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Original Article

Development and validation of a predictive model for postoperative residual low back pain following percutaneous kyphoplasty or percutaneous vertebroplasty

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Abstract: Objective: To identify risk factors for persistent postoperative low back pain in patients undergoing percutaneous kyphoplasty (PKP) or percutaneous vertebroplasty (PVP) and develop a predictive nomogram model. Method: This retrospective study included 749 patients with osteoporotic vertebral compression fractures (OVCF), who were allocated into a modeling cohort (n = 524) and a validation cohort (n = 225). Patients with a Visual Analog Scale (VAS) score > 4 at one month postoperatively were classified into the residual low back pain group, while the rest were classified as the normal group. Univariate and multivariate logistic regression analyses were performed to identify factors associated with postoperative back pain, and subsequently, a nomogram model was constructed for predictive validation. Results: In the modeling cohort, 61 patients reported persistent low back pain at one month after surgery. According to univariate and LASSO-Logistic regression analyses, the number of fractured vertebrae, bone cement distribution, bone cement leakage, 5-hydroxyvitamin D_3 [25-(OH)D_3] levels, concomitant lumbar and dorsal fascia injury, and Exercise Activity Questionnaire score (EAQ) score were identified as independent predictors ($P < 0.05$), representing the main factors influencing residual low back pain in patients after PKP/PVP. In the modeling cohort, the area under the receiver operating characteristic (ROC) curve (AUC) was 0.837, and the C-index of the calibration curve was 0.837 (95% CI, 0.719-0.883). In the validation cohort, AUC was 0.858, and the C-index of the calibration curve was 0.858 (95% CI, 0.802-0.914). Conclusion: Number of fractured vertebrae, insufficient bone cement distribution over the fracture line, bone cement leakage, serum 25-(OH)D_3 level, combined lumbar and dorsal fascia injury, and EAQ score were independent risk factors for residual low back pain in patients after PKP/PVP. The nomogram predictive model incorporating these factors demonstrated good predictive performance in internal validation.

Keywords: Residual low back pain, risk factor, prediction model, verification

Introduction

Osteoporotic vertebral compression fractures (OVCFs) have been on the rise due to the accelerating pace of population aging, and have become a major public health concern, particularly for the elderly [1]. The main risk factors for OVCF results from the interaction between decreased bone strength and increased external risks, including age, sex, genetic predisposition, low bone mineral density, and abnormal bone metabolism.

Percutaneous kyphoplasty (PKP) and percutaneous vertebroplasty (PVP) are minimally invasive surgical techniques widely applied in treating OVCFs. These procedures offer several advantages, including minimal surgical trauma, rapid pain relief, effective restoration of vertebral height, and correction of kyphosis deformity, and have been widely adopted in clinical practice [2]. The primary indications for PKP/PVP include osteoporotic vertebral compression fractures, persistent pain from old vertebral fractures, and severe pain caused by vertebral metastatic tumors. Although the indications for PKP and PVP are largely similar, PKP is superior to PVP for restoring vertebral height and correcting kyphosis. Specifically, PKP can better restore vertebral height and reduce the risk

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of bone cement leakage through balloon expansion within the vertebra [3].

Although PKP/PVP effectively relieves severe pain in most patients, some continue to experience lower back pain after the procedure, known as residual postoperative low back pain, which severely impairs patients' quality of life [4, 5]. Persistent postoperative pain can hinder early functional recovery, prolong hospitalization, lead to functional limitations, reduce patients' overall living quality, and increase the risk of subsequent fractures and psychological disorders. Therefore, it is a key factor limiting both surgical efficacy and patient satisfaction [6].

Currently, the pathophysiologic mechanisms underlying persistent low back pain after PKP or PVP remain incompletely clarified. Emerging evidence indicates that this condition arises from a complex interplay of multiple contributors, including procedure-related factors, patient-specific characteristics, neuroplastic changes in pain processing, and psychosocial determinants [7-9]. At present, no reliable predictive model exists that integrate multidimensional information for personalized risk assessment. In addition, objective and quantitative tools for perioperative risk assessment are lacking.

This retrospective study analyzed clinical data from OVCF patients who underwent PKP/PVP. It systematically examined multiple variables - including patient demographics, clinical and imaging characteristics, surgical factors - and evaluated their associations with postoperative residual low back pain. Key independent predictors of persistent low back pain were identified, and a simple, clinically applicable, and interpretable predictive model was developed to provide evidence-based support for risk stratification and individualized perioperative decision-making. By enabling early identification of high-risk patients, this model aims to optimize perioperative management in OVCF patients and improve long-term functional outcomes.

Materials and methods

Research subjects

This retrospective study included 749 cases with OVCF treated at our institution from March 2018 to March 2025. Patients were assigned to a modeling cohort (70%, 524 patients) and a validation cohort (30%, 225 patients). The study protocol was approved by the Ethics Committee of Dongguan First Hospital Affiliated to Guangdong Medical University.

