Original article

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Transforaminal lumbar interbody fusion in spondylolisthesis: a prospective evaluation of clinical, radiological, and functional outcomes in a Central Indian cohort

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Background: Spondylolisthesis, or anterior vertebral displacement, is a complex spinal disorder characterized by diverse symptoms and various treatment approaches. Transforaminal Lumbar Interbody Fusion (TLIF) is increasingly preferred over Posterior Lumbar Interbody Fusion (PLIF); however regional data in India are limited.

Objective: This prospective study evaluated clinical, radiological, and functional outcomes after TLIF in lumbar spondylolisthesis patients treated at a tertiary center in central India.

Methods: Fifty adult patients with Grade II–IV lumbar spondylolisthesis underwent TLIF. Assessments included pain (Visual Analogue Scale, VAS), disability (Oswestry Disability Index, ODI), neurological status, slip angle correction, fusion rates, and complications pre- and postoperatively. Statistical significance was set at $p < 0.05$.

Results: Locations L4–L5 (56%) and L5–S1 (44%) were the affected levels. The mean preoperative VAS and ODI scores were 7.4±1.0 and 74±10%. At 6 months follow-up, VAS decreased by 71.6% to 2.1, and ODI by 88% to 9.5% ($p < 0.001$). Neurological recovery included full motor deficit resolution and 92% sensory improvement. The mean slip angle correction was 14.6±5.3°, and the fusion success rate was 92%. Complications were minimal, including 4% wound infection and 4% transient neurological deficits, with no implant failures.

Conclusion: TLIF shows excellent short-term results, offering substantial pain relief, functional and neurological recovery, and high fusion rates in Indian patients with moderate-to-severe spondylolisthesis. Further studies with larger sample sizes and longer follow-up periods are warranted to validate these findings.

Keywords: *spondylolisthesis; spinal instability; TLIF; ODI; VAS*

Introduction

Spondylolisthesis, characterized by the anterior displacement of a vertebra over the one beneath it, is a common spinal pathology with complex etiology and management considerations. Often resulting from spondylolysis, its classifications—such as that proposed by Marchetti and Bartolozzi—distinguish developmental from acquired forms, helping to understand its natural history, risk of progression, and treatment implications [1].

The widely used Meyerding classification grades severity by measuring the degree of vertebral slippage on lateral radiographs, guiding clinical decision-making [1]. Although it is readily identified on imaging, there remains considerable uncertainty about its pathogenesis and optimal treatment. Its prevalence ranges from 5–6% in the general population to as high as 12% among adolescents engaged in vigorous physical activity such as gymnastics and weightlifting, emphasizing mechanical stress as a key factor [2]. Genetic predisposition is also significant, with familial clustering rates ranging from 27% to 69%, as well as associations with congenital anomalies, such as sacral spina bifida, affecting up to 42% of cases [3].

The most frequently involved segments are L4 and L5, vital for lumbo-sacral stability and load-bearing. Long-term follow-up studies indicate that spondylolisthesis is often benign; however, progression with neurological deficits and chronic pain may occur, correlating with higher Meyerding grades, disc degeneration, and sacral morphology.

Diagnostic accuracy has improved with modalities including oblique radiographs, which reveal the classic "Scotty dog" sign, computed tomography (CT) and single-photon emission computed tomography (SPECT) scans, which enhance the detection of pars interarticularis defects, and MRI, which assesses neural compression and soft tissue damage [4].

Clinically, pain patterns vary by age, with postural and gait abnormalities more common in children due to hamstring tightness, while whereas adults often present with back pain and sciatica, frequently dominated by neurogenic claudication.

Advances in imaging—particularly MRI and dynamic radiographs—have enhanced the evaluation of segmental instability, a critical factor in guiding treatment decisions.

The North American Spine Society (NASS) promotes "advancing spine evidence synthesis" through a rigorous, multidisciplinary approach to developing evidence-based clinical guidelines [5]. The guidelines conclude that low back pain should be diagnosed mainly using patient history and physical examination, with advanced tests reserved for severe or suspicious cases. First-line treatment should focus on non-pharmacological approaches such as exercise and education, while medications or interventions should only be used when clearly needed, with careful consideration of risks and benefits. Individualized care is emphasized to improve patient outcomes and avoid unnecessary interventions. More recently, integration of artificial intelligence in diagnostic imaging has further enhanced sensitivity and accuracy [6].

Despite clear surgical indications in selected patients, controversies persist concerning the optimal surgical technique. Among available techniques, Transforaminal Lumbar Interbody Fusion (TLIF) has gained prominence as the preferred surgical approach, owing to its ability to provide circumferential fusion through a unilateral posterior corridor while minimizing dural and neural retraction, perioperative blood loss, and procedure duration compared to Posterior Lumbar Interbody Fusion (PLIF) [7]. It achieves better restoration of disc height, indirect foraminal decompression, and sagittal alignment correction [7].

Advances in TLIF—particularly with the advent of minimally invasive and expandable cage technologies—have improved fusion rates, functional recovery, and reduced perioperative morbidity [7]. However, there is a paucity of prospective, region-specific data in countries like India, where epidemiological patterns, patient comorbidities, and healthcare accessibility differ significantly from those in Western cohorts. This gap hampers evidence-based surgical planning and decision-making tailored to local needs.

The current study addresses this by systematically correlating clinicoradiological features with outcomes following TLIF, aiming to generate robust evidence for optimizing surgical management in the Indian context, particularly within the tribal belt of central India. Such research is crucial for improving patient-centered outcomes, informing shared decision-making, and enabling efficient allocation of healthcare resources against a backdrop of increasing disability due to spondylolisthesis worldwide.

Materials and methods

Study design and setting

This prospective, observational, single-institution study was conducted in the Department of Neurosurgery at a tertiary care center located in the tribal belt of central India. The study duration was one year. The study protocol was reviewed and approved by the Institutional Ethics Committee. Written informed consent was obtained from all participants or their legal guardians before their inclusion in the study. The study adhered to the ethical principles outlined in the Declaration of Helsinki (2013 revision), ensuring respect for patient rights, safety, and well-being throughout the research process [8].

