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Comparison of capsule and posterior lumbar interbody fusion in cauda equina syndrome with retention: a 24-month follow-up study

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Abstract

Background and objectives Cauda equina syndrome with retention (CESR) is a severe lumbar condition characterized by painless urine retention due to cauda equina nerve injury. The standard treatment, posterior lumbar interbody fusion (PLIF), often yields suboptimal results. This study aims to compare the clinical safety and efficacy of a novel technique, capsule lumbar interbody fusion (CLIF), with PLIF in CESR patients, hypothesizing that CLIF can enhance neurological recovery by reducing nerve tension.

Methods A single-center, retrospective study was conducted on 83 patients with CESR due to lumbar disc herniation, who underwent either PLIF ($n=44$) or CLIF ($n=39$). Patients were assessed preoperatively and at 3, 12, and 24 months postoperatively using the Oswestry Disability Index (ODI), Visual Analogue Scale (VAS), International Consultation on Incontinence Questionnaire Short Form (ICI-Q-SF), and Rintala score. Urodynamic studies and nerve tension measurements were also performed. Statistical analysis included *t* tests, Mann–Whitney *U* tests, and Spearman's correlation.

Results Both groups showed significant postoperative improvements, but the CLIF group had superior outcomes. At 12 months, the CLIF group had lower VAS scores (1.15 ± 0.84 vs. 1.68 ± 0.60, $p=0.001$) and ODI scores (23.31 ± 7.51 vs. 28.30 ± 8.26, $p=0.005$). At 24 months, the CLIF group continued to show better results with ODI scores (15.97 ± 6.43 vs. 22.11 ± 6.41, $p<0.001$) and higher ODI recovery rates ($60.41\pm17.6\%$ vs. $44.71\pm18.99\%$, $p<0.001$). The CLIF group also had better ICI-Q-SF scores (2.13 ± 1.23 vs. 3.02 ± 1.45, $p=0.004$) and Rintala scores (17.97 ± 1.43 vs. 16.59 ± 1.54, $p<0.001$). Lower postoperative nerve tension in the CLIF group correlated with these improved outcomes.

Conclusions CLIF demonstrated superior efficacy over PLIF in treating CESR, with significant improvements in pain relief, functional recovery, and bladder and bowel function. This study highlights the potential of CLIF as a more effective surgical option for CESR, emphasizing its importance in improving patient outcomes and reducing the burden of CESR on patients and society.

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Keywords Capsule lumbar interbody fusion (CLIF), Posterior lumbar interbody fusion (PLIF), Cauda equina syndrome with retention (CESR), Nerve tension

Introduction

Cauda equina syndrome with retention (CESR) is a serious lower lumbar condition arising from injury to the cauda equina nerves, typically presenting with urinary retention [1, 2]. CESR markedly diminishes patients' quality of life and imposes considerable burdens on both families and society [3, 4]. The condition has garnered significant interest across multiple disciplines, including orthopedics, neurology, and urology, due to its unfavorable clinical outcomes [5]. Despite the frequent utilization of posterior lumbar interbody fusion (PLIF) as a treatment for CESR, its efficacy is less than ideal [6]. PLIF is accompanied by several drawbacks, including nerve root injury, significant blood loss, prolonged operative times, adjacent segment disease, and diminished spinal mobility. Moreover, PLIF often fails to sufficiently alleviate symptoms such as pain and bowel/bladder dysfunction; many patients continue to suffer from urinary retention and incontinence. Thus, the development of improved surgical interventions for CESR is imperative.

Clinical investigations have shown that lumbar disc herniation (LDH) is a frequent etiology of CESR; however, only approximately 2% of LDH cases culminate in CESR [7]. Furthermore, a subset of CESR patients exhibits no detectable cauda equina compression on imaging study [8]. These observations imply that LDH-induced compression is not the exclusive determinant of cauda equina nerve injury. Prior research suggested that severe nerve tension, either independently or in conjunction with compression injury, can precipitate significant loss of nerve function [9, 10]. In addition, there is evidence indicating that traction injury can cause significant nerve function loss [11], a condition that may be aggravated by concurrent compression injury. Consequently, we hypothesize that CESR patients may sustain both compression and severe nerve tension injuries. To address these issues, a new minimally invasive technique called Capsule Lumbar Interbody Fusion (CLIF) has been developed.[1] By shortening the spinal segments in the operative area, the CLIF technique may effectively alleviate tension on adjacent nerves, thereby improving patient symptoms. According previous study, nerve tension was closely associated with intervertebral disc,[2] demonstrating that the nerve root tension increased the risk of injury. Furthermore, our previous study demonstrated that CLIF reduces nerve traction and compression, resulting in better outcomes for patients with foot drop caused by nerve traction injury; in addition, CLIF provides greater symptom relief and shorter recovery times compared to traditional methods [9]. Therefore, CLIF might help lower the abnormally increased nerve tension. However, its efficacy in treating CESR remains uncertain. Further research is needed to assess the effectiveness of CLIF for CESR patients.

This study is pivotal as it evaluates the novel CLIF technique against traditional PLIF for treating CESR. It aims to address a critical gap in spinal surgery by potentially offering better symptom relief, reduced postoperative complications, and shorter recovery times. By comparing these methods, the study could lead to improved patient outcomes and influence clinical practices. In addition, it could stimulate further research into nerve injury and recovery, driving advancements in spinal surgery and refining treatment protocols for complex conditions like CESR.

Materials and methods

Study population

A single-center, retrospective study was conducted at the Spine Center of Changzheng Hospital in Shanghai, China, with a focus on patients diagnosed with CESR due to LDH. The inclusion criteria comprised patients who were hospitalized from February 2017 to March 2022, aged 18–75 years, and diagnosed with CESR due to LDH. In addition, eligible patients had complete medical records, including X-ray and MRI data, and were candidates for surgical intervention. Exclusion criteria excluded patients with CESR caused by other etiologies (e.g., tumors, trauma, or fractures), a history of previous spinal surgery, insufficient medical data during follow-up, severe comorbidities that could influence surgical outcomes, and those who did not provide informed consent. This study adhered to the principles of the Helsinki Declaration and received approval from the Ethics Committee of Changzheng Hospital.

The sample size for this study was calculated to ensure adequate power to detect a clinically meaningful difference between the PLIF and CLIF groups. Assuming an expected effect size of 10 units and a standard deviation of 15 units, with a significance level (alpha) of 0.05 and a desired power of 0.8, the sample size per group was determined using the following formula, where $Z_{\alpha/2}$ is the

[1] Sun et al. [9].