Inclusion criteria

(1) Diagnosis of OVCF according to the "Expert Consensus on the Diagnosis, Treatment, and Management of Osteoporotic Vertebral Compression Fractures". (2) Receipt of PKP or PVP as first-time surgical procedure. (3) Complete clinical and imaging data available. (4) A postoperative follow-up period of at least 3 months. (5) Receipt of PVP and PKP in accordance with standardized surgical protocols, including indications, operative techniques, and perioperative management of complications.

Exclusion criteria

(1) Non-osteoporotic fractures, such as acute comminuted fractures. (2) Severe intraoperative cement leakage causing nerve root or spinal cord compression and requiring revision surgery. (3) Confirmed intraoperative infection or occurrence of a new fracture at a different spinal segment postoperatively. (4) Severe spinal disorders, including ankylosing spondylitis, severe lumbar spondylolisthesis, spinal stenosis, or degenerative scoliosis. (5) Concurrent malignant tumors. (6) Severe dysfunction of major organs, including heart, liver, lungs, and kidneys. (7) Severe mental illness, cognitive impairment, or chronic opioid dependence.

Assessment criteria for persistent low back pain

Postoperative pain was assessed using the Visual Analogue Scale (VAS) at the one-month postoperative follow-up. The VAS score ranges from 0 to 10, with 0 indicating no pain and 10 indicating the most severe pain. Persistent low back pain was defined as a VAS score > 4.

Monitoring of indicators

Patient data, including sex, age, course of illness, body mass index (BMI), smoking history, alcohol consumption history, educational level, comorbidities (hypertension, diabetes, hyper-

lipidemia, chronic obstructive pulmonary disease [COPD]), bone mineral density [T-score], volume of bone cement injected, duration of surgery, postoperative vertebral height recovery rate, number of fractured vertebrae, surgical puncture approach, presence of concomitant lumbosacral fascia injury, bone cement distribution, bone cement leakage, 25-hydroxyvitamin D_3 [25(OH)D_3] levels, osteocalcin (BGP), parathyroid hormone (PTH), white blood cell (WBC) count, albumin (Alb), and Exercise Activity Questionnaire (EAQ) score, were all acquired from the institutional information system.

Postoperative vertebral height recovery rate: Patients underwent standard anteroposterior and lateral X-ray examinations of the thoracolumbar spine preoperatively and on postoperative day 3. Vertebral height was measured using the anterior vertebral height (AvH) method. On the lateral X-ray film, the vertical distance between the upper and lower endplates of the anterior edge of the injured vertebra was measured. Postoperative vertebral recovery rate (%) = (Postoperative AvH - Preoperative AvH)/(Expected normal height - Preoperative AvH) × 100%.

Surgical puncture: According to the puncture path guided by intraoperative C-arm fluoroscopy, puncture approaches were classified as unilateral transpedicular approach (unilateral) or bilateral transpedicular approach (bilateral).

Lumbar paraspinal fascia injury was evaluated through preoperative lumbar MRI using T2-weighted fat-suppressed (T2WI-FS) or short tau inversion recovery (STIR) sequences. Patchy or cord-like high-signal areas in the lumbar paraspinal fascia posterior to the injured vertebra indicated edema, hemorrhage, or inflammatory exudation within the fascia, corresponding to the injured vertebral segment.

Bone cement distribution and leakage: Postoperative plain CT scans of the thoracolumbar spine and three-dimensional reconstruction were performed to evaluate cement distribution and leakage. Distribution was assessed based on whether the cement adequately covered the fracture line. Bone cement leakage was defined as extrusion beyond the cortical bone boundary of the injured vertebra. The leakage site was determined based on CT images.

Statistical analysis

All statistical analyses were performed using SPSS 29.0. Measured data were expressed as mean ± standard deviation ($\bar{x} \pm s$), and counted data were presented as counts and percentages. Univariate and multivariate Logistic regression analyses were conducted to identify factors associated with postoperative residual low back pain. Based on independent predictors identified by multivariate logistic regression, a visual nomogram prediction model was constructed using the rms package in R software (version 4.2.1). For each patient, the corresponding score for each predictor was determined according to the specific value or classifications. The total score was then calculated by adding up all individual scores, and mapped to the prediction axis to estimate the probability of postoperative residual low back pain. The predictive performance of the nomogram was assessed using receiver operating characteristic (ROC) curve analysis. Statistical significance was defined as $P < 0.05$.

Results

Comparison of baseline data between modeling and validation cohorts

Comparison of baseline data between the modeling and validation cohorts revealed no significant differences (P > 0.05; **Table 1**), indicating good comparability between the two groups.

Baseline data comparison: residual low back pain group versus non-residual low back pain group in the modeling group

In the modeling cohort, 108 patients experienced residual low back pain at one month after surgery. