, PhD, Orthopaedic Department, General Hospital of Central Theater Command of PLA, #627 Wuluo Road, Wuchang District, Wuhan, China 430070 Tel:+86-13871162196; Fax: +027-50772548; Email: fengxu1969@163.com. Cheng-jie Xiong, Orthopaedic Department, General Hospital of Central Theater Command of PLA, #627 Wuluo Road, Wuchang District, Wuhan, China 430070 Tel: +86-13871162196; Fax: +027-50772548; Email: cjxiong1110@gmail.com
Ya-Wei Yao and Zhi-Peng Yao contributed equally to this work.
Co-first authors: Ya-wei and Zhi-peng Yao.
Received 5 January 2022; accepted 13 September 2022

Introduction

Lumbar degenerative diseases (LDD), such as lumbar disc herniation, lumbar spinal stenosis, and degenerative lumbar spondylolisthesis, are common musculoskeletal disorders that lead to low back pain in the elderly. Patients with LDD are usually associated with low back pain, radiculopathy, and claudication associated with decreased mobility.[1,2] Studies have demonstrated that surgical management is advised when conservative therapy failed within 6 weeks.[3,4] With the development of minimally invasive spine surgery (MISS), it can achieve equivalent clinical outcomes as compared with conventional open surgery with reduced operation-related comorbidities. Therefore, MISS was advocated as an optimal treatment for LDD. However, this mini-invasive procedure is performed in a deep and narrow corridor with limited surgical field and illumination, which require achievement of high-skilled surgical techniques after a long learning curve. Therefore, various devices have been applied to facilitate MISS operation.

As we know, operative microscopy (OM) has been widely applied in orthopedic surgery for its advantages such as illumination, stereo viewing and magnification.[5–8] Spine operation assisted with OM has become the gold standard in treating LDD. Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) assisted with an operative microscope (OM) has been widely used for the management of LDD recently.[8–11] However, several limitations of OM have also been mentioned, such as time-consuming refocusing requirements, poor ergonomics, difficult maneuverability and the limited working distance, which may result in fatigue and discomfort, thus limiting the surgeon's performance. It negatively affects the safety and efficiency of the procedure. Therefore, more advanced devices should be developed to facilitate surgical manipulation of MIS-TLIF.

Recently, the three-dimensional (3D) high-definition (HD) exoscope (EX), a novel visualization tool, has been applied in neurosurgery.[12–17] The EX not only provides better ergonomic advantages, longer working distance, and shorter refocusing time, but also has comparable illumination, stereovision, image quality, and higher magnification when compared with the OM.[12–17] With the extension application of this device, EX has been applied in the spine surgery. Several studies have demonstrated that the EX is compatible with many spinal surgical procedures including MIS-TLIF.[13,17–19] Therefore, EX-assisted MIS-TLIF (EMIS-TLIF) might become a promising alteration.

The application of the EX in the MIS-TLIF has been reported in several studies.[5–8,18,19] However, the comparison between EMIS-TLIF and OM-assisted MIS-TLIF (OMIS-TLIF) has never been reported to our knowledge. This retrospective study aims to compare the perioperative data and the clinical outcomes between two procedures in the management of LDD, meanwhile, to discuss the advantages and limitations between the EX and OM in the spine surgery.

Methods

Patient Population

A retrospective study was conducted to evaluate patients with LDD who underwent MIS-TLIF between January 2019 and September 2020. A total of 47 patients were enrolled in this study. A total of 22 of them were treated with EMIS-TLIF, and 25 of them received OMIS-TLIF. The inclusion criteria were as follows: (i) aged >18 years; (ii) patients were diagnosed with lumbar disc herniation, degenerative lumbar spinal stenosis, and degenerative lumbar spondylolisthesis (Meyerding Grade I and II);[20] (iii) patients who had received conservative therapy for at least 6 weeks while their symptoms did not show improvement; (iv) one-level (L4/5 or L5/S1 segment) MIS-TLIF assisted with the EX or OM; and (v) with at least 1 year of follow-up. The following exclusion standards were applied: (i) patients have had prior surgery at the same segment; (ii) degenerative lumbar spondylolisthesis (Meyerding Grade > II);[20] (iii) combined with active infection or spinal deformity; and (iv) patients who cannot tolerate spine surgery. This study was consistent with the Helsinki Declaration and ethical approval was obtained by the Ethics Committee of General Hospital of Central Theater Command ([2020]059-1).

Generation Features

This novel EX (Kestrel View II, Mitaka Kohli, Japan) is equipped with the following features: dual camera 3D HD 1080p with magnification ranging from 1.9 to 39.3×; the lens can be rotated freely in the range of front-back 210°, left–right 330° and horizontal 540°; laser-guided focus, electric autofocus system, LED cold-lighting source and working distance of 300–1000 mm; 32 inch 3D medical-grade display with viewing angle of 178°; fully balanced vibration absorbing system from astronomical telescope; foot switch and hand grip controls with focus and zoom (Fig. 1).

Surgical Procedure

EMIS-TLIF: After general anesthesia, the patient was placed in a prone position on a radiolucent operating table. First, a 3 cm posterior incision was made at the symptomatic side lateral to the midline (2.5–3 cm). Sequential dilators were inserted through the incision to establish a working channel. The tubular retractor was then introduced over the dilators and attached with a flexible arm. The 3D EX was then positioned over the sterile surgical field. The camera orientation was then adjusted to avoid any visual interference. Surgeons wore special 3D glasses and stood slightly staggered to each other to avoid viewing obstruction (Fig. 2). Following the paraspinal dissection at the index segment, the 3D EX was applied to perform posterior decompression, discectomy, and cage insertion. The inferior facet of upper lamina and partial superior facet were cut and removed with ultrasound bone scalpel and Kerrison rongeurs. The posterior-lateral portion of nerve roots and the dura were exposed. Then discectomy, interbody implantation preparation, bone grafting,