[2] Wu et al. [12].

critical value for the chosen alpha level (1.96 for a two-tailed test at 95% confidence), and Z_β is the critical value for the chosen power (0.84 for 80% power):

$$n = \frac{(Z_{\alpha/2} + Z_\beta)^2 * 2 * \sigma^2}{\Delta^2}$$

Thus, approximately 36 patients were needed per group to achieve 80% power to detect a difference of 10 units with a standard deviation of 15 units at a 5% significance level. This calculation ensures the study is adequately powered to detect meaningful differences between the groups.

Surgical technique

All surgical procedures in this study were performed by a lead spine surgeon (JG. S., with 41 years of experience in spine surgery) and a specialized surgical team. PLIF surgery was performed as described in earlier publications [13, 14]. The PLIF procedure typically included the following steps: under general anesthesia, the patient was placed in a prone position. An incision was made in the lower back to expose the affected vertebrae, the intervertebral disc was removed to create space for the bone graft, and the bone graft and/or interbody cages were inserted into the disc space to promote fusion. Finally, pedicle screws and rods were used to stabilize the spine until fusion occurred. The whole procedure of CLIF is illustrated in Fig. 1 and the procedures of CLIF were detailed as follows:

Step 1: Patient positioning and exposure.

The patient is placed in a prone position under general endotracheal anesthesia. The surgical segment (L4/L5) is determined using intraoperative positioning with a C-arm machine (Fig. 1A). A midline incision is made in the lower back to expose the spinous processes, laminae, and facet joints of the L4–L5 vertebrae.

Step 2: Pedicle screw placement.

Bilateral pedicle screws are inserted into the L4 and L5 vertebrae using fluoroscopic guidance. The screws are placed in the optimal trajectory to ensure adequate purchase and minimize the risk of nerve root injury. There are potential variations: different screw sizes and designs can be used based on patient anatomy and

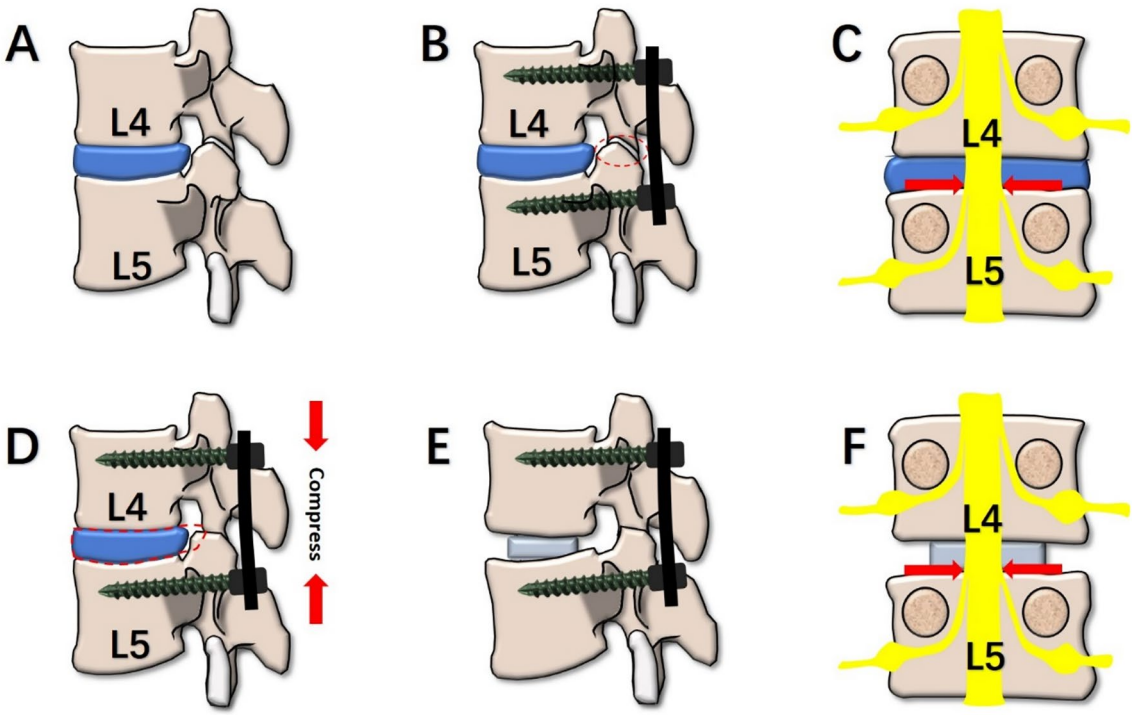

Fig. 1 Illustration of the CLIF procedure and measurement of nerve tension. **A** Surgical segment (L4/L5) was determined; **B** the pedicle screws were inserted bilaterally in L4–L5 segments, and then the titanium rods were implanted and locked bilaterally. The upper articular process of L5 and the lower articular process of L4 were partially excised; **C** the nerve tension was measured by a nerve tension surveying instrument and recorded as the nerve tension before intraoperative decompression. The arrow indicates the measuring point; **D** resect L4/5 intervertebral disc, decompress of nerve root canal sufficiently, and compress the operated segment (L4/L5). Compression of the spine is the most important difference between CLIF and traditional posterior surgery; **E** implant interbody fusion cage in L4/5; **F** the nerve tension was measured again in the same location. The arrow indicates the measuring point

surgeon preference; alternatively, a unilateral pedicle screw approach can be employed for less extensive decompression.

Step 3: Decompression.

The upper articular process of L5 and the lower articular process of L4 are partially excised, along with the ligamentum flavum, to expose the lateral recess and the connection between the dural sac and the L5 nerve root (Fig. 1B). The L4/5 intervertebral disc is carefully removed, and the nerve root canal is decompressed by removing any herniated disc material or bone spurs.

Step 4: Nerve tension measurement.

Before decompression, nerve tension is measured using a nerve tension surveying instrument at the point where the dural sac connects to the L5 nerve root on both sides (Fig. 1C).

Step 5: Intervertebral compression and cage placement.

The surgeon applies slow, controlled compression between the intervertebral bodies using a compression device or manual manipulation (Fig. 1D). This step aims to relieve tension on the cauda equina nerves by shortening the spinal segment. There is potential variation: the degree of controlled compression can be adjusted based on intraoperative nerve tension measurements and surgeon experience.

Step 6: Interbody fusion cage implantation.

An interbody fusion cage filled with bone graft material is implanted into the L4/5 disc space (Fig. 1E). The cage is positioned to maintain disc height and restore spinal alignment. There are potential variations: different types of interbody cages (e.g., PEEK, titanium) and graft materials (e.g., autograft, allograft, synthetic) can be used based on surgeon preference and patient factors.,[34]

Step 7: Post-decompression nerve tension measurement.

After decompression and cage placement, nerve tension is measured again at the same points as before (Fig. 1F) to assess the effectiveness of the procedure.

Step 8: Closure and postoperative care.

The wound is closed in layers, and the patient is monitored for postoperative complications. Patients are advised to wear a lumbar brace for 3 month post-surgery to support the spine during fusion.

