Journal of Pain Research

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ORIGINAL RESEARCH

Central Canal Stenosis Severity Does Not Predict Residual Leg Pain After Percutaneous Transforaminal Endoscopic Decompression in Frail Elderly Patients: A Propensity Score-Weighted Cohort Study

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Purpose: Severe central canal stenosis is often considered a relative contraindication for minimally invasive decompression in frail elderly patients with lumbar spinal stenosis, yet evidence supporting this practice is limited. This study evaluated whether stenosis severity predicts persistent leg pain after percutaneous transforaminal endoscopic decompression (PTED).

Methods: This retrospective cohort study included 152 frail elderly patients (age ≥75 years, FRAIL score ≥3) who underwent single-level PTED for unilateral symptomatic lumbar spinal stenosis (2022–2024). The primary outcome was persistent residual leg pain, defined as visual analogue scale (VAS) score ≥4 or regular analgesic use (≥3 days/week for >1 month) at all 3-, 6-, and 12-month follow-ups. Inverse probability of treatment weighting (IPTW) balanced 16 baseline covariates between severe (Schizas grade C–D) and non-severe (grade A–B) stenosis groups. Propensity score matching and multivariable regression were sensitivity analyses. Linear mixed models assessed recovery trajectories.

Results: Severe stenosis was present in 59 patients (38.8%). After IPTW, all covariates were well balanced (all SMD<0.1). Persistent leg pain occurred in 33 patients (21.7%), with similar rates between groups (non-severe: 21.5% vs severe: 22.0%). Severe stenosis was not associated with increased pain risk in any analysis: IPTW-adjusted OR=0.63 (95% CI: 0.26–1.52, P=0.306); PSM OR=0.38 (95% CI: 0.13–1.07, P=0.066); multivariable OR=0.56 (95% CI: 0.21–1.51, P=0.250). The strongest independent predictor was FRAIL score ≥4 (OR=15.57, 95% CI: 3.32–73.11, P=0.001). Recovery trajectories were similar between groups (group×time interaction: VAS P=0.535, ODI P=0.975). Recurrent pain occurred in only 3 patients (2.0%), none requiring reoperation.

Conclusion: Preoperative central canal stenosis severity does not predict persistent leg pain or recovery trajectory after PTED in frail elderly patients. These findings support a symptom-guided rather than image-guided surgical strategy. Patient frailty, rather than the degree of central canal narrowing, is a more important determinant of postoperative pain outcomes.

Keywords: lumbar spinal stenosis, central canal stenosis, percutaneous transforaminal endoscopic decompression, frail elderly, inverse probability of treatment weighting, propensity score, residual pain

Introduction

With the global aging population, lumbar spinal stenosis (LSS) has become increasingly prevalent among older adults. This condition, characterized by narrowing of the spinal canal and neural compression, manifests as pain, numbness, and intermittent claudication—substantially impairing quality of life.[1] In frail elderly patients, conservative management often exacerbates polypharmacy and immobility, potentially worsening comorbidities and frailty.[2] Thus, effective treatment of LSS in this population represents an important public health challenge.[3]

Surgical intervention more effectively improves quality of life and reduces medication burden compared to conservative treatment.[2] However, due to the high prevalence of medical comorbidities and increased risk of complications under general anesthesia in frail patients,[4] minimally invasive techniques under local anesthesia have gained attention.

https://doi.org/10.2147/JPR.S604803
Received: 23 February 2026
Accepted: 1 May 2026
Published: 7 May 2026

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Percutaneous transforaminal endoscopic decompression (PTED) has demonstrated promising safety and efficacy in treating LSS in the elderly, with lower complication rates and faster recovery compared to conventional open surgery.[5–7] Other minimally invasive approaches, such as percutaneous endoscopic interlaminar decompression (PEID) and unilateral laminotomy for bilateral decompression (ULBD), are also available for LSS. However, these techniques typically require general or epidural anesthesia, which may heighten perioperative risk in frail elderly patients. In contrast, PTED is routinely performed under local anesthesia with conscious sedation, offering a distinct safety advantage in this population.[8]

Nevertheless, severe degenerative changes—including central, lateral, and foraminal stenosis, as well as coronal and sagittal misalignment—are common in aged patients. A particular clinical concern arises when treating patients with severe central canal stenosis (Schizas grade C-D) via the transforaminal approach.[9] Many surgeons intuitively believe that the working trajectory of PTED, which approaches the spinal canal from a lateral direction, may provide inadequate access to centrally located compressive structures.[10] This perceived limitation raises concerns that severe central stenosis might not be adequately decompressed through a limited, symptom-focused approach, potentially leading to persistent residual symptoms—a scenario where the original radicular pain fails to resolve or improves only partially after surgery.

This concern has significant clinical implications. When encountering severe central stenosis on preoperative MRI, surgeons may be inclined to abandon the minimally invasive transforaminal approach in favor of more extensive procedures—such as open laminectomy or posterior decompression with fusion—which carry higher perioperative risks, particularly in frail elderly patients.[11] The underlying assumption is that more extensive decompression is necessary to achieve adequate symptom relief in severe central stenosis.

However, this assumption remains largely unexamined. It is unclear whether the degree of central stenosis truly influences the likelihood of achieving complete pain relief after PTED. The critical question is whether severe central canal stenosis independently predicts persistent residual leg pain—defined as ongoing radicular symptoms that are not alleviated by the procedure and persist beyond the early postoperative period. If no such association exists, the current practice of avoiding PTED in severe central stenosis may be unfounded, depriving frail patients of a less invasive treatment option.

Previous studies investigating this question have largely relied on conventional multivariable adjustment without fully addressing confounding by indication, leaving the possibility of residual confounding.[12,13] Using rigorous causal inference methods—including inverse probability of treatment weighting and propensity score matching—the present study aims to provide unbiased estimates of the association between central stenosis severity and postoperative outcomes, with a particular focus on persistent residual leg pain, in frail elderly patients undergoing PTED for unilateral symptomatic LSS.