Fig. 1 (A) Kestrel View II exoscope applies fully balanced vibration absorbing system from astronomical telescope; (B) a foot switch helps for fine-turning of focal length and changing where the EX is pointed on two axes; (C) the hand grip is truly ergonomic design, providing comfort for operators, which can rotate freely and adapt to the different operation habits of surgeons

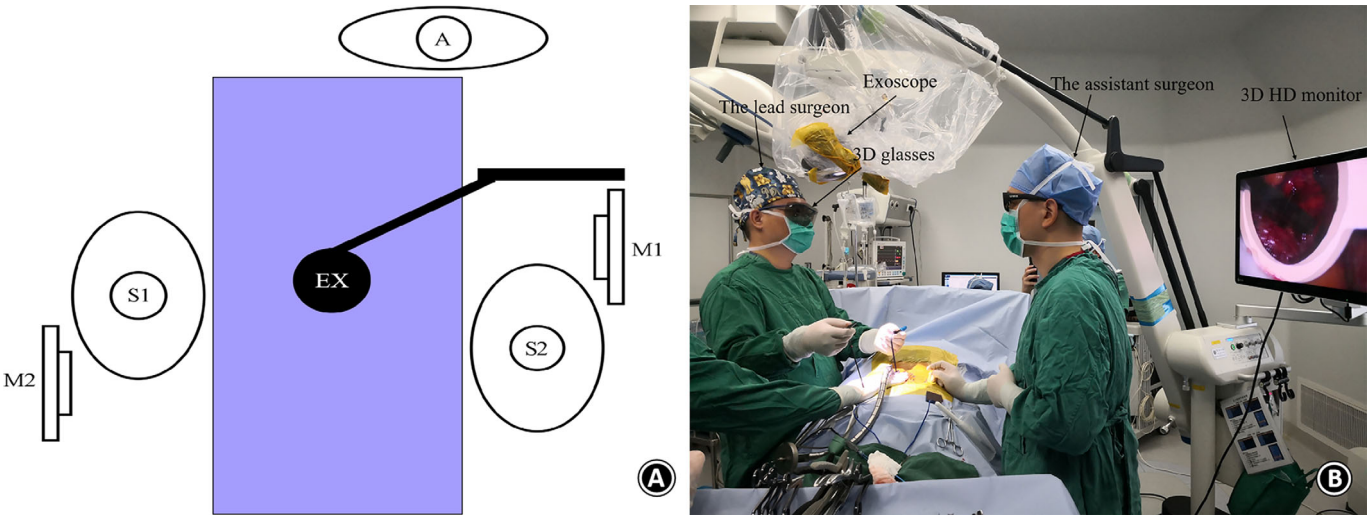

Fig. 2 (A, B) intraoperative setup, meanwhile surgeons being independent of the exoscope. A, anesthetist; EX, exoscope; M1, the first monitor; M2, the second monitor; S1, the chief surgeon; S2, the assistant surgeon

and cage placement were performed sequentially. Following the cage implantation, four pedicle screws were implanted percutaneously under C-arm fluoroscopic guidance. Two rods were applied to connect pedicle screws on both sides using the rod placement system. C-arm fluoroscopy was used to confirm the position of the cage and pedicle screws. Finally, a drainage tube was placed underneath the fascia, and then the wound was irrigated and sutured (Fig. 3). All participants or any identifiable individuals consented to publication of his/her image.

OMIS-TLIF

The incision, approach, and surgical steps of the OMIS-TLIF were the same as the EMIS-TLIF. The surgery process was performed according to a standard technique previously described by Park[20] and Foley et al.[10] Both EMIS-TLIF and OMIS-TLIF were performed by the same chef surgeon, who achieves sufficient experience in endoscopic and microscopic spine surgery previously.

Data Collection

Preoperative demographic variables (sex, age, number of fusion levels and body mass index [BMI]) and perioperative demographic variables (operation time, intraoperative blood loss, postoperative drainage, postoperative hospitalization stay, and duration of follow-up) were collected. Visual analogue scale (VAS) of back pain, VAS of leg pain and ODI