Inclusion criteria

All consecutive adult patients presenting with lower back pain suggestive of spinal instability were screened. Patients demonstrating both clinical features and radiological evidence of lumbar spondylolisthesis were prospectively enrolled. Patients were included if they met the following criteria:

1. Adults aged ≥18 years.
2. Presentation compatible with clinical features such as chronic low back pain with or without radiculopathy, neurogenic claudication, restricted lumbar spine mobility or segmental instability, neurological deficits including weakness, sensory impairment, or altered reflexes, and positive findings on instability or stretching tests such as the straight leg raising test, femoral stretch test, or instability catch sign.
3. Radiologically confirmed lumbar spondylolisthesis identified on standing lumbosacral X-rays (anteroposterior, lateral, flexion–extension views) and/or lumbar MRI.
4. Single-level spondylolisthesis was included.

Exclusion criteria

Patients were excluded under the following conditions:

1. Presence of scoliosis, abnormal lordosis, or congenital deformities other than spondylolisthesis.
2. Prolapsed intervertebral disc (PIVD) without evidence of spondylolisthesis.
3. Inflammatory spinal disorders (e.g., rheumatoid arthritis, ankylosing spondylitis, seronegative spondyloarthropathies).
4. Patients with previous lumbar spine surgery.
5. Active or recent spinal infections (tuberculous spondylitis, bacterial spondylodiscitis).
6. Spinal tumors or secondary metastatic disease.
7. Severe systemic comorbidities precluding surgery, such as uncontrolled diabetes mellitus, advanced cardiac disease, severe pulmonary compromise, or coagulopathy.
8. Pregnant or lactating women.
9. Patients unwilling or unable to provide informed consent or comply with scheduled follow-up visits.

Preoperative evaluation and data collection

For all included patients, detailed demographic data—including age, sex, residence, occupational history, and contact details—were systematically recorded. A comprehensive medical history was obtained, focusing on presenting symptoms, duration of illness, prior treatments, comorbidities, and both personal and family history. Clinical evaluation involved a thorough general physical examination and detailed neurological assessment, with attention to motor power, sensory perception, reflexes, gait, and spinal flexibility; findings such as instability, radiculopathy, and neurogenic claudication were specifically documented. Preoperative baseline laboratory investigations comprised complete blood count, renal and liver function tests, fasting

This article contains some figures that are displayed in color online but in black and white in the print edition.

or random blood sugar, serum electrolytes, calcium, rheumatoid factor, and C-reactive protein. The following radiological investigations were performed on a need basis:

- Plain X-rays (lumbosacral spine): Standing anteroposterior, lateral, oblique, and flexion–extension views were used to assess alignment, slip degree, slip angle, dynamic instability, scoliosis, and sagittal balance.

- Computed Tomography (CT) (when indicated): Used selectively for detailed bony anatomy in cases of high-grade slips or complex anomalies.

- Magnetic Resonance Imaging (MRI): Performed for all patients to evaluate neural compression, degree of canal stenosis, foraminal narrowing, facet joint morphology, disc degeneration, juxtafacet cysts, and ligamentum flavum hypertrophy. Signal changes on T2-weighted images were noted to assess neural element compromise and loss of cerebrospinal fluid (CSF) signal.

Key spinopelvic parameters include pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), and lumbar lordosis (LL). These are essential for assessing sagittal balance and spinal alignment [9]. PI, typically ranging from 30° to 80° (average 50°–55°), reflects pelvic anatomy and remains stable post-skeletal maturity; abnormal values may indicate structural imbalances. PT, generally between 10° and 15° (range 5° to 30°), measures pelvic orientation; elevated PT is often seen in spinal deformities. SS assesses the sacrum's inclination, normally 30° to 50°, with deviations indicating potential mechanical issues. LL, the inward curvature of the lower back, usually spans 40°–60° but can range from 20° to 80°; hypo- or hyper lordosis may be related to various pathologies (***Fig. 1***). Abnormalities in these parameters are associated with spinal malalignment, pain risk, and degenerative conditions.

Surgical intervention

Each patient underwent a thorough pre-anesthetic evaluation and fitness assessment. All patients in the study underwent open TLIF surgery. Additionally, reduction was performed in all high-grade spondylolisthesis cases to restore alignment. Operative steps included a midline posterior incision with subperiosteal exposure of the relevant spinal levels, followed by decompression of neural elements through laminotomy and foraminotomy as needed. The intervertebral disc space was then prepared with thorough disc removal, after which interbody fusion was performed using appropriately sized cages combined with autologous or local bone graft. Pedicle screw fixation with rods was employed to achieve spinal stabilization (***Fig. 2***). Adequate hemostasis was achieved, and the wound was closed in layers, with the placement of a suction drain as indicated. Intraoperative parameters, including blood loss, duration of surgery, complications, and the level of fusion, were carefully documented.