Methods

Study Design and Population

This single-center retrospective cohort study consecutively enrolled patients aged ≥80 years with symptomatic lumbar spinal stenosis treated at our institution from February 2022 to October 2024.The study was approved by the Institutional Review Board (approval number: KYLLKS20250202), and the requirement for informed consent was waived due to the retrospective nature of the study and the use of anonymized data. The reporting of this study follows the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.

Consecutive patients aged 75 years or older who underwent single-level percutaneous transforaminal endoscopic decompression (PTED) for unilateral symptomatic lumbar spinal stenosis (LSS) were screened for eligibility. Inclusion criteria were: (1) age ≥75 years; (2) preoperative FRAIL scale score ≥3, indicating frailty; (3) radiologically confirmed lumbar spinal stenosis on magnetic resonance imaging (MRI); (4) unilateral lower limb radicular pain as the dominant complaint; (5) failure of at least 3 months of structured conservative management; (6) completion of an ultrasound-guided diagnostic nerve root block confirming the symptomatic level; (7) absence of significant low back pain, defined as low back pain visual analogue scale (VAS) score <4 and lower than leg pain VAS score. Exclusion criteria included: (1) previous lumbar spine surgery; (2) acute spinal pathology (fracture, infection, malignancy); (3) concomitant neurological conditions that could confound symptom assessment; (4) severe hip or knee osteoarthritis based on radiographic

evaluation; (5) negative response to the diagnostic nerve root block; (6) American Society of Anesthesiologists physical status classification ≥4; (7) documented cognitive impairment; and (8) incomplete 12-month follow-up data.

Exposure Definition: Central Canal Stenosis Severity

All patients underwent preoperative lumbar magnetic resonance imaging (MRI) using a standardized protocol (1.5T or 3.0T scanner). Central canal stenosis severity was graded according to the Schizas classification system, which is based on the morphology of the dural sac and the ratio of cerebrospinal fluid (CSF) to nerve roots on axial T2-weighted images at the level of maximal stenosis.[14] For analysis, patients were dichotomized into two groups: non-severe stenosis (grades A–B) and severe stenosis (grades C–D). This cutoff is clinically meaningful as grades 3–4 represent loss of CSF signal and are considered "severe" in most studies.[13,15] Two independent spine surgeons, blinded to all clinical outcomes and patient identifiers, evaluated all MR images. Inter-rater reliability was assessed using Cohen's kappa coefficient (κ = 0.85, indicating excellent agreement). In borderline cases where initial independent readings differed between Schizas grades B and C, a consensus was reached through discussion. If consensus could not be achieved, a third senior spine surgeon made the final determination.

Outcome Measures

The primary outcome was persistent leg pain, defined based on the conceptual framework of postoperative pain trajectories following lumbar decompression. Consistent with previous studies examining postoperative neuropathic pain,[16,17] persistent pain was defined as the presence of a visual analogue scale (VAS) score for leg pain ≥4 (on a 0–10 scale) or the need for regular analgesic medication (≥3 days per week for more than one month) at all three follow-up time points: 3 months, 6 months, and 12 months after surgery. Information on analgesic use was collected via a structured follow-up interview (telephone or in-person) using a standardized questionnaire at each time point and cross-referenced with electronic pharmacy dispensing records. Medications qualifying as regular analgesic use included non-steroidal anti-inflammatory drugs (NSAIDs), gabapentinoids, or weak opioids (tramadol) specifically taken for leg pain. Routine prophylactic analgesics administered in the first postoperative month were excluded from this definition to avoid misclassifying normal postoperative recovery as persistent pain. This stringent definition was adopted to exclude transient postoperative pain related to surgical trauma (typically resolving within weeks) and to capture only symptoms that were not alleviated by the procedure. Patients who met the criteria at any single time point but not consistently were not considered as having persistent pain. Recurrent pain, defined as initial improvement followed by worsening after 6 months, was recorded separately but not included in the primary outcome due to its low incidence (n=3).

Covariates

We collected a comprehensive set of potential confounders based on clinical knowledge and previous literature. Covariates were categorized as:1. Demographic characteristics: age (years), sex (male/female), body mass index (BMI, kg/m^2).2. Clinical characteristics: American Society of Anesthesiologists (ASA) classification (II vs III), Charlson Comorbidity Index (CCI, continuous), FRAIL scale score (≥4 vs 3). The FRAIL scale includes five components: fatigue, resistance, ambulation, illnesses, and loss of weight; a score of 3–5 indicates frailty.[18] We dichotomized frailty as moderate-to-severe (≥4) vs mild (3) to better discriminate risk. 3. Anatomical characteristics: Pfirrmann disc degeneration grade at the operated level (grades 3, 4, or 5, treated as ordinal), pedicle rotation (present/absent), scoliosis (present/absent), kyphosis (present/absent), lateral recess stenosis (severe vs non-severe), foraminal stenosis (severe vs non-severe),[19] and index level (L4/5, L5/S1, L3/4). 4. Baseline functional status: preoperative VAS leg pain (continuous), preoperative ODI (continuous), and preoperative activities of daily living (ADL) score (continuous). All variables were assessed preoperatively and had no missing data.

Surgical Procedure

All PTED procedures were performed by two experienced spine surgeons using a standardized technique under local anesthesia with conscious sedation as previously described.[9] Under fluoroscopic guidance, a spinal needle was advanced to the ventral aspect of the superior articular process (SAP), and a working cannula was placed. Foraminoplasty was then

performed using a drill or trephine to resect the ventral SAP, enlarging the neural foramen and enabling safe entry into the lateral spinal canal. With the endoscope introduced, decompression was carried out in a symptom-targeted manner under direct visualization. This included resection of the hypertrophied ligamentum flavum overlying the symptomatic traversing and exiting nerve roots, removal of osteophytes at the superior pedicle and SAP impinging on the lateral recess, and extraction of pathological disc material or thickened posterior longitudinal ligament when present. Notably, the objective was to liberate the symptomatic nerve root; no attempt was made to excise the contralateral ligamentum flavum or to formally enlarge the central spinal canal. Adequacy of decompression was confirmed by direct visualization of free neural pulsation and mobilization of the nerve root, after which instruments were removed and the incision was closed.