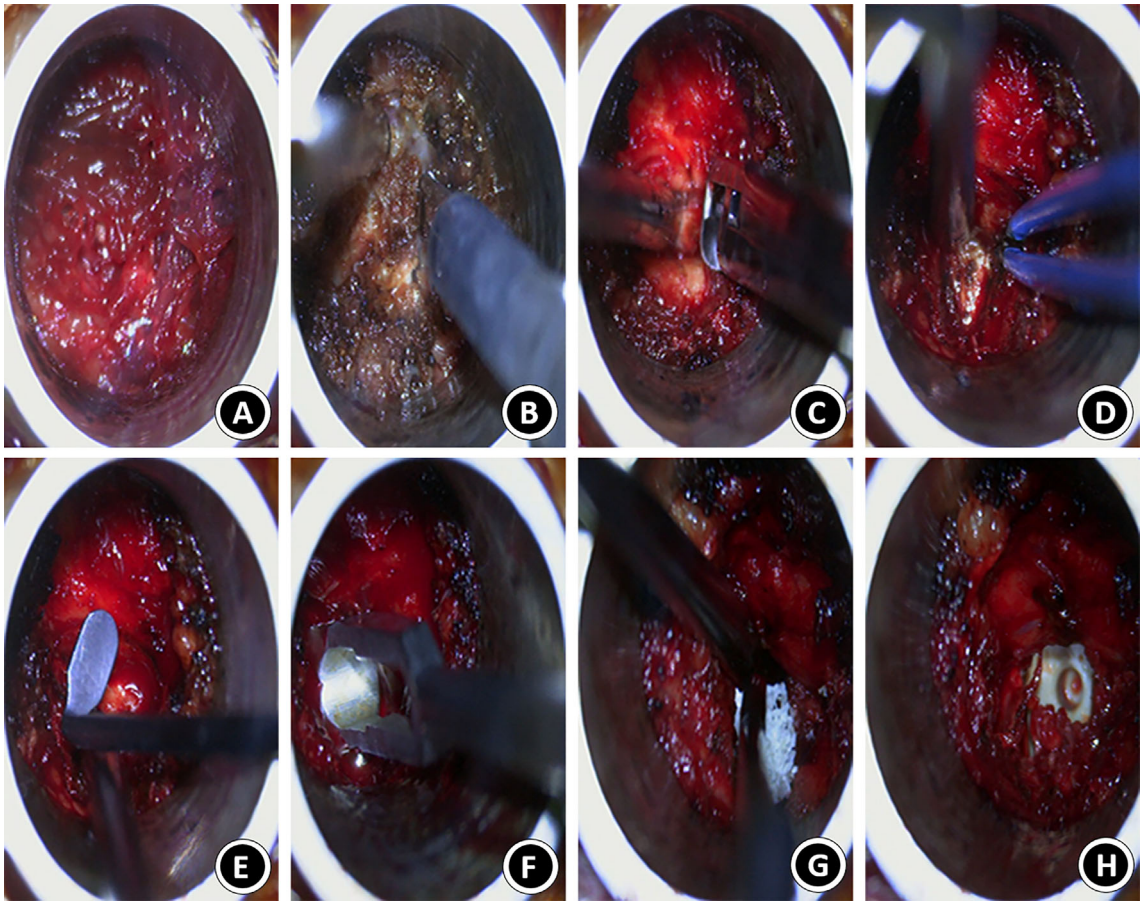

Fig. 3 (A) the working channel was established; (B, C) facetectomy was performed with ultrasound bone scalpel and Kerrison rongeurs; (D) bipolar coagulation was used to achieve hemostasis; (E) a micro-hook was applied to verify the decompression of neural structures; (F) cartilage endplate was excised; (G) bone grafting was performed after discectomy; (H) the interbody cage was placed into the intervertebral space

scores were obtained at 1 week, 3 month and 12 month postoperatively. At 12 month postoperatively, clinical outcomes were evaluated by Odom criteria.[21] The outcome was considered satisfactory if the subjective assessment was rated as good or excellent. We assessed perioperative complications, including cerebrospinal fluid fistula, never toot injury, lower extremity numbness, wound infection, screw loosening and reoperation. Measurements were made by two observers who were blinded to the clinical information of the patients.

After each EMIS-TLIF surgery, the participating surgeon and assistant answered the standardized questionnaire, regarding image quality, handling of equipment, subjective ergonomics, 3D glasses and educational usefulness questionnaire (Table 1). A five-point scale was used, ranging from 1 = the OM was considered to be superior, to 5 = the EX was superior (Table 1). All measurement data are expressed as mean ± standard deviation (SD), and the enumeration data are presented by the number of cases and percentage (%).

Statistical Analyses

Statistical analyses were performed by using SPSS statistical package 25.0 (SPSS, Chicago, IL, USA). Differences in sex and the number of fusion levels were determined using a chi-squared test. Significant differences between complication occurrence rates were found by Fisher's exact probability method. Significant differences between the two groups in age, BMI, operation time, intraoperative blood loss, postoperative drainage, postoperative hospitalization stay, duration of follow-up, and ODI and VAS scores at the same time point were analyzed using independent sample *t*-test. For the Odom criteria outcome, Mann–Whitney U tests were used. Paired *t*-test was conducted to compare the differences between VAS and ODI scores at different follow-up time point and the baseline scores. Differences were considered to be statistically significant when P values <0.05.

Results

General Results

A total of 47 participants (EMIS-TLIF group, 22 cases; OMIS-TLIF group, 25 cases) were assessed in the present

TABLE 1 Questionnaire about the experience of the exoscope (EX) compared with the operative microscope (OM)

Image quality on the monitor
1. How was the overall brightness of image by the EX compared with the OM?
2. How was the brightness of the field when the deep operative field was shown compared with the OM?
3. How was the overall image quality of the EX compared with the OM?
4. How was image quality of the EX than that to the OM when the operative field was magnified?
5. Was the magnification of the EX sufficient compared with the OM?

Handling of the equipment
6. How was the depth perception of the EX compared with the OM?
7. How easy was it to reposition and refocus on the operative field compared with the OM?
8. How easy was it to prepare and install compared with the OM?
9. How comfortable was the working distance compared with the OM?
10. How much space did the EX occupy in the operating room?

Subjective ergonomics
11. How much body comfortable did the surgeon feel using the EX compared with the OM?
12. How convenient was it to perform surgery while watching monitor compared with the OM?

3D glasses
13. How comfortable was it wearing the 3D glasses?

Education usefulness
14. Was the EX more useful as an educational tool compared the OM?

TABLE 2 Comparison of demographic variables in two groups

Items	EMIS-TLIF group	OMIS-TLIF group	t/x^2	*P* value
Cases	22	25		
Sex *n* (%)			0.046	0.831
Male	13 (59.09)	14 (56)		
Female	9 (40.91)	11 (44)		
Age (year)			−0.487	0.629
Range	41–68	40–70		
Mean ± SD	55.77 ± 7.89	56.96 ± 8.72		
Segment *n* (%)			0.238	0.770
L4/5	9 (40.91)	12 (48)		
L5/S1	13 (59.09)	13 (52)		
BMI (kg/m^2)	25.72 ± 1.90	26.01 ± 2.40	−0.446	0.658
Duration of follow-up (months)	16.05 ± 3.26	16.76 ± 3.53	−0.718	0.476

Abbreviations: EMIS-TLIF, exoscope-assisted minimally transforaminal lumbar interbody fusion; OMIS-TLIF: operative microscope-assisted minimally invasive transforaminal lumbar interbody fusion.

study. The preoperative demographic variables (sex, age, segment, BMI, and duration of follow-up) were collected and compared, but there were no statistically significant differences between the two groups regarding these demographic variables ($P > 0.05$) (Table 2).