The innovation of CLIF lay in its comprehensive approach to addressing both degeneration-associated compression and nerve tension, potentially leading to improved outcomes for patients with CESR due to LDH.

[3] Zhang et al. [15].

[4] Li et al. [16].

Clinical examination

The Oswestry disability index (ODI) is a widely validated and commonly used instrument for assessing functional disability in patients with pain. It covers various aspects of daily living, including pain intensity, personal care, lifting, walking, sitting, standing, sleeping, social life, and traveling. This comprehensive assessment allows us to evaluate the overall impact of the surgical procedures on patients' quality of life and functional status. The recovery of neurological function was assessed by ODI score [17] and its recovery rate (RR of ODI: (ODI before operation − ODI at the follow-up)/(ODI before operation) × 100%). The ODI is a widely used questionnaire designed to measure a patient's permanent functional disability. It consists of 10 sections, each with 6 statements. The sections include pain intensity, personal care, lifting, walking, sitting, standing, sleeping, social life, and traveling. Each section is scored from 0 to 5, with 0 indicating no disability and 5 indicating maximum disability.

The pain symptoms were assessed by visual analogue scale (VAS) [18]. The VAS is a simple and reliable tool for measuring the intensity of pain. Since pain is a significant symptom in CESR, the VAS provides a quantitative measure to assess the effectiveness of the surgical procedures in alleviating pain. The VAS is a tool used to measure the intensity of pain. It is typically a horizontal line, 10 cm in length, anchored by two descriptors at each end: "no pain" (score of 0) and "worst imaginable pain" (score of 10). Patients mark on the line the point that they feel represents their perception of their current state of pain. The VAS score is determined by measuring the distance in centimeters from the "no pain" end to the mark made by the patient.

The bladder function was assessed by international consultation on incontinence questionnaire short form score (ICI-Q-SF) and urodynamics [19]. The ICI-Q-SF is a brief, self-administered questionnaire used to evaluate the impact of urinary incontinence on quality of life. It includes questions about the frequency, severity, and impact of incontinence, with each item scored from 0 to 4. Higher scores indicate more severe symptoms. This allows us to assess the impact of the surgical procedures on bladder function, a crucial aspect of CESR.

Furthermore, the Rintala score was used to evaluate bowel function, particularly in patients with anorectal malformations or other bowel dysfunctions [20]. The Rintala score is specifically designed to evaluate bowel function in patients with anorectal malformations or other bowel dysfunctions. Given that bowel dysfunction is a common symptom in CESR, the Rintala score allows us to assess the impact of the surgical procedures on bowel function recovery. It includes parameters such as stool frequency, constipation, soiling, and the need

for enemas. Scores were assigned based on the severity of symptoms, with higher scores indicating better bowel function.

Meanwhile, the intraoperative nerve tension, preoperative symptom duration, operation duration, intraoperative blood loss, operation related complications were recorded.

Urodynamics assessment

The main parameters of urodynamics assessment included residual urine, maximum urinary flow rate, bladder compliance (bladder compliance refers to the ratio of changes in bladder volume to changes in pressure, which can affect the ability of urine to enter the bladder and hold back urine), external sphincter coordination (external sphincter coordination is expressed by TL value as follows: compare the EMG amplitude *T* value before urination with the minimum amplitude *L* value during urination, and then take the logarithm of the above ratio. The greater the TL value, the better the external sphincter coordination function) [21].

Nerve tension

A device designed for nerve tension measurement was employed to quantify the tension [12]. The tension of the cauda equina nerve in the dural sac could not be directly evaluated intraoperatively, as the dural sac was not opened in any of the cases. Consequently, the tension of the cauda equina nerve was indirectly estimated by measuring the tension of the dural sac. Meanwhile, to eliminate bias in case comparisons, we decided to measure the dural sac at the onset of the nerve root of the compressed nerve root in all instances. The nerve tension measurement apparatus was maintained at a consistent angle, and zero-point calibration was performed after the measurement site (the initial interface between the dural sac and the nerve root) was fully exposed. Subsequently, the measuring needle was incrementally inserted into the measurement site and directed toward the midline. The tension reading from the device was recorded when the dural sac exhibited distortion. Each site was measured thrice consecutively, with the average value documented as the pre- and post-decompression nerve tension. Moreover, the nerve roots at all compressed levels on both sides were measured, and the mean value was recorded as the patient's nerve tension. The rate of change in nerve tension was calculated as follows: (nerve tension before decompression − nerve tension after decompression)/(nerve tension before decompression) × 100%.

Imaging measurements

The study parameters included the anterior intervertebral height (AIH), posterior intervertebral height (PIH), foramen height (FH), and lumbar lordosis (LL), as determined from X-ray images [22, 23]. AIH refers to the vertical distance measured between the anterior edges of the adjacent vertebrae at the midpoint on a lateral X-ray view, indicating the space available at the front part of the intervertebral disc. PIH is the vertical distance between the posterior edges of the adjacent vertebrae at the midpoint on a lateral X-ray view, reflecting the space available at the back part of the intervertebral disc. FH measures the vertical height of the intervertebral foramen from the

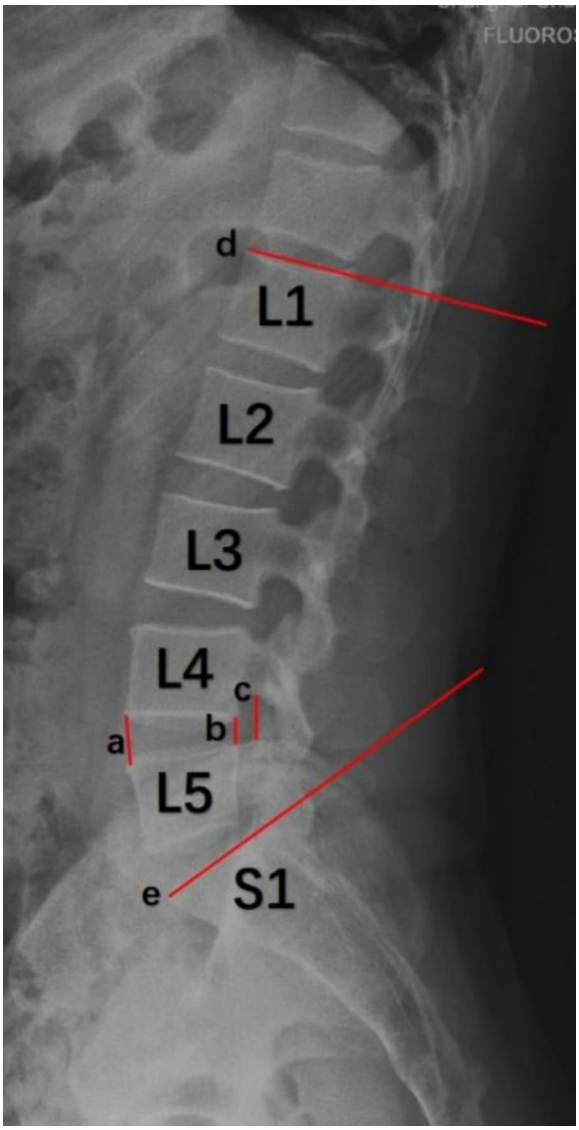

Fig. 2 Imaging measurements according to the X-ray image: (a) anterior intervertebral height (AIH); (b) posterior intervertebral height (PIH); (c) foramen height (FH); (d) line parallel to the upper edge endplate of the L1 vertebral body; (e) line parallel to the upper edge endplate of the S1 vertebral body. LL was defined as the angle between (d) and (e)