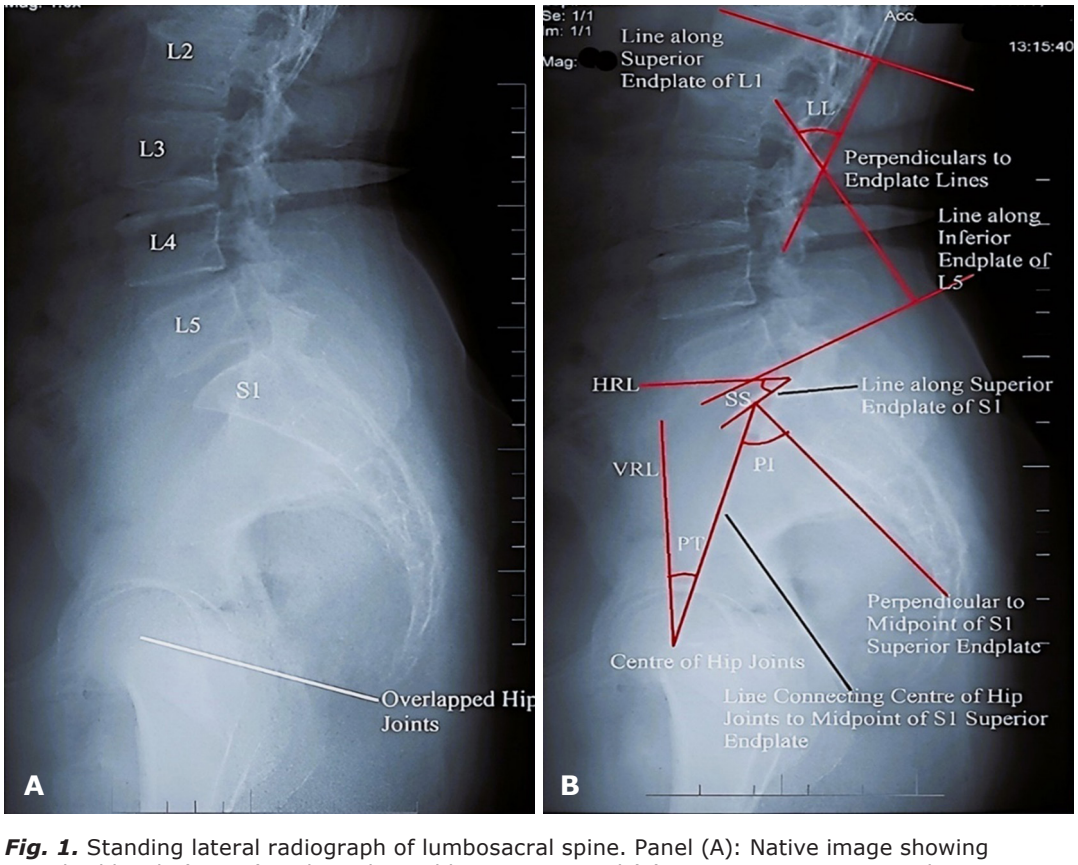

Fig. 1. Standing lateral radiograph of lumbosacral spine. Panel (A): Native image showing vertebral levels (L2–S1) and overlapped hip joints. Panel (B): Same image annotated to demonstrate measurement techniques for spinopelvic parameters. Red lines indicate the superior endplate of L1, the inferior endplate of L5, and the superior endplate of S1. Perpendiculars to endplate lines are shown to illustrate lumbar lordosis (LL), sacral slope (SS), pelvic incidence (PI), pelvic tilt (PT), and vertical reference line (VRL).

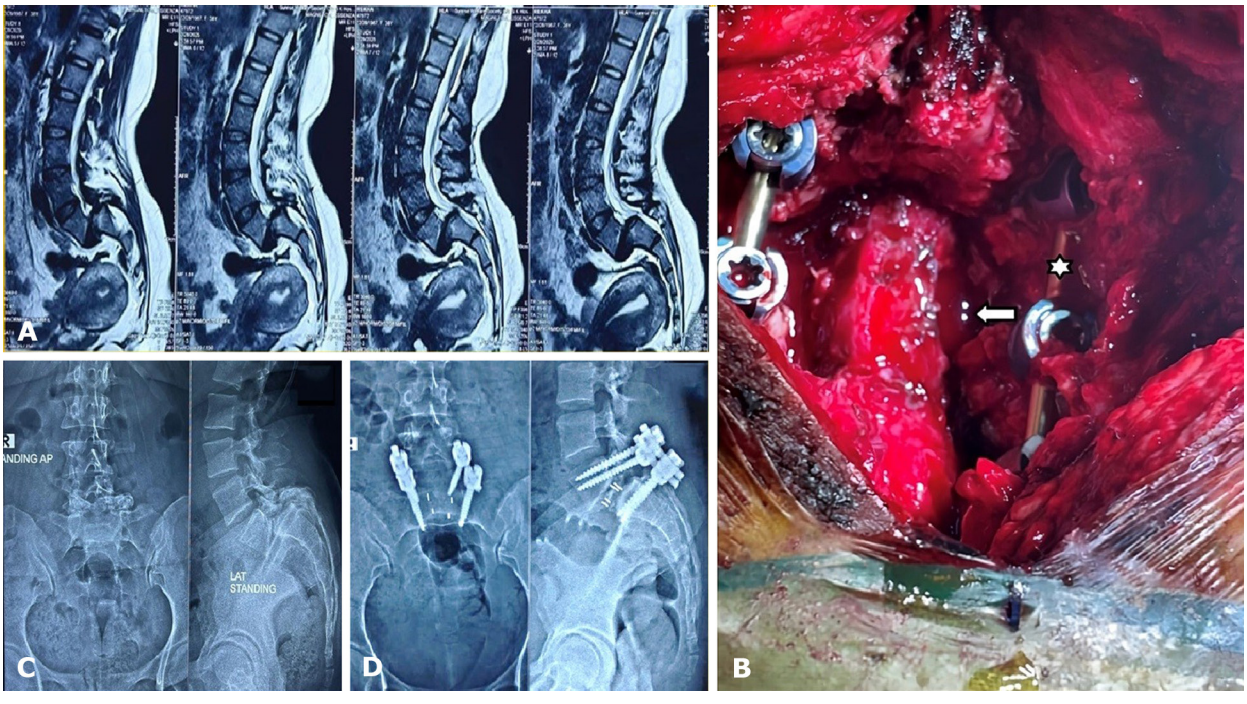

Fig. 2. A case study of grade 4 spondylolisthesis. Panel A – MRI of the lumbosacral spine (T2-weighted sagittal images) demonstrates lumbar spondylolisthesis with associated prolapsed intervertebral disc at the L4-L5 level. Panel B – Intraoperative photograph displaying laminotomy (solid white arrow) and placement of a pedicle screw rod construct (solid white star). Panel C – Plain X-rays of the lumbosacral spine (AP and lateral views, preoperative images) show loss of alignment due to spondylolisthesis. Panel D – Postoperative plain X-rays (AP and lateral views) illustrate the pedicle screws, rods, and interbody cage in situ, confirming realignment and stabilization

Postoperative care and follow-up

Patients were mobilized early with lumbar support. Postoperative radiographs were performed to confirm implant placement (***Fig. 2***). Analgesia, physiotherapy, and gradual rehabilitation were provided. Patients were discharged after achieving ambulation with adequate pain relief. Follow-up evaluations were carried out at 1 month, 3 months, and 6 months. Both outpatient visits and telephonic consultations were utilized when in-person visits were not possible.