The operation time in the OMIS-TLIF group (121.92 ± 16.92 min) was significantly increased compared with that in the EMIS-TLIF group (111.00 ± 19.87 min) ($P < 0.05$). However, no significant differences regarding intraoperative blood loss (57.23 ± 20.25 ml vs. 63.28 ± 20.34 ml), the postoperative drainage (52.86 ± 12.26 ml vs. 51.92 ± 13.48 ml) and postoperative hospitalization stay (11.14 ± 1.81 ml vs. 11.72 ± 2.54 ml) were found between the EMIS-TLIF group and the OMIS-TLIF group ($P > 0.05$) (Table 3).

Clinical Outcomes

The VAS of back pain, VAS of leg pain, and ODI scores in both groups were significantly decreased at 1 week postoperatively compared with pre-operation ($P < 0.001$). The VAS of back pain scores and ODI scores were significantly reduced in the EMIS-TLIF group compared with those in the OMIS-TLIF group at 1 week postoperatively ($P < 0.05$). However, no significant differences of VAS and ODI scores were found between the two groups at the other follow-up time points ($P > 0.05$) (Table 4, Fig. 4).

According to the Odom criteria, at 12 month postoperative assessment, 14 patients had excellent clinical outcomes, and six patients had good clinical outcomes, and two patients had fair clinical outcomes in the EMIS-TLIF group. While, in the OMIS-TLIF group, 15 patients had excellent clinical outcomes, and seven patients had good clinical outcomes, and two patients had fair clinical outcomes, and one patient had poor clinical outcomes. The overall good-to-excellent rate was 90.91% in the EMIS-TLIF group and 88.00% in the OMIS-TLIF group. Overall, there was no significant difference of good-to-excellent rate between the two groups regarding clinical outcomes ($P > 0.05$) (Table 5).

Complications

The overall comorbidities rate in the EMIS-TLIF group (9.09%) was lower compared with that (12.00%) in the OMIS-TLIF group ($P > 0.05$) (Table 3). Lower extremity

TABLE 3 Comparison of surgery-related indicators between the two group

Items	EMIS-TLIF group	OMIS-TLIF group	*t*	*P* value
Operation time (min)	111.00 ± 19.87	121.92 ± 16.92	−02.035	0.048*
Intraoperative blood loss (ml)	57.23 ± 20.25	63.28 ± 20.34	−1.020	0.313
Postoperative drainage (ml)	52.86 ± 12.26	51.92 ± 13.48	0.250	0.804
Postoperative hospitalization stay (days)	11.14 ± 1.81	11.72 ± 2.54	−0.896	0.375
Complications rates *n* (%)	2 (9.09%)	3 (12.00%)		1.000

Abbreviations: EMIS-TLIF, exoscope-assisted minimally transforaminal lumbar interbody fusion; OMIS-TLIF, operative microscope-assisted minimally invasive transforaminal lumbar interbody fusion.; * $p < 0.05$ were statically significant between the two groups.

numbness occurred in two patients in the OMIS-TLIF group and zero patient in the EMIS-TLIF group at 1 week postoperatively and recovered following conservative treatment for 4 weeks. Screw loosening occurred in two patients in the EMIS-TLIF group and one patient in the OMIS-TLIF group at 3 month postoperatively, and those patients were conservatively treated until solid bony fusion of the fractured vertebral body as observed. No patients developed serious

TABLE 4 Comparison of visual analog scale (VAS) and Oswestry disability index (ODI) scores in two groups

Items	EMIS-TLIF group	OMIS-TLIF group	*t*	*P* value
VAS of back pain				
Pre-operation	6.67 ± 1.23	6.50 ± 1.15	0.495	0.623
1 week postoperatively	2.54 ± 0.71	3.00 ± 0.76	−2.159	0.036**
3 month postoperatively	2.12 ± 0.68	2.37 ± 0.71	−1.243	0.220
12 month postoperatively	1.71 ± 0.52	1.90 ± 0.68	−1.088	0.282
P value	<0.05*	<0.05*		
VAS of leg pain				
Pre-operation	5.13 ± 1.31	5.48 ± 1.06	−0.996	0.325
1 week postoperatively	2.07 ± 0.59	2.23 ± 0.88	−0.737	0.465
3 month postoperatively	1.78 ± 0.45	1.76 ± 0.55	0.121	0.904
12 month postoperatively	1.48 ± 0.48	1.64 ± 0.43	−1.258	0.215
P value	<0.05*	<0.05*		
ODI				
Pre-operation	55.73 ± 9.07	58.12 ± 7.96	−0.963	0.341
1 week postoperatively	27.18 ± 4.84	30.08 ± 4.73	−2.075	0.044**
3 month postoperatively	22.05 ± 5.93	23.80 ± 5.32	−1.069	0.291
12 month postoperatively	15.05 ± 4.02	14.24 ± 3.70	0.715	0.478
P value	<0.05*	<0.05*		

Abbreviations: EMIS-TLIF, exoscope-assisted minimally transforaminal lumbar interbody fusion; ODI, Oswestry disability index; OMIS-TLIF, operative microscope-assisted minimally invasive transforaminal lumbar interbody fusion; VAS, visual analog scale.; * $P < 0.05$ for significant improvement when compared with baseline assessment,; ** $P < 0.05$ were statically significant between the two groups.