Statistical Analysis

Statistical analyses were performed using Stata version 18.0 (Stata Corp, College Station, TX, USA). All tests were two-sided, and a P-value <0.05 was considered statistically significant, except where specified for exploratory analyses.

Descriptive Statistics

Continuous variables were summarized as mean ± standard deviation (SD) or median (interquartile range) as appropriate, and categorical variables as frequencies (percentages). Baseline characteristics were compared between stenosis severity groups using independent samples *t*-test or Mann–Whitney *U*-test for continuous variables, and chi-square test or Fisher's exact test for categorical variables. Standardized mean differences (SMD) were calculated to assess imbalance; an absolute SMD >0.1 was considered indicative of meaningful imbalance.

Propensity Score and Inverse Probability of Treatment Weighting (IPTW)

To account for confounding by indication in this observational study, we used inverse probability of treatment weighting (IPTW) based on the propensity score.[20] The propensity score—the probability of having severe stenosis given baseline covariates—was estimated using a multivariable logistic regression model that included all covariates listed in Table 1. From the estimated propensity scores, we derived stabilized inverse probability weights to reduce variability and improve

Table 1 Baseline Characteristics and Balance Assessment Before and After Inverse Probability of Treatment Weighting (IPTW)

Characteristic	Non-Severe Stenosis (n=93)	Severe Stenosis (n=59)	P-value	SMD Before Weighting	SMD After Weighting
Demographic Characteristics					
Age (years), mean ± SD	82.3 ± 4.2	82.0 ± 3.8	0.647	−0.077	−0.011
Male, n (%)	40 (43%)	33 (56%)	0.120	0.258	0.007
BMI (kg/m^2), mean ± SD	23.1 ± 3.2	23.2 ± 3.8	0.831	0.035	0.023
Clinical Characteristics and Scores					
ASA classification, n (%)			0.155	0.238	0.046
ASA II	44 (47%)	21 (36%)			
ASA III	49 (53%)	38 (64%)			
Charlson Comorbidity Index, mean ± SD	7.4 ± 1.5	7.3 ± 1.0	0.695	−0.068	0.002
Severe frailty (FRAIL score ≥4), n (%)	58 (62%)	41 (69%)	0.369	0.07	0.033
Preoperative VAS leg pain, mean ± SD	6.5 ± 0.5	6.6 ± 0.5	0.209	−0.009	0.087
Preoperative ODI, mean ± SD	67.8 ± 4.8	68.9 ± 5.9	0.233	0.195	0.055
Preoperative ADL, mean ± SD	61.1 ± 5.8	60.0 ± 6.1	0.274	−0.182	−0.073
Anatomical Characteristics					
Pfirrmann classification, n (%)			**0.008**	0.445	0.034
Mild (grade 3)	30 (32%)	13 (22%)			
Moderate (grade 4)	52 (56%)	27 (46%)			
Severe (grade 5)	11 (12%)	19 (32%)			
Index level L4/5, n (%)	70 (75%)	42 (71%)	0.578	0.157	0.053

(*Continued*)

Table 1 (Continued).

Characteristic	Non-Severe Stenosis (n=93)	Severe Stenosis (n=59)	P-value	SMD Before Weighting	SMD After Weighting
Pedicle rotation (present), n (%)	39 (42%)	32 (54%)	0.138	0.246	−0.016
Lateral recess stenosis (severe), n (%)	81 (87%)	54 (92%)	0.399	0.143	0.071
Foraminal stenosis (severe), n (%)	25 (27%)	19 (32%)	0.481	0.117	0.021
Spinal Deformity Characteristics					
Scoliosis (present), n (%)	29 (31%)	30 (51%)	**0.015**	0.400	0.016
Kyphosis (present), n (%)	22 (24%)	18 (31%)	0.350	0.154	0.011

Notes: Continuous variables are presented as mean ± standard deviation; categorical variables are presented as number (percentage). Group comparisons were performed using independent samples *t*-test for continuous variables and chi-square test for categorical variables. Bold P-values indicate P<0.05. All covariates achieved adequate balance after IPTW weighting (SMD <0.1).

Abbreviations: BMI, body mass index; ASA, American Society of Anesthesiologists; VAS, visual analogue scale; ODI, Oswestry Disability Index; ADL, activities of daily living; SMD, standardized mean difference.

efficiency. Weights were truncated at the 99th percentile to mitigate the influence of extreme values. Covariate balance after weighting was assessed using standardized mean differences (SMD) for each variable, with an absolute SMD <0.1 considered indicative of adequate balance.[21] The effective sample size (ESS) after weighting was calculated to quantify information loss. Weighted logistic regression with robust standard errors was then used to estimate the association between stenosis severity and residual pain.

Primary Outcome Analysis

The association between central canal stenosis severity and persistent residual leg pain was evaluated using weighted logistic regression with IPTW. Results are presented as adjusted odds ratios (aOR) with 95% confidence intervals (CI) and corresponding P-values. Robust standard errors were used to account for the weighting.

Sensitivity Analyses

To assess the robustness of the primary findings, we performed two sensitivity analyses:

Propensity score matching (PSM): Using a 1:1 nearest neighbor matching algorithm without replacement and a caliper of 0.2 times the standard deviation of the logit of the propensity score. Patients in the severe stenosis group were matched to those in the non-severe group based on the logit of the propensity score. Matching quality was assessed by calculating post-match SMD for all covariates; an SMD <0.1 indicated good balance. In the matched sample, we fitted a conditional logistic regression model accounting for matched pairs to estimate the OR for the exposure.

Multivariable logistic regression: In the original unweighted sample, we fitted a multivariable logistic regression model adjusting for a parsimonious set of clinically important covariates selected based on univariate associations (P<0.2) and clinical relevance. The final model included stenosis severity, FRAIL score (≥4 vs 3), pedicle rotation, scoliosis, and preoperative VAS leg pain. Model fit was assessed using the Hosmer-Lemeshow goodness-of-fit test and pseudo-R^2.