Outcome measures

Primary outcome measures included postoperative pain, assessed using VAS; functional disability, evaluated with ODI; neurological recovery encompassing motor strength, sensory function, and reflexes; and the average duration of hospital stay [10]. Secondary outcome measures comprised radiographic assessment of vertebral displacement correction, measurement of slip angle reduction, and evaluation of surgical complications, including wound infections, implant-related issues, and any neurological deterioration.

Data analysis

All collected data were entered into a structured database and analyzed using SPSS version 26.0. Continuous variables were expressed as mean±standard deviation (SD), while categorical variables were presented as frequencies and percentages. Paired *t*-tests were used to compare preoperative and postoperative continuous variables, such as VAS and ODI scores. Chi-square tests were employed for the analysis of categorical data. A *p*-value of less than 0.05 was considered statistically significant.

Results

The demographics and baseline characteristics of the study population are shown in (***Table 1***).

The study cohort comprised 50 patients with a mean age of 58±6.9 years (range 41–83), including 44% males and 56% females. The average BMI was 25.4±3.2 (22.5–31.1), with 72% of participants engaging in mixed occupational activity and 28% being sedentary. Comorbidities included hypertension (32%), diabetes (24%), and cardiovascular disease (20%). The mean duration of symptoms was 5.2±1.1 months. Pain was predominantly radicular (72%), with 48% reporting mechanical pain. Prior conservative treatments were physiotherapy (52%), medications (100%), and injections (36%). Lumbar levels L4–L5 and L5–S1 were affected in 56% and 44% respectively. No patients had Grade I spondylolisthesis; 52% had Grade II, 28% Grade III, and 20% Grade IV. In the study population, isthmic spondylolisthesis accounted for 62% (31 cases), whereas degenerative spondylolisthesis comprised 38% (19 cases). Preoperative VAS averaged 7.4±1.0, and ODI was 54±12%. Baseline neurological deficits were noted in 8% of patients as motor and in all patients as sensory. Imaging revealed canal stenosis in 28%, foraminal stenosis in 76%, and facet arthropathy in 12%. Dynamic X-rays showed instability in 92% of patients. The surgical and radiographic outcomes of the study are shown in (***Table 2***).

Table 1. Patient demographics and baseline characteristics (n=50) of the study population

Characteristic	Value / Number (%)	Range / Mean±SD
Age (years)	–	58±6.9 (41–83)
Gender (male/female)	22 (44%) / 28 (56%)	–
Body Mass Index (BMI)	–	25.4±3.2 (22.5–31.1)
Occupational status	Mixed: 36 (72%) Sedentary: 14 (28%)	–
Comorbidities	Hypertension: 16 (32%) Diabetes: 12 (24%) CVD: 10 (20%)	–
Duration of symptoms (months)	–	5.2±1.1 (1–9)
Pain characteristics	Mechanical: 24 (48%) Radicular: 36 (72%)	–
Previous conservative treatment	Physiotherapy: 26 (52%) Medications: 50 (100%) Injections: 18 (36%)	–
Spine levels affected	L4–L5: 28 (56%) L5–S1: 22 (44%)	–
Grade of spondylolisthesis (Meyerding)	Grade I: 0 (0%) Grade II: 26 (52%) Grade III: 14 (28%) Grade IV: 10 (20%)	–
Types of spondylolisthesis	Isthmic: 31 (62%) Degenerative: 19 (38%) Dysplastic: 0 (0%)	
Preoperative VAS score	–	7.4±1.0 (6–9)
Preoperative ODI (%)	–	54±12 (40–80)
Baseline neurological deficit	Motor: 24(8%) Sensory: 50 (100%)	–
Imaging findings	Canal stenosis: 14 (28%) Foraminal stenosis: 36 (76%) Facet arthropathy: 6 (12%)	–
Instability on dynamic X-rays	Yes: 46 (92%) No: 4 (8%)	–

Table 2. Radiographic outcomes and surgical complications in the study population

Parameter	Mean±SD / Number of patients (n=50)	Range	Percentage (%)	Notes
Slip angle reduction (degrees)	14.6±5.3	9–30	–	Significant correction
Fusion rate at 6 months	46 patients / 50	–	92%	2 cases of non-union (pseudoarthrosis)
Wound infection (n, %)	2	–	4%	Superficial, resolved with treatment
Implant-related complications (n, %)	0 (0%)	–	0%	None reported
Neurological deterioration (n, %)	1	–	2%	Transient deficit, recovered
Cardiac complication	1	–	2%	Developed heart failure with atrial fibrillation, managed medically
Reoperation rate (n, %)	0 (0%)	–	0%	None
Average hospital stay (days)	12.5±2.1	5–18	–	Standard postoperative stay
Intraoperative blood loss (mL)	610±85.4	410–930	–	Moderate blood loss
Operative time (minutes)	175.2±24.8	140–220	–	Within the expected range

Surgical intervention resulted in a mean reduction of 14.6±5.3 degrees in slip angle (range, 9–30 degrees). Fusion was successful in 92% (46/50) of patients at 6 months. Complications were minimal, with 4% experiencing wound infection (2 patients), 0% having implant-related issues, and 2% presenting with transient neurological deterioration (1 patient). No reoperations were needed. Average hospital stay was 12.5±2.1 days, intraoperative blood loss averaged 610±85.4 mL, and operative time was 175.2±24.8 minutes. At the 6-month follow-up, spinopelvic parameter assessment revealed that pelvic incidence remained stable (55.4°±7.8° pre-operatively vs. 55.2°±7.5°), indicating no significant change. In contrast, pelvic tilt demonstrated a significant reduction, while sacral slope and lumbar lordosis also showed significant postoperative improvements (***Table 3***). These findings suggest better sagittal alignment and restoration of lumbar curvature following TLIF surgery.