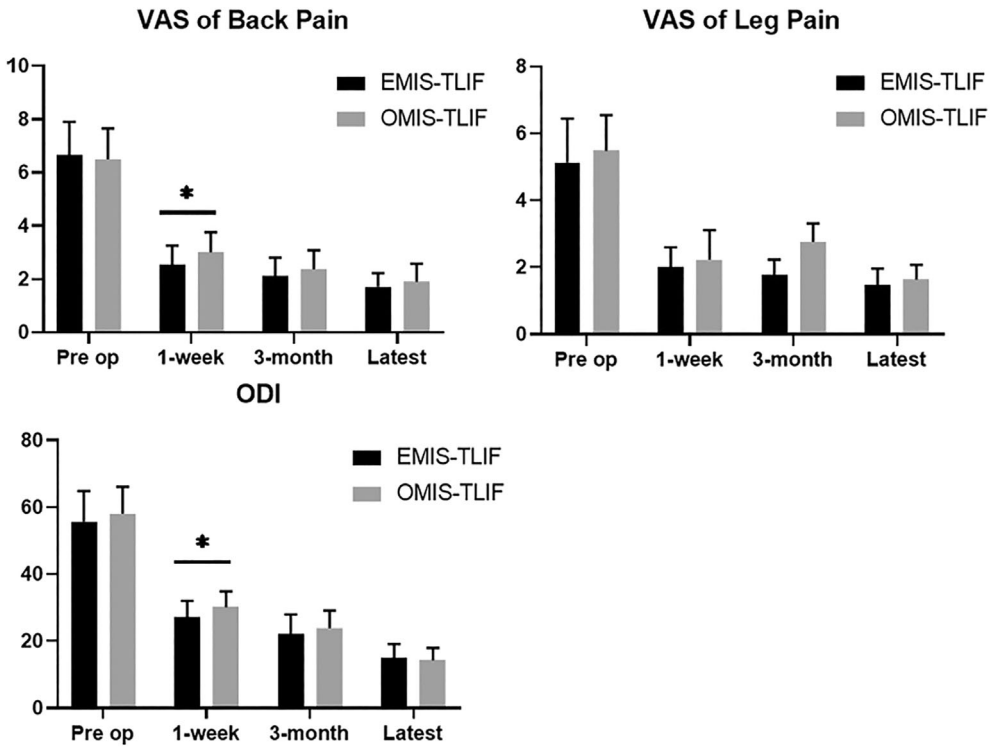

Fig. 4 *$P < 0.05$ were statistically significant between two groups; EMIS-TLIF, exoscope-assisted minimally invasive transforaminal lumbar interbody fusion group; ODI, Oswestry disability index; OMIS-TLIF, operative microscope-assisted minimally invasive transforaminal lumbar interbody fusion group; VAS, visual analog scale

TABLE 5 Comparison of Odom criteria between the two group

Outcome	Criteria	EMIS-TLIF group	OMIS-TLIF group	z	*P* value
Excellent	Improvement of preoperative symptoms and signs	14 (63.67%)	15 (60.00%)	−0.359	0.720
Good	Partial relief of symptoms with full activity	6 (27.27%)	7 (28.00%)		
Fair	Improvement but limitation of activity	2 (9.09%)	2 (8.00%)		
Poor	Symptoms and signs unchanged or exacerbated	0 (0.00%)	1 (4.00%)		

Abbreviations: EMIS-TLIF, exoscope-assisted minimally transforaminal lumbar interbody fusion; OMIS-TLIF, operative microscope-assisted minimally invasive transforaminal lumbar interbody fusion.

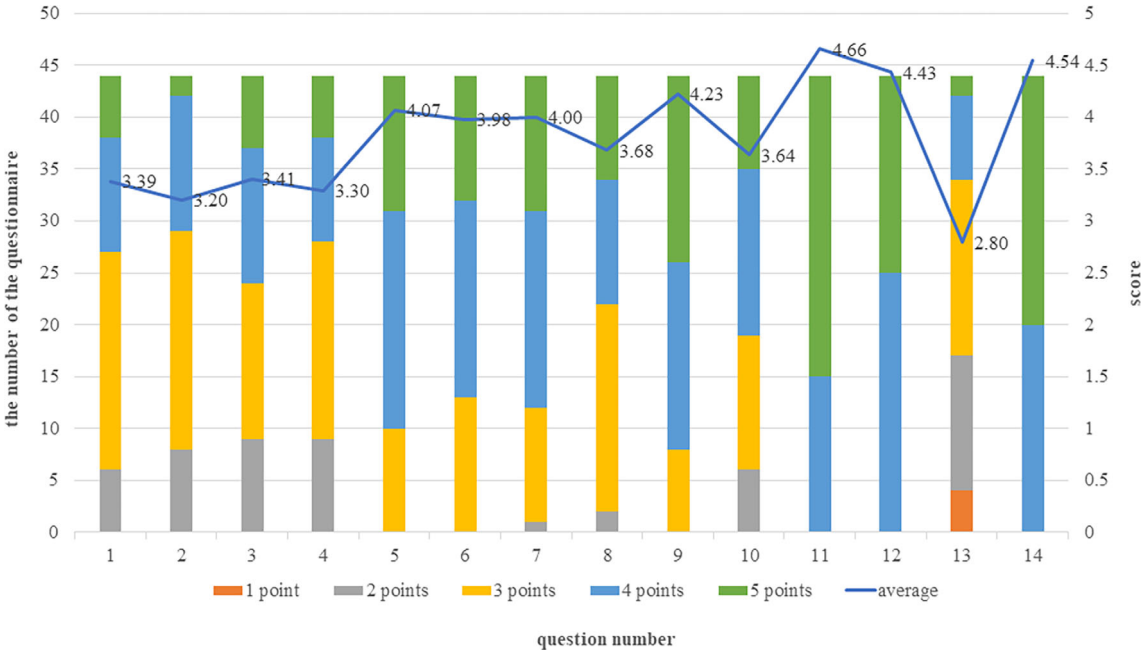

Fig. 5 Summary of the results for question 1–14 which aimed to compare the EX and OM on 5-point scale. 1 = EX very inferior to OM. 5 = EX very superior to OM

comorbidities such as cerebrospinal fluid fistula, nerve toot injury, wound infection and reoperation in both groups.

Rating scale questionnaire

After each EMIS-TLIF surgery, the main surgeon (a senior spinal surgeon) and assistant (intermediate-grade surgeon) from the Department of Orthopedic, General Hospital of Central Theater Command of PLA answered the standardized questionnaire. A total of 44 participants (22 main surgeons and 22 assistants) responded to the questionnaire. According to the questionnaire, questions about subjective ergonomics and education usefulness, receive the highest score (4.66, 4.43, and 4.54). The characteristic of handling of equipment was superior than the OM. Another characteristic of the EX, image quality on the monitor during the procedure were almost equivalent to the OM. However, question 13 about 3D glasses, was rated as the lowest (2.80) (Fig. 5).

Discussion

This retrospective study was conducted to investigate two visualization devices (the EX and OM) that have been applied to facilitate MIS-TLIF for the management of LDD. Lower operation time and comorbidities rates in the EMIS-LIF group were observed. As we mentioned above, spine surgery assisted with the OM is a gold standard in this field. Therefore, OMIS-TLIF served as a reference in this study to assess and compare the perioperative data and clinical results of EMIS-TLIF. The preliminary outcomes have shown that EMIS-TLIF can be regarded as a safe and effective alternative solution in treating degenerative lumbar disease.

Why Does the Surgeon Use the EX in MIS-TLIF?

MIS-TLIF was first described by Foley *et al.* in 2002 and has been widely used to treat LDD up to now.[10] MIS-TLIF has been demonstrated to achieve equivalent and even superior

clinical outcomes as compared with conventional TILF. It can improve fusion rates, reduce time to ambulation and length of hospitalization, and alleviate postoperative back pain.[8–11] However, a long learning curve should be overcome before becoming proficient in this operation. The incidence of comorbidities associated with MIS-TLIF has been reported as high as 33.3%.[9] It is due to limited surgical field and inefficient illumination during the surgical manipulation. Especially, the chief surgeon who receive traditional training was not familiar with this endoscopic operation. At the beginning of popularization of this operation, the decompression of MIS-TLIF was performed under the endoscopy. Therefore, multiple intraoperative visualization devices have also been developed to improve the illumination, visualization and magnification of surgical view field, meanwhile facilitate surgical manipulation.

The OM provides favorable intraoperative illumination, stereovision and magnification during surgical manipulation, which has been applied to assist MIS-TLIF.[6–8] Compared with endoscopic surgery, spine surgeons were more familiar with OM since most of them have receive OM training when engaging in spine surgical practice. Zhang *et al.*[8] have reported a series of cases with LDD who received tubular operation with assistance of OM. It can achieve favorable clinical outcomes in the management of LDD. Subsequently, a series studies have reported that the application of microscope improves the visualization of the surgical field, and it makes the operation more efficient and safer.[6,22] However, limitations of the OM have also been mentioned. It includes narrow depth of field, limited working distance, poor ergonomics, difficulty maneuverability and encumbrance.[12–17,23] These disadvantages might cause discomfort to the surgeon and negatively affect the surgical outcomes.[24] Therefore, new devices should be developed to overcome these disadvantages.

The Advantages and Disadvantages of the EX in MIS-TLIF

The EX, an alternative tool to the OM, provides not only 3D visualization, but also 4K definition and feasibility for most spinal surgical procedures.[12–18,25] According to our questionnaire, the EX has a few strengths compared with the OM, which is consistent with other reports.[18,24,26,27] First, the EX has shown great educational potential compared with the standard OM.[24] Unlike the traditional spine surgery assisted with the OM, 3D HD visualization on the screen can be watch by the entire surgical team. It not only achieves an educational goal, but also presents delicate surgical manipulation and facilities cooperation for the surgeons, anesthesiologists, nurses and medical students. All nurses, participated in our surgery commented an improved and more immersive experience, therefore overcoming the limitations of conventional OM.[24] Second, the EX provides some ergonomic superiority, which is beneficial for longer surgical procedure. The surgeon and assistant can obtain visualization on the monitor without distorting their posture.[18] If a surgeon often distorts their posture during the procedure, it is deleterious to the health of the spine. A previous study has reported that the usage of the OM in plastic surgery for more than 3 h per week was related to the surgeons' cervical and thoracic pain.[26] The reduction of ergonomics-related exhaustion during the long surgical procedure is necessary to maintain high-level surgeon performance.[28] Third, the EX can provide superior depth perception compared to the OM.[18,24] The good depth perception, vital in spine surgery, might help surgeon identify microstructural anatomy and improve efficiency and clinical outcomes (lower operation time and complication rates). Fourth, the EX also has shown advantages in depth of field. Previous studies demonstrated that the good field depths of the EX minimized the frequency and time of repositioning and refocusing during the procedure.[24,27] The main features between the EX (Kestrel View II, Mitaka Kohli, Tokyo, Japan) and OM (Leica M520 MS3, Wetzlar, Germany) are compared in Table 6. Subjectively, the image quality and illumination of the EX were comparable to the OM according the questionnaire.

However, there was a hint of eye strain, headache, or nasal pain in some participating with the 3D glasses in this study. Many of the same disadvantages were observed in other clinical studies,[18,29,30] which could have affected the surgeons, performance during the operation. In our research, the 3D glasses are general, nor tailored to the different surgeons, which might be one of the reasons of the nasal pain. Whereas problems like dizziness, eye strain, and headache are reported and discussed with the 3D EX, these occurrences have decreased with the development of this system.[31] Nevertheless, as a new technology, the 3D EX is not mature and the phenomena of visual intolerance existed; thus, further studies are needed to evaluate the adaptation between the 3D EX and surgeons.

TABLE 6 Comparison of the characteristics between the exoscope (EX) and the traditional operative microscope (OM)

Characteristics	EX	OM
Magnification	1.9–39.3×	1–17×
Image quality	Excellent	Good
Image capture	3D HD monitor	Eyepiece
Depth of field	Longer	Short
Focal length	Longer	Short
Working distance	300–1000 mm	Shorter
Light source	LED	Xenon
Auto-focusing	Yes	Yes
Controller type	Foot switch and hand grip	Hand grip
Refocusing time	Short	Longer
Stereopsis	3D	Yes
Depth perceptions	Yes	Yes
Education usefulness	High	Low
Subjective ergonomics	Good	Poor
Surgeon discomfort	Low	Medium/high
Maneuverability	Easy	Difficulty
Occupied space	Little	Large
Portability	Easy	Difficulty

Abbreviations: 3D, three-dimensional; EX, exoscope; HD, high definition; LED, light-emitting diode; OM, operative microscope.