Longitudinal Analysis

To evaluate recovery trajectories over time, we used linear mixed models with random intercepts for each patient. Separate models were fitted for VAS leg pain and ODI scores as dependent variables. Fixed effects included stenosis severity group (severe vs non-severe), time (in weeks, treated as a continuous variable), and the group-by-time interaction. Time was coded as 0 (preoperative), 1 (1 week), 4 (1 month), 12 (3 months), 24 (6 months), and 52 (12 months). An unstructured covariance structure was assumed for the random effects. The significance of the group-by-time interaction term was used to test whether recovery trajectories differed between groups.

Additional Analyses

We performed univariate logistic regression analyses for all candidate risk factors and presented them in Supplementary Table S1 as exploratory findings. Given the limited number of events (n=33), we did not conduct extensive multivariable modeling beyond the prespecified sensitivity analyses to avoid overfitting.

Sample Size Considerations

With 152 patients and 33 events of the primary outcome, the study had 80% power at a two-sided α=0.05 to detect an odds ratio of approximately 2.5, assuming an equal distribution of exposure and a baseline event rate of 20% in the non-exposed group. The effective sample size after IPTW was 117.5, which still provided adequate power for the primary analysis.

Results

Study Population and Baseline Characteristics

A total of 152 frail elderly patients (mean age 82.2 ± 4.0 years, 48.0% male) who underwent PTED for unilateral symptomatic lumbar spinal stenosis were included in the analysis (Figure 1). Based on preoperative MRI assessment, 59 patients (38.8%) were classified as having severe central canal stenosis (Schizas grades C–D), while 93 patients (61.2%) had non-severe stenosis (grades A–B). Baseline characteristics of the study population are presented in Table 1. Before inverse probability of treatment weighting (IPTW), several covariates showed imbalance between groups. Patients with severe stenosis had a higher prevalence of scoliosis (51% vs 31%, P=0.015) and more advanced disc degeneration (Pfirrmann grade 5: 32% vs 12%, P=0.008). The standardized mean differences (SMD) for these variables exceeded 0.1, indicating substantial imbalance (scoliosis: SMD=0.400; Pfirrmann classification: SMD=0.399). After applying IPTW with

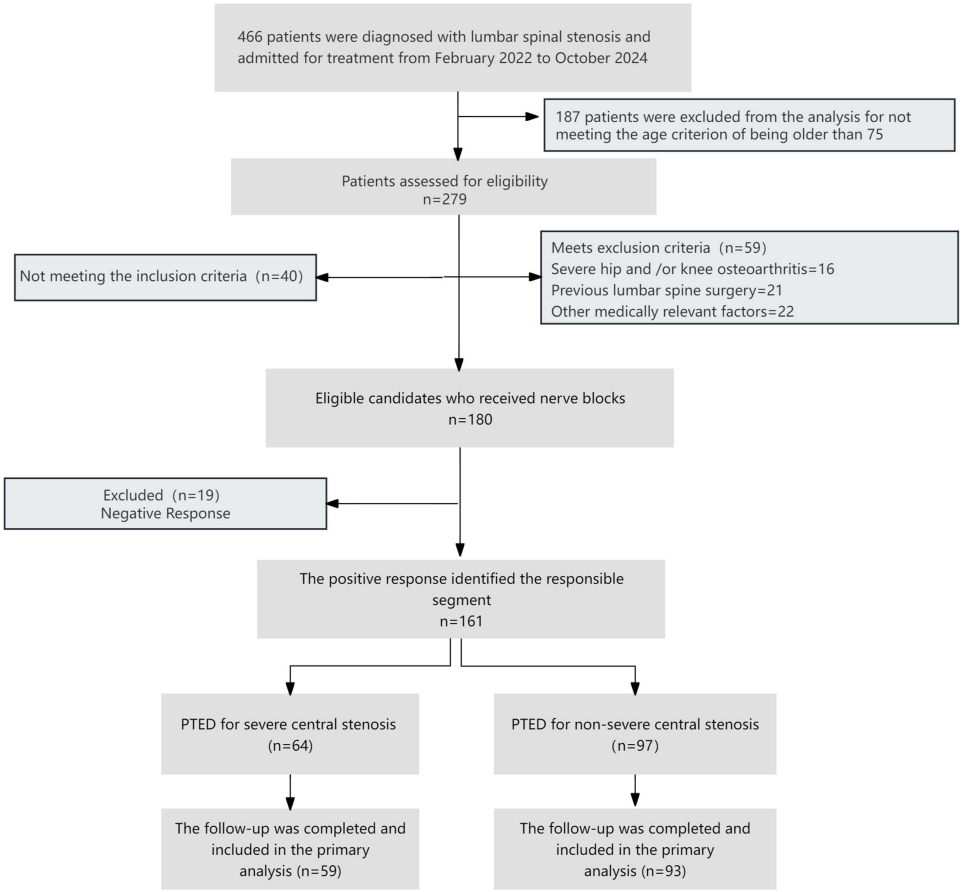

Figure 1 Patient flow diagram. Of 152 frail elderly patients undergoing PTED for unilateral symptomatic lumbar spinal stenosis, 93 had non-severe (Schizas grades 0–2) and 59 had severe (grades 3–4) central canal stenosis.

https://doi.org/10.2147/JPR.S604803

truncation at the 99th percentile, excellent balance was achieved across all measured covariates, as illustrated in Figure 2. All post-weighting SMD values were below 0.1 (range: 0.011–0.073), with the largest improvements observed for scoliosis (SMD decreased from 0.400 to 0.016) and pedicle rotation (SMD decreased from 0.246 to –0.016). Prior to truncation, the estimated inverse probability weights ranged from 1.07 to 8.27. After truncation at the 99th percentile, the range was narrowed to 1.07–6.94. The effective sample size after weighting was 117.5, representing 77.3% of the original sample.

Primary Outcome: Persistent Residual Leg Pain

At 12 months postoperatively, 33 patients (21.7%) met the definition of persistent residual leg pain, defined as VAS leg pain ≥4 or regular analgesic use at all three follow-up time points (3, 6, and 12 months). The distribution was similar between groups: 20 patients (21.5%) in the non-severe stenosis group and 13 patients (22.0%) in the severe stenosis group.

Table 2 summarizes the association between central canal stenosis severity and persistent residual leg pain using multiple analytical approaches. In univariate analysis, severe stenosis showed no significant association with persistent pain (OR=1.03, 95% CI: 0.48–2.22, P=0.939). Several other factors demonstrated strong univariate associations, most notably FRAIL score ≥4 (OR=15.40, 95% CI: 3.53–67.17, P<0.001), scoliosis (OR=4.43, 95% CI: 2.01–9.78, P<0.001), and pedicle rotation (OR=4.09, 95% CI: 1.79–9.34, P=0.001).

In the multivariable logistic regression model adjusting for FRAIL score, anatomical factors (pedicle rotation, scoliosis), and baseline pain level, severe stenosis remained non-significant (aOR=0.56, 95% CI: 0.21–1.51, P=0.250). The strongest independent predictor was FRAIL score ≥4 (aOR=15.57, 95% CI: 3.32–73.11, P=0.001). Preoperative VAS leg pain showed a protective effect (aOR=0.35 per point, 95% CI: 0.13–0.92, P=0.034). The model demonstrated good fit (Hosmer-Lemeshow test: P=0.985, pseudo-R^2=0.265).

Causal Inference and Sensitivity Analyses

The IPTW-adjusted analysis, which created a balanced pseudo-population simulating a randomized trial, confirmed the absence of significant association between stenosis severity and persistent pain (aOR=0.63, 95% CI: 0.26–1.52, P=0.306) (Table 2).

Propensity score matching as a sensitivity analysis yielded consistent results. After 1:1 nearest neighbor matching with a caliper of 0.2, 40 matched pairs (80 patients) were obtained, representing 52.6% of the original sample. The matched sample showed excellent balance with a post-match mean bias of 9.1% (compared to 17.2% pre-match). In the matched cohort, severe stenosis was associated with a non-significant reduction in persistent pain risk (OR=0.38, 95% CI: 0.13–1.07, P=0.066).

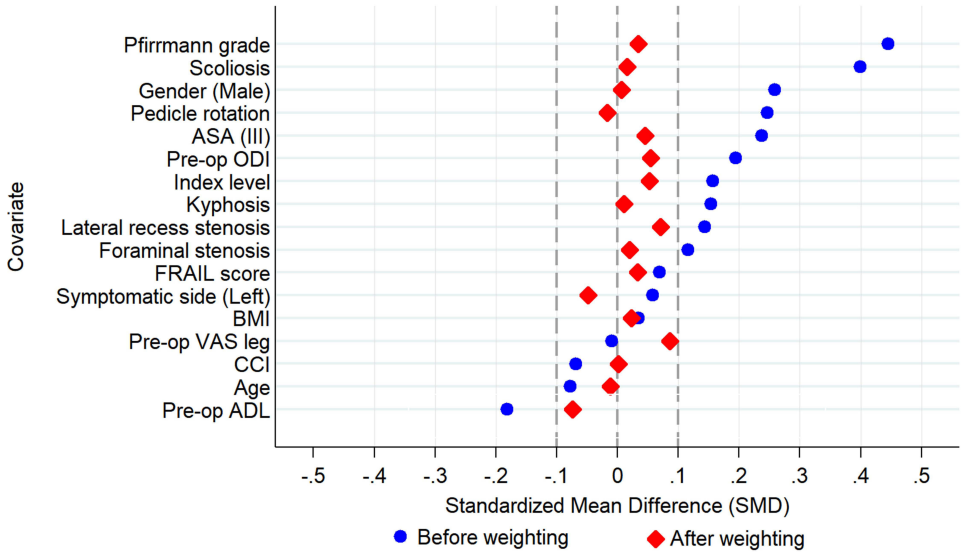

Figure 2 Covariate balance before and after inverse probability of treatment weighting (IPTW). Standardized mean differences (SMD) for all baseline covariates are shown before (blue circles) and after (red diamonds) weighting. Dashed lines indicate adequate balance (SMD = ±0.1). All covariates achieved SMD <0.1 after weighting.

https://doi.org/10.2147/JPR.S604803

Table 2 Association Between Central Canal Stenosis Severity and Other Factors with Postoperative Residual Leg Pain

Analysis Method	Variable	OR	95% Confidence Interval	P-value	Notes
Univariate Analysis					
	Central canal stenosis (severe)	1.03	0.48–2.22	0.939	Unadjusted
	FRAIL score ≥4 (vs 3)	15.40	3.53–67.17	<0.001	Unadjusted
	Scoliosis (present)	4.43	2.01–9.78	<0.001	Unadjusted
	Pedicle rotation (present)	4.09	1.79–9.34	0.001	Unadjusted
	Preoperative VAS leg (per point)	0.36	0.15–0.84	0.017	Per-point reduction in risk
Multivariable Adjusted Analysis					
	Central canal stenosis (severe)	0.56	0.21–1.51	0.250	Adjusted for FRAIL score, anatomical factors, and baseline pain
	FRAIL score ≥4 (vs 3)	15.57	3.32–73.11	<0.001	Adjusted
	Scoliosis (present)	3.59	0.93–13.84	0.064	Adjusted
	Pedicle rotation (present)	2.34	0.62–8.82	0.211	Adjusted
	Preoperative VAS leg (per point)	0.35	0.13–0.92	0.034	Adjusted
Causal Inference Methods					
IPTW-adjusted analysis	Central canal stenosis (severe)	0.63	0.26–1.52	0.306	All covariates balanced (SMD <0.1) after weighting
Propensity score matched analysis	Central canal stenosis (severe)	0.38	0.13–1.07	0.066	40 matched pairs, post-match mean bias 9.1%

Notes: 1. Univariate analyses were performed using logistic regression without adjustment. 2. The multivariable logistic regression model was adjusted for variables selected based on clinical importance and univariate association (P<0.2): FRAIL score (≥4 vs 3), pedicle rotation (present vs absent), scoliosis (present vs absent), and preoperative VAS leg pain (continuous). Model fit: Hosmer-Lemeshow test P=0.985, pseudo R^2=0.265. 3. IPTW analysis: Weights were derived from a propensity score model that included all baseline covariates listed in Table 1. Weights were truncated at the 99th percentile to mitigate the influence of extreme values. Balance was achieved for all covariates (post-weighting SMD <0.1; effective sample size=117.5). 4. PSM analysis: 1:1 nearest neighbor matching with a caliper of 0.2 was performed, resulting in 40 matched pairs (80 patients). The matched sample showed adequate balance (post-match mean bias 9.1%). 5. All analyses consistently demonstrated no significant association between central canal stenosis severity and residual leg pain.

Abbreviations: OR, odds ratio; CI, confidence interval; IPTW, inverse probability of treatment weighting; SMD, standardized mean difference; PSM, propensity score matching.

The consistent direction and magnitude of effect estimates across different analytical methods support the robustness of the primary finding that severe central canal stenosis does not increase the risk of persistent residual leg pain after PTED.

Longitudinal Recovery Trajectories

Table 3 presents the results from linear mixed models analyzing longitudinal changes in pain and functional scores over the 12-month follow-up period. Both VAS leg pain and ODI scores showed significant improvement over time. VAS scores decreased by 0.043 points per week (95% CI: –0.048 to –0.037, P<0.001), and ODI scores decreased by 0.528 points per week (95% CI: –0.578 to –0.479, P<0.001).

Critically, the group × time interaction terms were not significant for either outcome measure (VAS: coefficient=0.003, P=0.534; ODI: coefficient=–0.001, P=0.975). This indicates that patients with severe and non-severe central canal stenosis experienced similar recovery trajectories for both pain relief and functional improvement throughout the

Table 3 Linear Mixed Models for Longitudinal Changes in Pain and Functional Scores

Parameter	VAS Leg Pain Score		ODI Functional Score	
Fixed Effects	**Coefficient (SE)**	**P-value**	**Coefficient (SE)**	**P-value**
Central canal stenosis (severe)	0.001 (0.128)	0.996	1.918 (1.411)	0.174
Time (weeks)	−0.043 (0.003)	<0.001	−0.528 (0.025)	<0.001
Stenosis × Time interaction	0.003 (0.005)	0.535	−0.001 (0.040)	0.975
Intercept	4.588 (0.079)	<0.001	52.949 (0.879)	<0.001
Random Effects				
Between-patient variance (SE)	0.144 (0.048)		38.179 (6.742)	
Residual variance (SE)	1.547 (0.079)		117.325 (6.027)	

Notes: 1. Linear mixed models were fitted with fixed effects for group (severe vs non-severe stenosis), time (weeks, treated as continuous), and group × time interaction, and a random intercept for each patient. Time was coded as 0 (preoperative), 1 (1 week), 4 (1 month), 12 (3 months), 24 (6 months), and 52 (12 months).2. The models included 152 patients with 6 time points each (912 total observations). The non-significant group × time interactions (VAS: P=0.535; ODI: P=0.975) indicate that the recovery trajectories did not differ significantly between groups.3. Variance components are reported as estimates with standard errors. The between-patient variance represents variability in baseline scores across individuals, while residual variance represents within-individual variability over time.
Abbreviations: VAS, visual analogue scale; ODI, Oswestry Disability Index; SE, standard error.

postoperative period. The similarity in recovery patterns is visually depicted in Figure 3 (VAS leg pain) and Figure 4 (ODI). Only three patients (2.0%) experienced recurrent pain after initial improvement, none of whom underwent reoperation; these cases were not classified as persistent pain in the primary analysis.

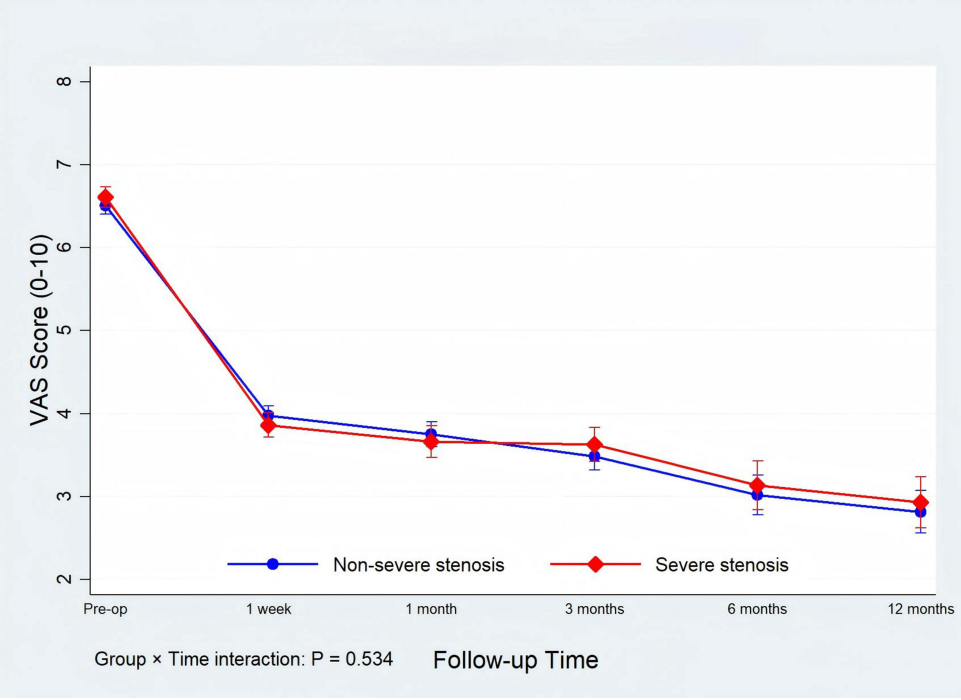

Figure 3 Longitudinal trajectories of VAS leg pain scores over 12 months postoperatively, stratified by stenosis severity (mean ± SE). Both groups showed significant improvement over time (time effect: P<0.001). The group × time interaction was not significant (P=0.535), indicating similar recovery trajectories.
Abbreviations: VAS, visual analogue scale; SE, standard error.