Pre- and post-operative pain assessment is shown in (***Fig. 3***).

The mean VAS scores showed a progressive decrease from 7.4±1.0 preoperatively (median 7, range 5–9) to 4.2±1.3 at 1-month post-op (median 4, range 2–7), reflecting a 43.2% improvement with 44% of patients achieving ≥50% pain reduction (p=0.015). At 3 months, the mean VAS further declined to 3.3±1.2 (median 3, range 1–5), with a 55.4% improvement and 64% of patients with ≥50% improvement (p=0.009). Significant pain relief continued at 6 months, with a mean VAS of 2.1±0.8 (median 2, range 1–4), representing a 71.6% reduction and 84% attaining ≥50% improvement ($p < 0.001$) (***Table 4***).

The functional outcome of the study is shown in (***Fig. 4***). The mean ODI scores decreased from a preoperative value of 74±10% (median 75, range 55–90) to 62.5±6.8% at 1 month (median 60, range 45–78), reflecting a 16% improvement with 28% of patients achieving ≥30% improvement (p=0.08). At 3 months, mean ODI further improved to 36.5±4.2% (median 35, range 22–53), representing a 51% reduction and 72% of patients with ≥30% improvement (p=0.005). By 6 months, the mean ODI declined markedly to 9.5±1.6% (median 9, range 3–18), showing an 88% improvement with 96% of patients achieving ≥30% improvement ($p < 0.001$) (***Table 5***).

The neurological outcomes demonstrated significant recovery over time (***Fig. 5***).

Table 3. Pre- and post-operative assessment of spinopelvic parameters using paired t-test

Parameter	Pre-op	Follow-up (6 months)	t-value	*p*-value
Pelvic incidence (PI)	55.4°±7.8°	55.2°±7.5	-0.13	0.8972
Pelvic tilt (PT)	21.3°±7.4°	17.2°±5.1°	-3.23	0.0017
Sacral slope (SS)	33.6°±9.5°	37.8°±8.3°	2.35	0.0211
Lumbar lordosis (LL)	46.5°±12.4°	51.4°±11.2°	2.07	0.0410

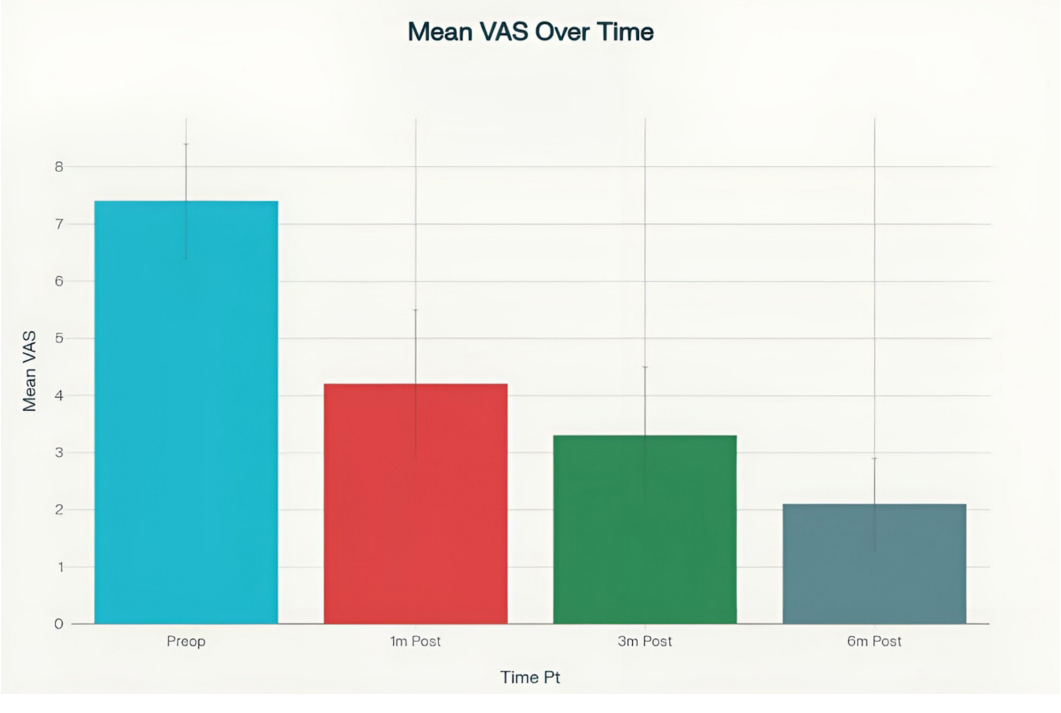

Fig. 3. Mean Visual Analogue Scale of patients during pre-op and follow-up

Table 4. Pre-operative and post-operative pain assessment using VAS

Time point	Mean VAS±SD	Median VAS	Range	% Improvement from Baseline	Number of patients with ≥50 % Improvement (%)	*p*-value (vs Pre-op)
Preoperative	7.4±1.0	7	6–9	–	–	–
1 Month post-op	4.2±1.3	4	2–7	43.2%	22 (44%)	0.015
3 Months post-op	3.3±1.2	3	1–6	55.4%	32 (64%)	0.009
6 Months post-op	2.1±0.8	2	1–4	71.6%	42 (84%)	<0.001