upper to the lower margin on a lateral X-ray view, indicating the space available for the exiting nerve roots. LL is defined as the angle formed between a line parallel to the upper edge of the endplate of the L1 vertebral body and a line parallel to the upper edge of the endplate of the S1 vertebral body, measured on a lateral X-ray view to indicate the curvature of the lumbar spine. Figure 2 illustrates these measurements, showing the positions and methods for measuring AIH, PIH, FH, and LL on lateral X-ray images of the lumbar spine. These parameters were chosen to evaluate the structural changes and alignment of the lumbar spine preoperatively and postoperatively, providing insight into the efficacy of the surgical interventions.

Statistics analysis

Statistical analysis was conducted using GraphPad Prism 9 (GraphPad Software Inc., La Jolla, CA). Data in this present study were presented as mean (SD). The independent *t* test was used to detect the statistical differences of demographic parameters (patients' age, duration of symptoms, duration of follow-up, operation time and intraoperative blood loss), clinical scores (ODI score, VAS score, ICI-Q-SF score, and Rintala score), urodynamics outcomes (residual urine, maximum urinary flow rate, bladder compliance, and TL value), nerve tension, and radiological outcomes (AIH, PIH, FH, and LL) between the two groups. The Mann–Whitney *U* test was used to detect the statistical differences of RR of ODI and change rate of nerve tension between the two groups. The Fisher's exact test was used to compare the gender, surgical segments, and comorbidities between the two groups. Spearman's correlation analysis was performed to assess whether there was any significant relationship between relevant parameters of nerve tension and ODI. The data analysis was conducted blinded to the treatment group assignments. This ensures that the analysis was not influenced by knowledge of which patients received CLIF or PLIF. In addition, the study data were independently verified by a second researcher to ensure accuracy and consistency. Besides, the study used objective outcome measures, such as the ODI, VAS, ICI-Q-SF, Rintala score, and urodynamic parameters, to assess patient outcomes. These measures are widely validated and minimize the potential for subjective bias. Furthermore, the follow-up data were collected through clinical visits and phone calls. The primary outcome measures were assessed at 3, 12, and 24 month post-surgery. This systematic approach to data collection and outcome assessment helps to ensure the reliability of the study outcomes. Values that were less than 0.05 ($p < 0.05$) were considered statistical significance.

Results

Demographics and intraoperative data

A total of 83 patients were included in this study. Before surgery, all patients were thoroughly informed of the benefits and potential risks associated with PLIF and CLIF procedures. The follow-up period for this study was a minimum of 24 months. There were 44 patients in the PLIF group and 39 in the CLIF group. The mean ages were 35.93 years (PLIF) and 38.97 years (CLIF), with no significant difference ($p = 0.205$). Gender distribution, hypertension, diabetes, cardiopathy, symptom duration, and follow-up duration showed no significant differences between the groups. Final follow-up period was 24 months or longer follow-up. This study compared PLIF and CLIF treatments for CESR. Although the CLIF group had a shorter operation time (114.76 min) compared to the PLIF group (122.67 min), no statistical significance was observed ($p = 0.087$). In addition, blood loss and surgical segment distribution were similar between the groups. These findings suggest no difference in baseline between the two groups (Table 1).

Clinical outcomes

This present study evaluated the clinical outcomes of patients treated with PLIF and CLIF and the results are presented in Table 2. Preoperative VAS scores were similar between groups (PLIF: 8.34 ± 1.24, CLIF: 8.77 ± 1.11, $p = 0.103$). At 3 months after surgery, the CLIF group had significantly lower VAS scores (4.10 ± 1.65) compared to the PLIF group (5.30 ± 1.75, $p = 0.002$). This trend continued at 12 months (CLIF: 1.15 ± 0.84, PLIF: 1.68 ± 0.60, $p = 0.001$), but not at 24 months ($p = 0.661$). The significant reduction in VAS scores at 12 month post-surgery indicates that CLIF effectively relieves pain compared to PLIF. This improvement in pain management can significantly enhance patients' quality of life and functional abilities. Preoperative ODI scores were comparable ($p = 0.927$). At 12 months after surgery, the CLIF group had significantly lower ODI scores (23.31 ± 7.51) than the PLIF group (28.30 ± 8.26, $p = 0.005$). This was consistent at 24 months, with CLIF showing lower ODI scores (15.97 ± 6.43) compared to PLIF (22.11 ± 6.41, $p < 0.001$). The recovery rates of ODI at 12 and 24 months were significantly higher in the CLIF group ($p = 0.004$ and $p < 0.001$, respectively). The significant improvement in ODI scores and recovery rates at 12 and 24 month post-surgery suggests that CLIF facilitates better functional recovery compared to PLIF. This means that patients who undergo CLIF are likely to experience greater improvements in their ability to perform daily activities and participate in social interactions. Rintala scores at 12 and 24 months were significantly higher in the CLIF group ($p = 0.040$ and $p = 0.001$, respectively). In addition,

Table 1 Clinical characteristics of patients in the PLIF group and CLIF group

Variables	PLIF ($n=44$)	CLIF ($n=39$)	Statistic	p
Age (years), mean ± SD	35.93 ± 10.64	38.97 ± 11	−1.277	0.205
Gender, *n* (%)			0.647	0.421
Female	21 (48)	23 (59)		
Male	23 (52)	16 (41)		
Hypertension, *n* (%)			0	1
No	29 (66)	26 (67)		
Yes	15 (34)	13 (33)		
Diabetes, *n* (%)			0.001	0.976
No	27 (61)	25 (64)		
Yes	17 (39)	14 (36)		
Cardiopathy, *n* (%)			0	1
No	32 (73)	28 (72)		
Yes	12 (27)	11 (28)		
Duration of symptoms (days), mean ± SD	59.68 ± 19.49	57.53 ± 21.01	0.482	0.631
Duration of follow-up (months), median (Q1, Q3)	29.7 (27.1, 31.85)	28.8 (26.35, 30.7)	−0.84	0.401
Operation time (min), mean ± SD	122.67 ± 20.85	114.76 ± 20.64	1.735	0.087
Blood loss (mL), mean ± SD	195.2 ± 64.98	199.48 ± 59.75	−0.313	0.755
Surgical segment, *n* (%)				1
L4/5	28 (64)	24 (62)		
L5/S1	11 (25)	10 (26)		
L4-S1	5 (11)	5 (13)		