https://doi.org/10.2147/JPR.S604803

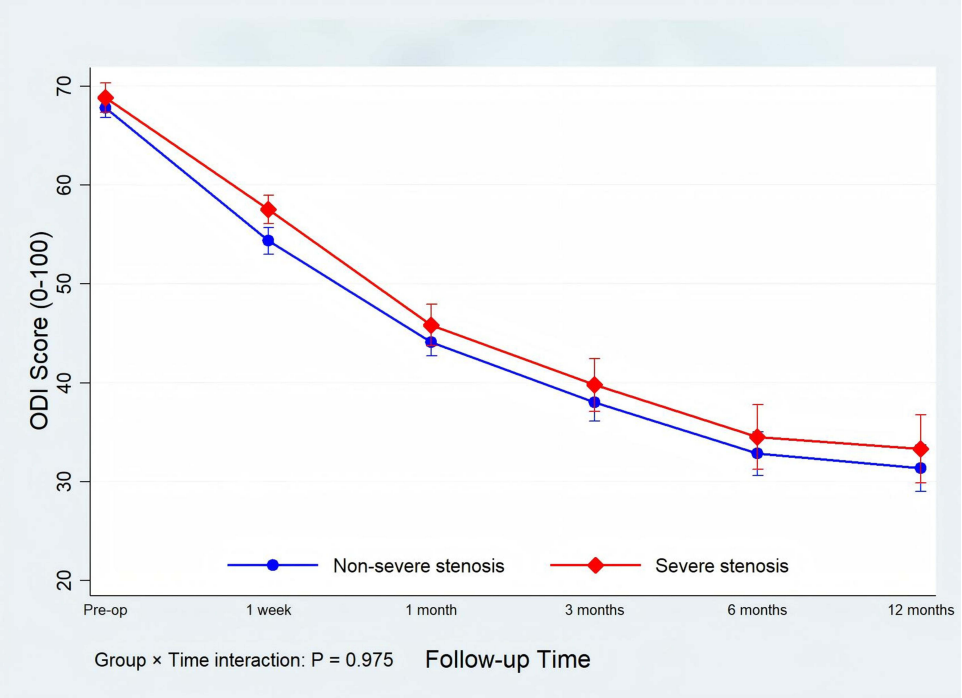

Figure 4 Longitudinal trajectories of ODI scores over 12 months postoperatively, stratified by stenosis severity (mean ± SE). Both groups showed significant functional improvement over time (time effect: P<0.001). The group × time interaction was not significant (P=0.975), indicating similar recovery trajectories.
Abbreviations: ODI, Oswestry Disability Index; SE, standard error.

Exploratory Univariate Analyses

Exploratory univariate analyses of all candidate risk factors are presented in Supplementary Table S1. Several variables showed significant unadjusted associations with persistent residual leg pain beyond those included in the primary multivariable model, including Charlson Comorbidity Index (OR=1.39 per point, P=0.019), ASA III classification (OR=4.43, P=0.002), Pfirrmann grade (OR=4.29 per grade, P<0.001), preoperative ODI (OR=1.18 per point, P<0.001), and preoperative ADL (OR=0.72 per point, P<0.001). These exploratory findings informed the selection of covariates for the primary multivariable model and highlight potential risk factors warranting further investigation in larger studies.

Discussion

With the global aging population, effective treatment of lumbar spinal stenosis in older adults has become a significant clinical challenge.[3] Accumulating evidence has confirmed the important role of frailty in perioperative complications, recovery trajectory, and surgical outcomes in elderly patients undergoing spinal surgery.[4,22] As a classic minimally invasive decompression technique, percutaneous transforaminal endoscopic decompression (PTED) under local anesthesia has demonstrated safety and efficacy in treating lumbar spinal stenosis in older adults.[6,7] However, whether frailty status influences surgical outcomes and recovery in this specific population, and whether severe central canal stenosis on imaging compromises the adequacy of unilateral transforaminal decompression—manifesting as early symptom recurrence or persistent long-term pain—has not been established. Fortunately, in clinical practice, frail elderly patients with varying degrees of central canal stenosis show high acceptance of PTED under local anesthesia, providing sufficient cases for observational study.

In this propensity score-weighted cohort study of 152 frail elderly patients with unilateral radicular pain undergoing PTED, we found that severe central canal stenosis was not associated with increased risk of persistent residual leg pain. This finding was consistent across multiple analytical approaches, including IPTW (OR=0.63, 95% CI 0.26–1.52), PSM (OR=0.38, 95% CI 0.13–1.07), and multivariable adjustment (OR=0.56, 95% CI 0.21–1.51). Longitudinal analysis revealed similar recovery trajectories between severe and non-severe stenosis groups for both pain (VAS) and functional

(ODI) outcomes. Notably, patient frailty (FRAIL score ≥4) emerged as the strongest independent predictor of persistent pain (OR=15.57), far outweighing the contribution of central canal morphology.

Our core null finding—that preoperative central canal stenosis severity does not predict postoperative residual leg pain—receives direct validation from high-quality randomized controlled trial data.[23] In a secondary analysis of 704 patients from the NORDSTEN two randomized controlled trials of lumbar spinal stenosis surgery, Nomeland et al similarly found no significant association between Schizas grade (C/D vs A/B) and poor prognosis at 2 years post-operatively (OR=0.72, 95% CI 0.45–1.15). This finding challenges the traditional notion that "more severe imaging stenosis predicts worse surgical outcomes" and supports prioritizing clinical symptoms over imaging severity in surgical decision-making. Notably, the NORDSTEN study also identified three independent prognostic factors: radicular pain duration >12 months (OR=2.58), psychological distress (OR=1.60), and advanced disc degeneration (OR=1.98).[23] These factors are all "patient-related factors" or "non-stenosis-related imaging factors" rather than central canal stenosis itself, complementing our conclusions.