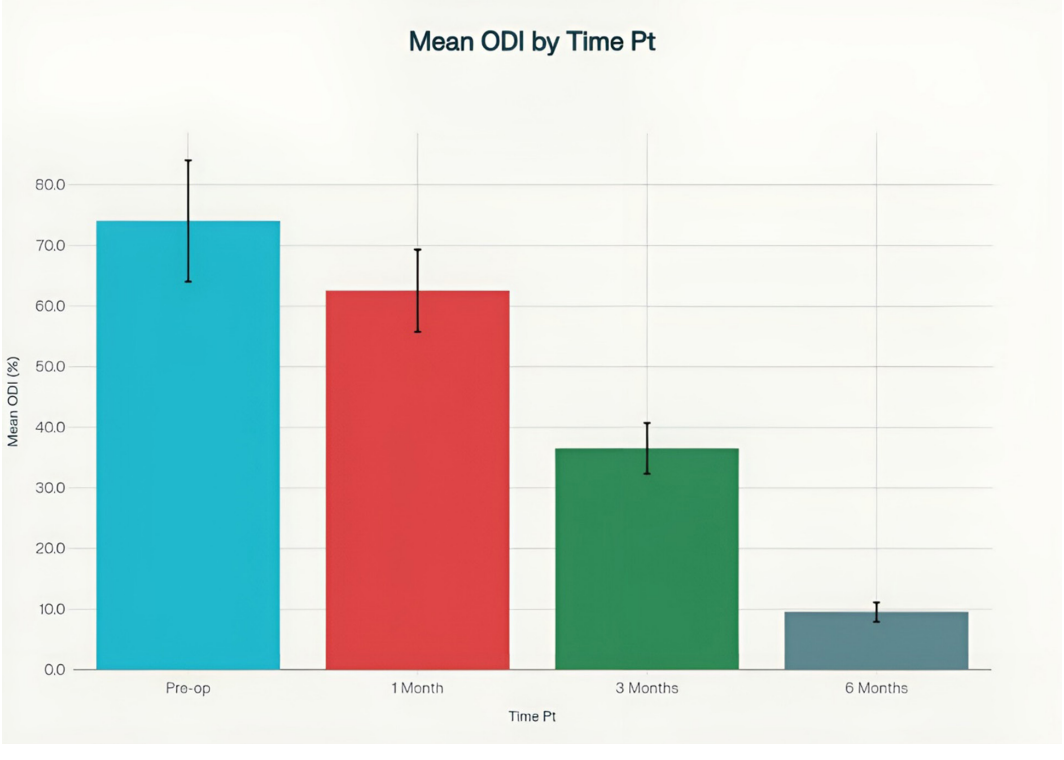

Fig. 4. Mean Oswestry Disability Index (ODI) during pre-op and follow-up

Table 5. Functional disability assessed by ODI during pre-op and follow-up.

Time Point	Mean ODI (%) (Mean±SD)	Median (%)	Range	% Improvement from Baseline	≥30% Improvement (n, %)	*p*-value
Pre-op	74±10	75	55–90	–	–	–
1 Month	62.5±6.8	60	45–78	16%	14 (28%)	0.08
3 Months	36.5±4.2	35	22–53	51%	36 (72%)	0.005
6 Months	9.5±1.6	9	3–18	88%	48 (96%)	<0.001

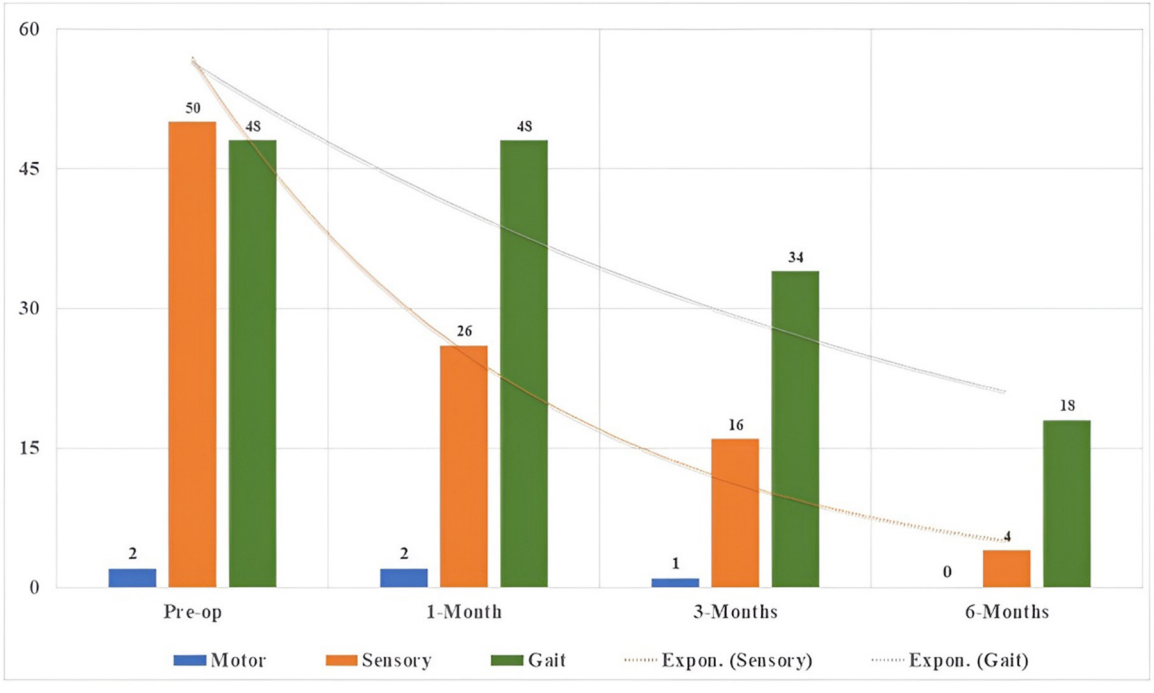

Fig. 5. Neurological recovery histogram at 1,3, and 6 months

A motor deficit was present in 4% of patients preoperatively and persisted immediately and at 1 month postoperatively but resolved completely by 6 months, representing 100% resolution (p=0.04). The sensory deficit was universal preoperatively (100%) and reduced to 52% immediately post-op, 32% at 1 month, and 8% at 6 months, reflecting a 92% overall improvement (p < 0.001). Gait disturbance affected 96% preoperatively and immediately post-op, improved to 68% at 1 month, and further to 36% at 6 months, demonstrating a 62.5% improvement (p=0.001) (***Table 6***).