PLIF posterior lumbar interbody fusion, *CLIF* capsule lumbar interbody fusion

Table 2 Clinical evaluation of patients in the PLIF group and CLIF group

Variables	PLIF ($n=44$)	CLIF ($n=39$)	statistic	p value
VAS_pre, mean ± SD	8.34 ± 1.24	8.77 ± 1.11	0.747	0.103
VAS_3m, mean ± SD	5.30 ± 1.75	4.10 ± 1.65	0.113	0.002
VAS_12m, mean ± SD	1.68 ± 0.60	1.15 ± 0.84	4.604	0.001
VAS_24m, mean ± SD	1.41 ± 1.06	1.31 ± 1.03	0.115	0.661
ODI_pre, mean ± SD	41.11 ± 6.41	41.00 ± 4.60	0.094	0.927
ODI_3m, mean ± SD	28.09 ± 7.45	26.26 ± 6.32	1.213	0.229
RR_of_ODI_3m (%), mean ± SD	30.03 ± 22.22	34.95 ± 18.04	−1.111	0.270
ODI_12m, mean ± SD	28.30 ± 8.26	23.31 ± 7.51	2.881	0.005
RR_of_ODI_12m (%), median (Q1, Q3)	34.79 (17.75, 41.75)	41.67 (35.29, 52.34)	−2.888	0.004
ODI_24m, mean ± SD	22.11 ± 6.41	15.97 ± 6.43	4.347	<0.001
RR_of_ODI_24m (%), mean ± SD	44.71 ± 18.99	60.41 ± 17.6	−3.908	<0.001
Rintala_score_pre, mean ± SD	6.00 ± 1.35	6.62 ± 1.53	0.782	0.055
Rintala_score_3m, mean ± SD	8.18 ± 1.63	8.87 ± 1.73	0.032	0.066
Rintala_score_12m, median (Q1, Q3)	13 (12, 14)	14 (13, 15.5)	−2.056	0.040
Rintala_score_24m, mean ± SD	15.39 ± 1.85	16.74 ± 1.73	0.371	0.001
ICI-Q-SF_pre, mean ± SD	17.25 ± 0.31	17.03 ± 0.28	0.533	0.596
ICI-Q-SF_3m, mean ± SD	15.70 ± 1.80	14.95 ± 2.03	0.108	0.075
ICI-Q-SF_12m, median (Q1, Q3)	13 (11, 15)	11 (10, 12)	−3.703	<0.001
ICI-Q-SF_24m, mean ± SD	8.95 ± 2.02	6.90 ± 1.80	1.464	<0.001

PLIF posterior lumbar interbody fusion, *CLIF* capsule lumbar interbody fusion, *VAS* Visual Analogue Scale, *ODI* Oswestry Disability Index, *RR* recovery rate, *ICI-Q-SF* International Consultation on Incontinence Questionnaire Short Form Score

ICI-Q-SF scores were significantly lower in the CLIF group at 12 and 24 months ($p<0.001$ for both), indicating better outcomes. The significant improvements in ICI-Q-SF and Rintala scores indicate that CLIF effectively restores bladder and bowel function compared to PLIF. This is crucial for patients with CESR, as bladder and bowel dysfunction can significantly impact their quality of life and overall well-being.

Urodynamics outcomes

The results of urodynamics outcomes are presented in Table 3. Residual urine volume preoperatively was comparable between the groups ($p=0.182$). At 24 months, the CLIF group had significantly lower residual urine volume (39.84 ± 22.27 ml) compared to the PLIF group (71.58 ± 24.6 ml, $p<0.001$). Bladder compliance preoperatively showed no significant difference ($p=0.961$). However, at 3 months, bladder compliance was significantly higher in the CLIF group (7.98 ± 1.19 ml/cm H_2O) compared to the PLIF group (6.3 ± 1.57 ml/cm H_2O, $p<0.001$). This trend continued at 12 months (CLIF: 8.91 ± 1.71, PLIF: 7.83 ± 1.22, $p=0.002$) and 24 months (CLIF: 10.93 ± 2.17, PLIF: 8.46 ± 2.12, $p<0.001$). Maximum urinary flow rate showed no significant differences preoperatively ($p=0.324$), at 3 months ($p=0.702$), 12 months ($p=0.207$), and 24 months ($p=0.093$). TL values were similar preoperatively ($p=0.13$) and at 3 months ($p=0.418$). However, at 12 months, the CLIF group had significantly lower TL values (0.09 ± 0.17) compared to the PLIF group (0.22 ± 0.23, $p=0.006$). At 24 months, TL values showed no significant difference ($p=0.73$).

Nerve tension

Nerve tension before and after decompression in patients treated with PLIF and CLIF was evaluated (Table 4). Precompression nerve tension was comparable between the groups (PLIF: 22.28 ± 4.56 g, CLIF: 24.06 ± 4.71 g, $p=0.085$). However, postcompression nerve tension was significantly lower in the CLIF group (12.4 g, Q1: 11.4, Q3: 13.5) compared to the PLIF group (15.85 g, Q1: 14.52, Q3: 18.1), with a highly significant difference ($p<0.001$). In addition, the change rate of nerve tension

Table 3 Urodynamics parameters of patients in the PLIF group and CLIF group

Variables	PLIF ($n=44$)	CLIF ($n=39$)	Statistic	*p* value
Residual urine pre (ml), mean ± SD	83.72 ± 24.72	89.91 ± 16.77	−1.348	0.182
Residual urine 3m (ml), mean ± SD	77.32 ± 26.94	75.41 ± 30.26	0.303	0.763
Residual urine 12m (ml), mean ± SD	75.29 ± 29.35	69.51 ± 28.06	0.916	0.362
Residual urine 24m (ml), mean ± SD	71.58 ± 24.6	39.84 ± 22.27	6.17	<0.001
Bladder compliance pre (ml/cm H_2O), mean ± SD	5.79 ± 2.04	5.77 ± 1.89	0.049	0.961
Bladder compliance 3m (ml/cm H_2O), mean ± SD	6.3 ± 1.57	7.98 ± 1.19	−5.517	<0.001
Bladder compliance 12m (ml/cm H_2O), mean ± SD	7.83 ± 1.22	8.91 ± 1.71	−3.286	0.002
Bladder compliance 24m (ml/cm H_2O), mean ± SD	8.46 ± 2.12	10.93 ± 2.17	−5.227	<0.001
Maximum urinary flow rate pre (ml/min), Median (Q1, Q3)	11.15 (7.68, 13.5)	9.7 (6.75, 12.85)	−0.986	0.324
Maximum urinary flow rate 3m (ml/min), Mean ± SD	9.1 ± 4.52	9.45 ± 3.85	−0.384	0.702
Maximum urinary flow rate 12m (ml/min), Mean ± SD	8.71 ± 4.43	9.89 ± 3.98	−1.273	0.207
Maximum urinary flow rate 24m (ml/min), Mean ± SD	10.03 ± 3.53	8.64 ± 3.86	1.701	0.093
TL value pre, median (Q1, Q3)	0.2 (0.1, 0.32)	0.1 (0, 0.4)	−1.516	0.13
TL value 3m, median (Q1, Q3)	0.15 (0, 0.4)	0.2 (0.1, 0.4)	−0.81	0.418
TL value 12m, mean ± SD	0.22 ± 0.23	0.09 ± 0.17	5.638	0.006
TL value 24m, mean ± SD	0.16 ± 0.25	0.14 ± 0.21	0.911	0.73