Why does preoperative frailty predict postoperative pain outcomes more strongly than imaging severity? A systematic review and meta-analysis by Saraiva et al published provides important mechanistic insights. The study included five prospective longitudinal studies with 13,120 participants and found that older adults with persistent pain at baseline had a 2.22-fold increased risk of developing frailty during follow-up (pooled RR=2.22, 95% CI 1.14–4.29).[24] Integrating these findings, we can construct a causal framework for understanding prognosis in elderly patients with lumbar spinal stenosis: chronic neurogenic pain accelerates the frailty process through multiple mechanisms—reduced activity leading to muscle loss and functional decline, pain-related psychological distress affecting pain perception and rehabilitation adherence, and decreased nutritional intake contributing to weight loss and diminished energy reserves. Preoperative frailty, in turn, impairs the patient's ability to cope with surgical stress, increasing the risk of persistent postoperative pain. This framework aligns closely with the predictive value of "psychological distress" and "symptom duration" identified in the NORDSTEN studies.[23]

Building on this mechanistic understanding, the clinical utility of frailty screening in this population is further supported by prospective evidence. Song et al validated the predictive value of the FRAIL scale in 207 geriatric spine surgery patients, finding that frailty (≥3 points) was an independent risk factor for postoperative complications (OR=4.80) and poor recovery (OR=6.43), while age itself had no independent predictive value.[25] This reinforces our conclusion that patient systemic factors—assessed by a simple 5-item scale—outweigh chronological age and local imaging findings in determining surgical outcomes.

Additionally, postoperative residual leg pain may be heterogeneous and requires differentiation from "post-decompressive neuropathy" (PDN). The concept of PDN, defined as new-onset neuropathic pain in the lower extremities that is qualitatively different from preoperative symptoms after lumbar decompression, offers a novel perspective for understanding postoperative pain.[17] In their cohort, the incidence of PDN was as high as 77%, with typical symptom characteristics including non-dermatomal distribution, nocturnal exacerbation (often awakening patients), pure sensory symptoms, and no exacerbation with activity. Notably, 81% of early-onset PDN cases resolved spontaneously within one year postoperatively, which is highly consistent with our observation that only 2.0% of patients experienced recurrence and none required reoperation. The mechanistic hypothesis proposed by Boakye et al—surgical trauma-induced neuroinflammation and demyelinating changes[17] —resonates with our mechanistic explanation: frail patients, due to diminished physiological reserve and immune dysregulation, may be more susceptible to surgical trauma-induced neuroinflammatory responses and more likely to develop persistent neuropathic pain. This recognition of postoperative pain heterogeneity underscores the importance of accurate symptom characterization, which complements our main finding that imaging severity alone is insufficient for prognostication.

These findings challenge the prevailing clinical assumption that severe central canal stenosis—particularly when visualized on MRI as loss of cerebrospinal fluid signal—may be inadequately addressed by the transforaminal approach, potentially leading to residual symptoms and prompting surgeons to choose more extensive decompressive procedures. Our results suggest that this concern may be unwarranted. Because PTED targets the lateral recess and exiting nerve root —the primary pain generators in unilateral radiculopathy—rather than the central canal, the adequacy of decompression depends on lateral pathology, not on the degree of central narrowing. The lack of association between stenosis severity

and persistent pain further supports that limited, symptom-focused decompression via PTED can achieve comparable outcomes regardless of the degree of central canal narrowing. Synthesizing evidence from multiple studies,[15,26,27] we propose that surgical decision-making in elderly patients with lumbar spinal stenosis should prioritize patient systemic factors—frailty, psychological distress, symptom duration—over the degree of central canal stenosis on imaging. This has important implications for frail elderly patients, for whom minimizing procedural invasiveness is paramount. Prioritizing a symptom-guided over an image-guided approach could spare many patients from more invasive surgeries with higher perioperative risks.

Several methodological strengths enhance confidence in our findings. IPTW effectively balanced 16 baseline covariates between groups (all SMD<0.1), approximating randomized trial conditions and reducing confounding by indication. Consistency across IPTW, PSM, and multivariable adjustment further supports robustness. Our stringent definition of persistent pain—requiring symptoms at 3, 6, and 12 months—captures clinically meaningful treatment failure rather than transient discomfort, while longitudinal trajectory analysis provides a comprehensive view of recovery patterns.

Several limitations should be acknowledged. First, residual confounding from unmeasured variables cannot be entirely excluded despite rigorous adjustment. Second, single-center design may limit generalizability. Third, sample size, while adequate for detecting moderate effects, may be insufficient for extensive subgroup analyses. Fourth, our definition of persistent pain, while clinically meaningful, is not a validated outcome measure. Fifth, absence of postoperative imaging prevents correlation of surgical adequacy with outcomes. Sixth, all procedures were performed by two high-volume endoscopic spine surgeons at a single center. Given the well-documented learning curve for PTED, the favorable outcomes observed—particularly the low rates of persistent pain and reoperation—may not be fully generalizable to surgeons or centers in the early phases of endoscopic adoption. Finally, 12-month follow-up may not capture longer-term outcomes.

Conclusion

In conclusion, preoperative central canal stenosis severity does not predict persistent residual leg pain or recovery trajectory after PTED in frail elderly patients. These findings support a shift toward symptom-guided rather than image-guided surgical decision-making in this vulnerable population. Patient frailty, rather than the degree of central canal narrowing, appears to be a more important determinant of postoperative pain outcomes.

Research Ethics

This study was approved by the Ethics Committee of Suining Central Hospital (Approval No.: KYLLKS20250202), and all procedures complied with the ethical principles of the Declaration of Helsinki. Written informed consent was obtained from all participants.

Acknowledgments

The first author extends heartfelt thanks to Ms. Xue-Wen Yin for her unwavering personal support and assistance with project coordination, which greatly facilitated the completion of this work.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Funding

This study received no specific funding.

Disclosure

The authors report no conflicts of interest in this work.

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