The correlation analysis of demographic, clinical, and radiographic variables with study outcomes is shown in ***Table 7***. The analysis of study variables showed that older patients (>70 years) and those with obesity had higher disability and pain scores, with obesity significantly affecting both ODI (9.90±1.52 vs. 8.85±1.74, p=0.029) and VAS (2.05±0.69 vs. 2.30±0.82, p=0.001) outcomes. The L4-L5 spinal level was associated with greater disability (ODI 10.06±1.84) compared to L5-S1 (8.79±1.63, p=0.014). Higher grades of spondylolisthesis correlated with worse outcomes, with grade 4 showing the highest ODI (11.27±1.55, p < 0.001). No significant outcome differences were noted based on sex or hypertension.

Discussion

This prospective study evaluated the short-term clinical, radiological, and functional outcomes of TLIF in patients with spondylolisthesis, with an emphasis on pain relief, functional recovery, and fusion success. Our results demonstrate that TLIF provides effective correction of deformity, promotes high fusion rates, and achieves substantial improvements in pain scores, disability indices, and neurological function, with a low complication profile.

The demographic profile of the cohort—mean age 58 years, female predominance (56%), high prevalence of comorbidities (hypertension 32%, diabetes 24%), and a relatively high rates of grade II–IV slips—reflects the typical clinical scenario of Indian patients presenting for spinal surgery. Compared with international cohorts, where many surgical series focus on lower-grade slips and younger patients, our series included a greater proportion of advanced Meyerding grades (48% grade III–IV) [11]. This may highlight a delay in diagnosis and surgical referral in our setting, likely influenced by socioeconomic and healthcare access disparities.

The pre- and post-operative assessment of spinopelvic parameters demonstrated significant changes in PT, SS, and LL at 6 months follow-up, while PI remained stable with no significant difference (p=0.8972). Specifically, PT decreased significantly from 21.3°±7.4° to 17.2°±5.1° (t=-3.23, *p*=0.0017), indicating improved pelvic alignment post-surgery. SS and LL showed a significant increase, suggesting enhanced lumbar curvature contributing to sagittal balance restoration. These findings are consistent with prior studies. Shafiei *et al*. reported that abnormalities in standing pelvic tilt are significantly associated with poorer functional outcomes after total hip arthroplasty, and improvement in PT correlates with better recovery [12]. Similarly, Williams et al. found that PT and LL improved significantly post-lumbar fusion surgery, consistent with the paired t-test findings observed in the present study [13]. These studies collectively confirm that surgical realignment positively impacts the key sagittal parameters PT, SS, and LL, while PI remains a fixed anatomical parameter unaffected by surgery.

Table 6. Neurological recovery outcomes during follow-up

Neurological Parameter	Preoperative (n, %)	Immediate post-op (n, %)	1-Month post-op (n, %)	6-Month post-op (n, %)	Improvement (%)	*p*-value
Motor deficit	2 (4%)	2 (4%)	2 (4%)	0 (0%)	100% resolution	0.04
Sensory deficit	50 (100%)	26 (52%)	16 (32%)	4 (8%)	92% improvement	<0.001
Gait disturbance	48 (96%)	48 (96%)	34 (68%)	18 (36%)	62.5% improvement	0.001

Table 7. Correlation of various demographic, clinical, and radiographical parameters of the study population with study outcomes

Variables	Subclass	Outcome (ODI) Mean±SD	T value / F value (ODI)	P value (ODI)	Outcome (VAS) Mean±SD	T value / F value (VAS)	P value (VAS)
Sex	Male (n=22)	9.79±1.45	1.37157	0.17658	1.83±0.72	1.92345	0.05500
	Female (n=28)	9.27±1.23			2.23±0.78		
Age	<50 Yrs (n=27)	9.00±1.67	4.67581	0.01406	1.97±0.88	2.15790	0.12600
	51-70 Yrs (n=18)	9.95±1.31			2.12±0.74		
	>70 Yrs (n=5)	10.96±1.90			2.31±0.80		
Obesity	Present (n=31)	9.90±1.52	2.24392	0.02949	2.05±0.69	3.33521	0.00110
	Absent (n=19)	8.85±1.74			2.30±0.82		
HTN	Present (n=16)	10.15±1.38	1.76022	0.08474	2.26±0.77	1.15840	0.24560
	Absent (n=34)	9.19±2.00			2.08±0.83		
DM	Present (n=12)	10.00±1.41	0.99836	0.32311	1.85±0.82	3.23211	0.00160
	Absent (n=38)	9.38±1.58			2.21±0.78		
CVD	Present (n=10)	10.02±1.72	1.33140	0.18935	2.49±0.72	2.00822	0.05220
	Absent (n=40)	9.37±1.29			2.03±0.87		
Location	L4-L5 (n=28)	10.06±1.84	2.54546	0.01418	2.19±0.65	1.92830	0.05810
	L5-S1 (n=22)	8.79±1.63			2.00±0.90		
Grade of spondylolisthesis	Grade 2 (n=26)	8.59±1.47	9.79907	0.00028	1.89±0.95	9.36251	0.00150
	Grade 3 (n=14)	9.93±2.10			2.09±0.72		
	Grade 4 (n=10)	11.27±1.55			2.43±0.78		

Postoperative VAS scores demonstrated a significant and sustained decline from 7.4 preoperatively to 2.1 at 6 months, with 84% of patients reporting ≥50% pain relief. Similarly, ODI improved by 88% at final follow-up, with almost all patients (96%) achieving a clinically meaningful improvement. These outcomes are consistent with previous reports demonstrating the efficacy of TLIF for spondylolisthesis. For instance, Hartmann *et al*. have reported VAS backache pain reduction of 69.6 % at 12 weeks post-TLIF, comparable to our 71.6% VAS reduction at 6 months [14]. Also, the ODI scores in this study improved by 53.8% comparable to our study comparable to our study (51% reduction) [14].