PLIF posterior lumbar interbody fusion, *CLIF* capsule lumbar interbody fusion, *TL value* compare the EMG amplitude *T* value before urination with the minimum amplitude *L* value during urination, and then take the logarithm of the above ratio

Table 4 Nerve tension before and after decompression in the PLIF group and CLIF group

Variables	PLIF ($n=44$)	CLIF ($n=39$)	statistic	*p* value
Nerve tension precompression (g), mean ± SD	22.28 ± 4.56	24.06 ± 4.71	−1.744	0.085
Nerve tension postcompression (g), median (Q1, Q3)	15.85 (14.52, 18.1)	12.4 (11.4, 13.5)	−6.092	<0.001
Change rate of nerve tension (%), median (Q1, Q3)	28.05 (18.6, 37.11)	46.48 (39.61, 55.35)	−5.557	<0.001

PLIF posterior lumbar interbody fusion, *CLIF* capsule lumbar interbody fusion

was significantly greater in the CLIF group (46.48%, Q1: 39.61, Q3: 55.35) compared to the PLIF group (28.05%, Q1: 18.6, Q3: 37.11), also showing a highly significant difference ($p<0.001$). In addition, the values of nerve tension in both PLIF and CLIF were remarkably lowered after surgeries compared to that in groups before decompression, and nerve tension in CLIF after decompression was significantly lower than that in the PLIF (Fig. 3). These findings indicate that CLIF significantly reduces nerve tension more effectively than PLIF. The significant reduction in postoperative nerve tension observed in the CLIF group is associated with better long-term functional outcomes. This suggests that addressing nerve tension, in addition to nerve compression, is crucial for optimizing neurological recovery and functional outcomes in patients with CESR.

Radiographic

Radiological outcomes between the PLIF and CLIF groups were compared (Table 5). Preoperative AIH was similar between the groups ($p=0.327$). At 3 days postoperatively, the PLIF group had a significantly higher AIH (10.07 ± 1.23 mm) compared to the CLIF group (7.97 ± 1.67 mm, $p<0.001$). The change rate of AIH at 3 days was also significantly different, with a median of −29.78% in the PLIF group and 0% in the CLIF group ($p<0.001$). At 24 months, the CLIF group showed a smaller reduction in AIH ($p=0.009$) and a significantly different change rate ($p=0.01$). Preoperative PIH showed no significant difference ($p=0.262$). However, the PLIF group had significantly higher PIH at 3 days (8.83 ± 1.38 mm) compared to the CLIF group (5.72 ± 1.46 mm, $p<0.001$). The PIH change rate at 3 days ($p<0.001$) and 24 months ($p<0.001$) was significantly different, favoring the CLIF group for better maintenance of PIH. For FH, there were no significant differences preoperatively ($p=0.759$), at 3 days ($p=0.352$), or at 24 months ($p=0.609$). The change rates were also not significantly different. Preoperative lumbar lordosis (LL) was comparable ($p=0.491$). At 24 months, the CLIF group had a significantly better greater ($27.72\pm3.26°$) compared to the PLIF group ($26.11\pm2.58°$, $p=0.016$), indicating a more favorable outcome for CLIF in maintaining spinal alignment.

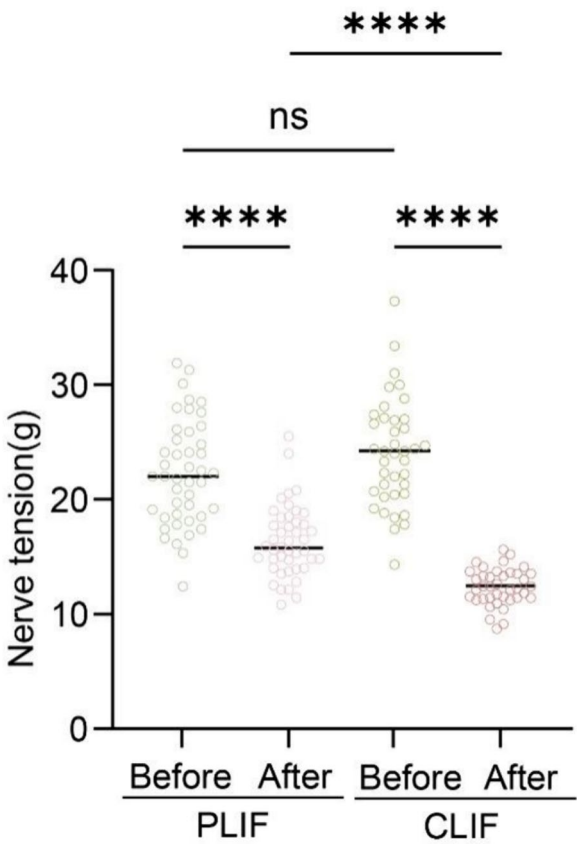

Fig. 3 Nerve tension before and after decompression in the PLIF group and CLIF group. * $p<0.05$; ** $p<0.01$; *** $p<0.001$; **** $p<0.0001$; ns no statistical significance

Correlation analysis

The relationship between nerve tension and ODI scores at different time points is presented in Fig. 4. No significant correlation was observed between precompression nerve tension and preoperative ODI scores ($r^2=0.00179$, $p=0.6972$) (Fig. 4A). In addition, Fig. 4B indicates a lack of significant correlation between postcompression nerve tension and ODI scores at 3 months postoperatively ($r^2=0.003484$, $p=0.5961$). It is worth noting that significant positive correlation between postcompression nerve tension and ODI scores at 12 months postoperatively ($r^2=0.08703$, $p=0.0068$) was observed (Fig. 4C). This trend continues at 24 months. A stronger positive correlation is observed between postcompression nerve tension and ODI scores at 24 months ($r^2=0.1413$, $p=0.0005$) (Fig. 4D). These results suggest that higher nerve tension after decompression is associated with worse functional outcomes at 12 and 24 months postoperatively, highlighting the importance of effective nerve tension management in improving long-term patient outcomes.