Clinical Outcomes

The application of different EX in MIS-TLIF has been reported in two studies previously. Both studies found that the EX is well suited for MIS-TLIF.[18,19] However, limitations of two studies should be mentioned. First, Shirzadi *et al.*[19] found that the EX (VITOM) provided comparable operation time and clinical results to the OM in MIS-TLIF. However, a drawback of VITOM is absence of stereoscopic vision since 2D technology is applied in this system. It makes the spinal surgical procedures slower and riskier.[24] Another drawback is the scope holder of the EX. Unlike the EX used in our study, the hydraulic counter balance mechanism accommodates frequent and rapid repositioning in a wide range at different angles just with a simple button control, the VITOM holder in that study was relatively static. Fully balanced vibration absorbing system of our EX system may allow for a wider surgical field of view with significantly improved easy during frequent repositioning. Second, Ariffin *et al.*[18] also described EX-assisted MIS-TLIF for patients with LDD in a case series, and it is not a well-designed case–control study. We cannot evaluate the efficiency, safety and advantages of EX-assisted MIS-TLIF compared with other MIS-TLIF procedures.

In our study, the results illustrated a significant reduction of operation time in the EMIS-TLIF group compared with the OMIS-TLIF group ($P < 0.05$). It is due to the following reasons. First, a longer working distance provided by the EX facilitates the surgical manipulation and permits spine surgeons to operate bimanually without interruption from the camera (as a solid barrier).[32] Second, the EX has several strengths such as good depth of field, laser focus guide and an electric autofocus system, which might minimize the time used for repositioning and refocusing.[24,27] It was reported that up to 40% of the operation time was spent in adjusting either focus, viewing angle and the microscope's position.[33] Third, the chief surgeon in our team has obtained abundant hand-eye-coordination experience of endoscopic surgery, which is definitely beneficial for the surgeons to perform MIS-TLIF with EX with good cooperation between hand and eye. However, a well-designed comparison study is necessary to testify this speculation.

Both the ODI and VAS scores of the two groups were significantly improved compared with those before surgery. The postoperative ODI scores and VAS of back pain in the EMIS-TLIF group were significantly reduced compared with the OMIS-TLIF group at 1 week postoperatively. This phenomenon is due to the fact that the prolonged tubular retraction in the OMIS-TLIF group may result in ischemia and denervation of the paraspinal muscle, subsequently leading to lower back muscle atrophy and pain after the operation in the OM group.[33] It has been reported that a shorter operation time is associated with VAS scores of the back pain in the short-term postoperative period.[34] The ODI score is widely applied to evaluate the quality of life in patients postoperatively. More than 15% improvements of ODI score are associated with favorable outcomes.[35] The similar changes in ODI were observed in both groups. In addition, as a previous study has shown, the ODI score is closed related to the VAS,[36] so the changes in the ODI score could be responsible for corresponding changes in VAS observed in our study.

Limitations

This study had several limitations. First, only single-segmental MIS-TLIF was included in this study. Patients with two or three levels should be investigated in the future. Second, ergonomics was only evaluated by the subjective questioner in this study, and objective ergonomics and fatigue are still missing. Also, this study evaluated clinical outcomes in small-population and short-term, and these findings may be biased. A large-scale and long-term prospective clinical study should be performed to investigate the performance of MIS-TLIF with the EX.

Conclusions

Both the EMIS-TLIF and OMIS-TLIF resulted in similar clinical outcomes for LDD. This present study illustrates that the EMIS-TLIF is associated with shorter operation time than the OMIS-TLIF. We suppose that this EX could be an effective alternative tool to the OM in spine surgery, providing advantages in handling of the equipment, ergonomics and education usefulness for the surgical team, and safety and effectiveness for the patients.

Author Contributions

Feng Xu and Cheng-Jie Xiong designed this study and performed the operations. All authors were involved in drafting, revising and iteratively finalizing the manuscript. Ya-Wei Yao and Zhi-Peng Yao collected and analyzed the data, and performed the statistics. All authors (Ya-Wei Yao, Zhi-Peng Yao, Ming Jiang, Wen-Xiong Zhu, Fang-qiang Zhu, Cheng-Jie Xiong and Feng Xu) have read the final version of the manuscript and approved it.

Acknowledgment

This study was funded by the Wuhan Municipal Science and Technology Bureau (grant no. 2019020701011423).

References

1. Gao T, Lai Q, Zhou S *et al*. Correlation between facet tropism and lumbar degenerative disease: a retrospective analysis. BMC Musculoskelet Disord 2017; 18(1):483.

2. Mo Z, Li D, Zhang R, Chang M, Yang B, Tang S. Comparative effectiveness and safety of posterior lumbar interbody fusion, Coflex, Wallis, and X-stop for lumbar degenerative diseases: a systematic review and network meta-analysis. Clin Neurol Neurosurg. 2018;172:74–81.

3. Shamji MF, Mroz T, Hsu W, Chutkan N. Management of degenerative lumbar spinal stenosis in the elderly. Neurosurgery. 2015;77(Suppl 4): S68–74.