The early disability improvement lag at 1 month, followed by sharp gains at 3 and 6 months, may reflect the time required for postoperative rehabilitation and gradual fusion-related stability. Integrating high-intensity interval training (HIIT) into rehabilitation protocols can accelerate these functional gains, as HIIT has been shown to significantly boost cardiovascular fitness, quality of life, and postoperative recovery in patients—suggesting a promising strategy to optimize outcomes in surgical populations [15]. The mean correction in slip angle (14.6 degrees) and the high 6-month fusion rate (92%) confirm TLIF's biomechanical advantages in restoring sagittal balance and promoting stability. Our fusion rate aligns with previously published pooled values of 84.7-94.3% in TLIF series and compares favorably to PLIF, where fusion is often slightly lower and implant-related complications are higher due to bilateral retraction [16]. Notably, our series achieved this with minimal complications and no implant failures, supporting TLIF as a reliable technique for correcting multi-grade spondylolisthesis. Compared to other studies, where at least one complication rates range from approximately 20%—including dural tears, nerve injuries, and pseudoarthrosis—our outcomes were at the lower end, possibly reflecting careful case selection and adherence to surgical protocols [17-18].

Neural decompression is a key advantage of TLIF, where cage placement restores disc height and foramina. In our study, 76% had foraminal stenosis, yet the majority showed neurological recovery. Neurological deterioration was transient in one patient, and there was a single cardiac complication involving heart failure with atrial fibrillation [19-21]. It was managed medically, in line with modern perioperative risk assessments that highlight cardiac morbidity as rare but significant in this and similar populations [3, 22]. Average hospital stays (12.5±2.1 days), intraoperative blood loss (610±85.4 mL), and operative time (175.2±24.8 minutes) were consistent with results from large comparative studies, supporting TLIF's status as an effective technique for spondylolisthesis with a favourable safety and recovery profile that matches current evidence-based guidelines and outcomes research [18].

In the evaluation of neurological outcomes, significant improvements were observed across motor, sensory, and gait parameters over six months. Motor deficits resolved completely by six months (p=0.04). Sensory deficits were initially present in 100% of patients but improved dramatically to 8% at six months, reflecting a 92% improvement with high statistical significance. Gait disturbance was noted in 96% preoperatively, decreasing to 36% by six months, indicating a 62.5% improvement (p=0.001). These findings align well with published data by Balasubramanian *et al*. showing that TLIF effectively decompresses neural elements, promotes nerve root recovery, and facilitates substantial functional neurological recovery, with most deficits improving gradually over months postoperatively without persistent major deficits [23].

Studies have also emphasized that the unilateral posterior approach preserves posterior soft tissues, aiding neurological recovery, and that early motor improvements portend good clinical outcomes [24]. Although some sensory symptoms may persist longer, a profound reduction over time indicates successful nerve decompression and stabilization achieved by TLIF. These neurological outcome trends are supported by both retrospective and prospective clinical series investigating TLIF in the treatment of spondylolisthesis [25]. However, our cohort adds valuable data specific to the Indian context, where higher preoperative disability, advanced slip grades, and delayed presentation are common.

The correlation of various demographic, clinical, and radiographic parameters with study outcomes, measured by ODI and VAS, reveals significant associations, particularly with age, obesity, location of pathology, and grade of spondylolisthesis. Patients >70 years had higher disability scores. Obesity was significantly correlated with worse outcomes in both ODI (p=0.02949) and VAS (p=0.00110), consistent with recent findings by Garcia *et al*., who reported that higher BMI negatively affects recovery and results in elevated pain and disability scores postoperatively [26]. Spondylolisthesis grade also showed a highly significant correlation with both ODI (p=0.00028) and VAS (p=0.00150), with higher grades associated with worse disability and pain, echoing the observations by Nedelea *et al*. regarding functional impairment increasing with severity of spondylolisthesis [27]. The location at L5-S1 was associated with significantly higher ODI compared to L5-S1 (p=0.00848). Sex and hypertension showed no significant correlation with outcomes in this cohort. Diabetes mellitus was significantly correlated with VAS scores (p=0.00160), which aligns with recent data highlighting altered pain perception in diabetic patients [28]. These findings underscore the need for individualized patient assessment incorporating these variables to optimize treatment strategies and prognostication in spinal disorders.

Study strengths and limitations

This study possesses many strengths including its prospective design, which ensures systematic and unbiased data collection; comprehensive evaluation of multiple clinical, radiographic, and functional outcomes such as pain (VAS), disability (ODI), neurological recovery, and fusion rates, providing a holistic picture of TLIF efficacy; and its focus on an Indian patient cohort, filling an important regional data gap and addressing demographic and healthcare nuances. Additionally, the detailed reporting of neurological and functional improvements with statistically significant results, strengthens the clinical relevance of the findings. However, the study has few limitations such as a relatively small sample size of 50 patients, potentially limiting the power to detect rare complications and

reducing generalizability; a short-term follow-up period of six months, which is insufficient to assess long-term fusion success and late complications. Furthermore, its single-center nature, absence of a control or comparison group, and limited detail on rehabilitation protocols may influence functional recovery outcomes and prevent standardization of postoperative care. Despite these limitations the study provides important contribution to Indian spine surgery literature while identifying areas for further research to confirm and expand these findings in larger, multi-center, randomized trials with extended follow-up.

Conclusion

This prospective study highlights that TLIF is an effective and safe surgical option for managing spondylolisthesis in an Indian patient cohort, demonstrating significant postoperative improvements in pain, disability, neurological recovery, and sagittal spinal alignment. Key findings include a significant reduction in pelvic tilt, increased sacral slope and lumbar lordosis, and high fusion rates with minimal complications. Clinical outcomes were influenced by patient- and disease-related factors including age, obesity, diabetes, anatomical level, and grade of spondylolisthesis, emphasizing the need for individualized patient assessment. These results contribute valuable region-specific data to support tailored surgical planning and improve functional and neurological outcomes in patients with varying degrees of spondylolisthesis. However, larger, multi-center studies with longer follow-up are warranted to validate these findings, assess the long-term durability of fusion, and optimize perioperative care protocols tailored to regional patient populations.

Disclosure

Conflict of Interest

None

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Authors' Contributions

Neeraj Prasad designed the study, acquired the data, and supervised the work; Manish Kumar Nirala contributed to data collection, methodology, and manuscript revision; Abhishek Kumar performed statistical analysis, data interpretation, and literature review; Manisha Gupta assisted with data validation, figures, editing, and final approval. All authors reviewed and approved the final manuscript.

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