Discussion

This study demonstrates that CLIF significantly outperforms PLIF in treating CESR in several aspects. The findings reveal superior outcomes for CLIF in terms of pain relief, functional recovery, and improvements in bladder, and bowel functions. Notably, CLIF achieved a significant reduction in nerve tension, which correlated with better long-term functional outcomes.

Table 5 Radiological results of patients in the PLIF group and CLIF group

Variables	PLIF ($n=44$)	CLIF ($n=39$)	statistic	*p* value
AIH pre (mm), mean ± SD	7.85 ± 2.02	8.21 ± 1.24	−0.986	0.327
AIH 3 days (mm), mean ± SD	10.07 ± 1.23	7.97 ± 1.67	6.429	<0.001
ATH 3 day change rate (%), median (Q1, Q3)	−29.78 (−55.89, −5.82)	0 (−19.82, 20.65)	−4.101	<0.001
AIH 24m (mm), mean ± SD	8.1 ± 1.61	7.24 ± 1.34	2.663	0.009
AIH 24m change rate (%), median (Q1, Q3)	−5.77 (−30.5, 21.9)	12.75 (0.75, 23.55)	−2.573	0.01
PIH pre (mm), mean ± SD	7.09 ± 0.97	6.79 ± 1.34	1.132	0.262
PIH 3 days (mm), mean ± SD	8.83 ± 1.38	5.72 ± 1.46	9.979	<0.001
PIH 3 day change rate (%), mean ± SD	−27.25 ± 27.34	10.85 ± 35.34	−5.443	<0.001
PIH 24m (mm), mean ± SD	7.73 ± 0.93	5.57 ± 0.98	10.287	<0.001
PIH 24m change rate (%), mean ± SD	−11.45 ± 22.18	15.62 ± 19.46	−5.921	<0.001
FH pre, mean ± SD	17.52 ± 2.39	17.69 ± 2.46	−0.308	0.759
FH 3 days (mm), mean ± SD	17.21 ± 2.2	16.78 ± 1.93	0.936	0.352
FH 3 day change rate (%), mean ± SD	−0.51 ± 21.33	3.52 ± 15.77	−0.985	0.328
FH 24m (mm), median (Q1, Q3)	16.7 (15.1, 18)	16.6 (15.85, 17.5)	−0.511	0.609
FH 24m change rate (%), mean ± SD	3.33 ± 19.73	3.11 ± 16.17	0.056	0.955
SL pre (°), mean ± SD	26.06 ± 3.54	25.52 ± 3.55	0.693	0.491
SL 3 days (°), mean ± SD	28.68 ± 2.81	27.97 ± 2.68	1.169	0.246
SL 3 day change rate (%), median (Q1, Q3)	−8.44 (− 24.26, 1.71)	−6.16 (− 24.09, 1.95)	−0.132	0.895
SL 24m (°), mean ± SD	26.11 ± 2.58	27.72 ± 3.26	−2.459	0.016
SL 24m change rate (%), median (Q1, Q3)	1.6 (− 10.01, 11.16)	−5.76 (− 19.6, 6.69)	−1.572	0.116

PLIF transforaminal lumbar interbody fusion, *CLIF* situ lumbar interbody fusion, *AIH* anterior intervertebral height, *PIH* posterior intervertebral height, *FH* foramen height, *SL* lumbar lordosis

Previous studies on PLIF have shown varying results regarding its efficacy in treating CESR. While some studies report improvements in pain relief and functional outcomes, they also highlight significant complications such as nerve root injury, dural tears, substantial blood loss, and prolonged operative times. For instance, studies reported a 6.5–17% incidence of nerve root injury during PLIF procedures [24–26], which might be associated with the persistence of postoperative urinary and bowel dysfunction in CESR patients treated with PLIF, similar to our findings. In addition, a study focusing on nerve root tension during PLIF revealed that when the height of the intervertebral space was increased to 140% of the original height, the nerve root tension increased the risk of injury significantly [12].

Cauda equina nerve injury was thought to be produced by compression and subsequent nerve tissue ischemia in classic nerve injury theory; however, not all patients with severe compression of the cauda equina nerve would have CESR [3, 4, 27]. Furthermore, some patients with only minor or no compression of the cauda equina nerve experienced CESR [28]. Why? We hypothesized that, aside from nerve compression and ischemia, excessive nerve tension was another major damage mechanism. During the study's operation, it was discovered that the dural sac and nerve root of all CESR patients had rather high tension. Based on the circumstances described above, we proposed a unique CLIF surgery. The main distinction between CLIF and typical posterior surgery is that CLIF can successfully shorten the spine through compression, lowering tension on neighboring nerves. Our study revealed that CLIF, which addresses both nerve compression and tension, results in superior clinical outcomes compared to PLIF. Specifically, the significant improvements in VAS, ODI, ICI-Q-SF, and Rintala scores in the CLIF group underscore the efficacy of this approach.

Our previous research has highlighted the importance of reducing nerve tension to enhance neurological recovery. Our previous prospective, observational study involving 27 patients with foot drop due to lumbar degenerative diseases showed that those who underwent CLIF experienced better early recovery of foot drop 3 months after operation than those in the TLIF group [9]. The study reported that the patient's nerve root tension acquired satisfactory axial release via spine shortening [9]. The study attributed these outcomes to the effective reduction in nerve tension, assessed by IoUS, and improved decompression achieved with CLIF [9]. This present study builds on this evidence, showing that CLIF, by effectively lowering nerve tension, leads to better neurological recovery in CESR patients. The marked