4. Weinstein JN, Tosteson TD, Lurie JD, et al. Surgical versus nonoperative treatment for lumbar spinal stenosis four-year results of the spine patient outcomes research trial. Spine. 2010;35(14):1329–38.
5. Uluç K, Kujoth GC, Başkaya MK. Operating microscopes: past, present, and future. Neurosurg Focus. 2009;27(3):E4.
6. Peng P, Chen K, Chen H *et al*. Comparison of O-arm navigation and microscope-assisted minimally invasive transforaminal lumbar interbody fusion and conventional transforaminal lumbar interbody fusion for the treatment of lumbar isthmic spondylolisthesis. J Orthop Transla 2020;20: 107–12.
7. Vergara P, Timofeev I. Minimally invasive anterior cervical discectomy and fusion: a valid alternative to open techniques. Acta Neurochir. 2018;160(12): 2467–71.
8. Zhang F, Zhang W, Zhang R, Chen B, Shang X, Han J, et al. Modified minimally invasive-transforaminal lumbar interbody fusion under microscopic view to achieve bilateral decompression and fusion through a single approach to treat developmental lumbar spinal stenosis. J Clin Neurosci. 2021;84:46–9.
9. Karikari IO, Isaacs RE. Minimally invasive transforaminal lumbar interbody fusion: a review of techniques and outcomes. Spine. 2010;35(26 Suppl): S294–301.
10. Foley KT, Lefkowitz MA. Advances in minimally invasive spine surgery. Clin Neurosurg. 2002;49:499–517.
11. Peng CW, 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):1385–9.
12. Roethe AL, Landgraf P, Schröder T, Misch M, Vajkoczy P, Picht T. Monitor-based exoscopic 3D4k neurosurgical interventions: a two-phase prospective-randomized clinical evaluation of a novel hybrid device. Acta Neurochir. 2020; 162(12):2949–61.
13. Kwan K, Schneider JR, Du V, et al. Lessons learned using a high-definition 3-dimensional exoscope for spinal surgery. Oper Neurosurg. 2019;16(5):619–25.
14. Bakhsheshian J, Strickland BA, Jackson C *et al*. Multicenter investigation of channel-based subcortical trans-sulcal exoscopic resection of metastatic brain tumors: a retrospective case series. Oper Neurosurg 2019;16(2):159–66.
15. Khalessi AA, Rahme R, Rennert RC *et al*. First-in-man clinical experience using a high-definition 3-dimensional exoscope system for Microneurosurgery. Oper Neurosurg 2019;16(6):717–25.
16. Barbagallo GMV, Certo F. Three-dimensional, high-definition exoscopic anterior cervical discectomy and fusion: a valid alternative to microscope-assisted surgery. World Neurosurg. 2019;130:e244–e50.
17. Oertel JM, Burkhardt BW. Vitom-3D for exoscopic neurosurgery: initial experience in cranial and spinal procedures. World Neurosurg. 2017;105:153–62.
18. Ariffin MHM, Ibrahim K, Baharudin A, Tamil AM. Early experience, setup, learning curve, benefits, and complications associated with exoscope and three-dimensional 4K hybrid digital visualizations in minimally invasive spine surgery. Asian Spine J. 2020;14(1):59–65.
19. Shirzadi A, Mukherjee D, Drazin DG *et al*. Use of the video telescope operating monitor (VITOM) as an alternative to the operating microscope in spine surgery. Spine 2012;37(24):E1517-23.
20. Park Y, Ha JJS. Comparison of one-level posterior lumbar interbody fusion performed with a minimally invasive approach or a traditional open approach. Spine. 2007;32(5):537–43.
21. Odom GL, Finney W, Woodhall B. Cervical disk lesions. JAMA. 1958;166(1): 23–8.
22. Chen K, Chen H, Zhang K *et al*. O-arm navigation combined with microscope-assisted MIS-TLIF in the treatment of lumbar degenerative disease. Clin Spine Surg 2019;32(5):E235-e40.
23. Adogwa O, Elsamadicy A, Reiser E, et al. Comparison of surgical outcomes after anterior cervical discectomy and fusion: does the intra-operative use of a microscope improve surgical outcomes. Int J Spine Surg. 2016;2(1):25–30.
24. Muhammad S, Lehecka M, Niemelä M. Preliminary experience with a digital robotic exoscope in cranial and spinal surgery: a review of the synaptive modus V system. Acta Neurochir. 2019;161(10):2175–80.
25. Krishnan KG, Schöller K, Uhl E. Application of a compact high-definition exoscope for illumination and magnification in high-precision surgical procedures. World Neurosurg. 2017;97:652–60.
26. Capone AC, Parikh PM, Gatti ME, Davidson BJ, Davison SP. Occupational injury in plastic surgeons. Plast Reconstr Surg. 2010;125(5):1555–61.
27. Mamelak AN, Nobuto T, Berci G. Initial clinical experience with a high-definition exoscope system for microneurosurgery. Neurosurgery. 2010;67(2): 476–83.
28. Fargen KM, Turner RD, Spiotta AM. Factors that affect physiologic tremor and dexterity during surgery: a primer for neurosurgeons. World Neurosurg. 2016;86: 384–9.
29. Ricciardi L, Chaichana KL, Cardia A, et al. The exoscope in neurosurgery: an innovative "point of view". A systematic review of the technical, surgical and educational aspects. World Neurosurg. 2019;124:136–44.
30. Lin H, Chen F, Mo J, Lin T, Wang Z, Liu W. Cervical spine microsurgery with the high-definition 3D exoscope: advantages and disadvantages. World Neurosurg. 2022;161:e1–7.
31. Herlan S, Marquardt JS, Hirt B, Tatagiba M, Ebner FH. 3D exoscope system in neurosurgery-comparison of a standard operating microscope with a new 3D exoscope in the cadaver lab. Oper Neurosurg. 2019;17(5):518–24.
32. Mamelak AN, Danielpour M, Black KL, Hagike M, Berci G. A high-definition exoscope system for neurosurgery and other microsurgical disciplines: preliminary report. Surg Innov. 2008;15(1):38–46.
33. Taylor H, McGregor AH, Medhi-Zadeh S, et al. The impact of self-retaining retractors on the paraspinal muscles during posterior spinal surgery. Spine. 2002;27(24):2758–62.
34. Franke J, Greiner-Perth R, Boehm H, et al. Comparison of a minimally invasive procedure versus standard microscopic discotomy: a prospective randomised controlled clinical trial. Eur Spine J. 2009;18(7):992–1000.
35. Casal-Moro R, Castro-Menéndez M, Hernández-Blanco M, Bravo-Ricoy JA, Jorge-Barreiro FJ. Long-term outcome after microendoscopic diskectomy for lumbar disk herniation: a prospective clinical study with a 5-year follow-up. Neurosurgery. 2011;68(6):1568–75.
36. Liu H, Tao H, Luo Z. Validation of the simplified Chinese version of the Oswestry disability index. Spine. 2009;34(11):1211–6.