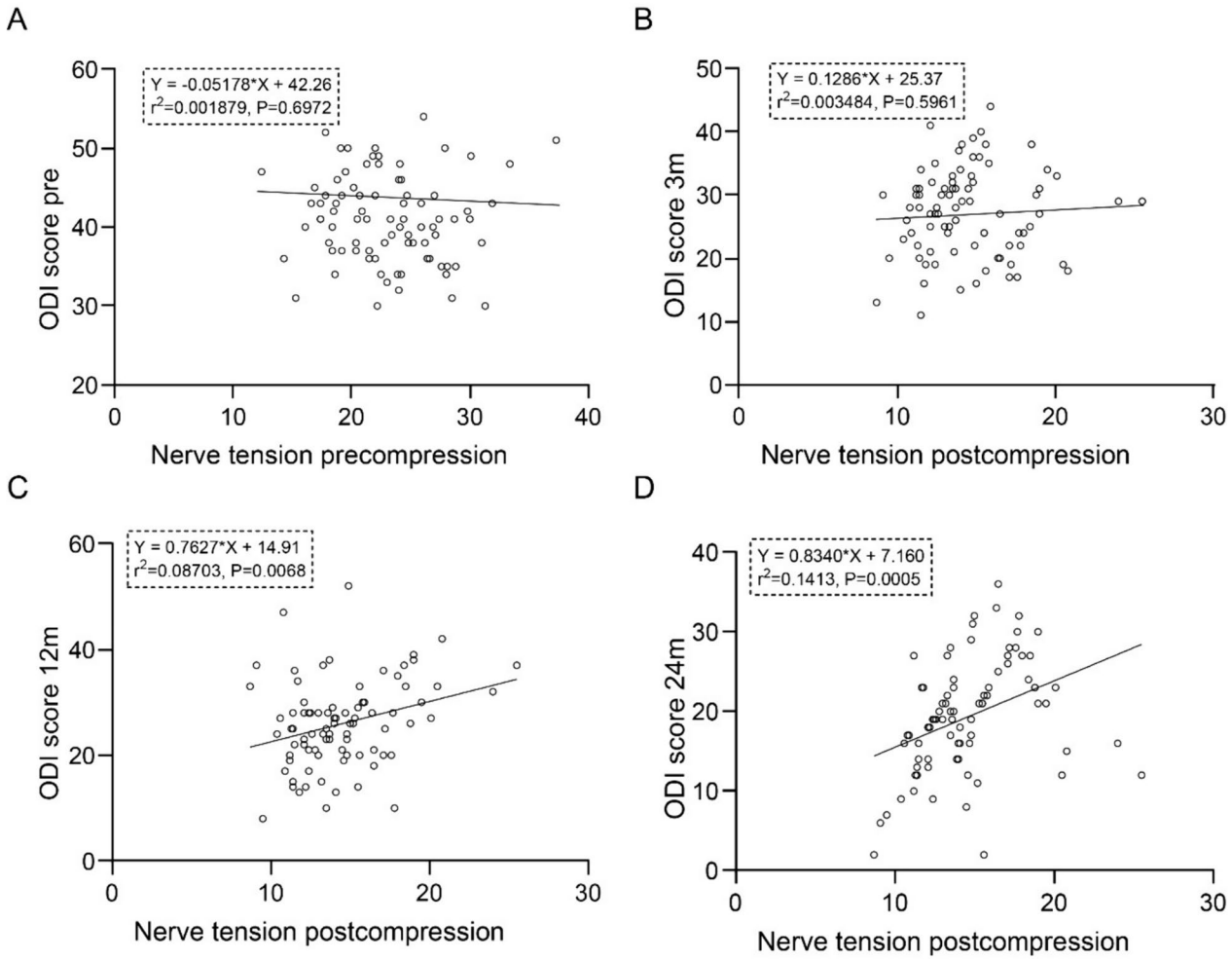

Fig. 4 Correlations of nerve tension and ODI related parameters: **A** preoperative ODI had no statistical correlation with nerve tension before decompression ($p > 0.05$); **B** ODI score at 3 months after surgery; **C** ODI score at 12 months after surgery; **D** ODI score at 24 months after surgery. ODI: Oswestry disability index; RR: recovery rate

improvements in bladder and bowel functions in the CLIF group, further validate this approach.

The impact of surgical techniques on the quality of life of CESR patients has been a focal point in previous studies. For example, a study by Byvaltsev et al. reported that patients undergoing PLIF for CESR experienced improvements in pain and disability scores, but the persistence of urinary and bowel dysfunction significantly impacted their quality of life [29]. In our study, while PLIF showed some improvements in pain and disability scores, the persistent urinary and bowel dysfunctions highlight the limitations of this approach. On the other hand, CLIF, by addressing both nerve compression and tension, resulted in significant improvements in quality of life, as evidenced by better ICI-Q-SF and Rintala scores.

The incidence of surgical complications is a critical factor in evaluating the efficacy of different surgical techniques. Studies have reported significant worse complication rates associated with PLIF, including nerve root injury, blood loss, and operative times [29, 30]. However, in our present study, CLIF showed similar results regarding blood loss and operation time when compared with PLIF. This might be resulted from the small sample size in our present study. Although in our present study, the complications in 24 months were assessed, both CLIF and PLIF involve fusion of spinal segments, which could potentially lead to increased stress on adjacent segments and the development of adjacent segment disease over time.

CESR presents unique challenges that require a comprehensive surgical approach. Previous studies have often focused on nerve decompression, but not on both nerve decompression and tension reduction. For instance, studies by Campbell et al. emphasized the importance of nerve decompression but did not adequately address the

impact of nerve tension [31]. Our study addresses this gap by incorporating both decompression and tension reduction through CLIF, leading to superior clinical outcomes. The significant improvements in neurological and functional outcomes observed in the CLIF group highlight the importance of addressing both aspects in the surgical management of CESR.

There are several limitations to this study. First, although we assessed nerve tension before and after decompression during the procedure, the lack of data from healthy individuals made it difficult to determine the abnormality threshold for nerve tension. Second, the use of nerve tension measurement equipment required the partial removal of the ligamentum flavum and articular process to expose the dural sac and nerve root, which likely resulted in lower measured nerve tension compared to the true pre-procedural values. Third, to reduce research bias, we included only CESR cases caused by lumbar disc herniation, leading to a modest sample size. Fourth, the retrospective design may introduce selection bias and confounding factors that are not accounted for in the analysis. Future high-quality randomized controlled trials (RCTs) are necessary to validate these findings. Fifth, the single-center design limits the generalizability of the study findings to other patient populations and healthcare settings. Sixth, this study was conducted by a single lead spine surgeon with a dedicated surgical team. While this ensures consistency in the surgical technique, it does not account for potential variability among different surgeons. Future studies involving multiple surgeons would help to assess the reproducibility of the results across different practices.

Conclusion

In conclusion, the findings from our study have significant implications for clinical practice. While PLIF has been widely used for CESR, its limitations in addressing urinary and bowel dysfunctions and higher complication rates necessitate the exploration of alternative approaches. Our study suggests that CLIF, by effectively addressing both nerve compression and tension, offers a more effective and safer surgical option for CESR patients. These findings support the integration of CLIF into clinical practice, potentially leading to improved patient outcomes and quality of life.

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Author contributions
Fudong Li and Bin Zhang designed the study. Fudong Li conducted data analysis, data visualization, and manuscript writing. Fudong Li, Chenglong Ji, Linhui Han, and Kaiqiang Sun collected the data. Jiangang Shi and members in the surgery team performed the surgeries. All authors revised the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethical approval
This study was approved by the institutional review board of Shanghai Changzheng Hospital.

Informed consent
All patients signed informed consent.

Competing interests
The authors declare no competing interests.

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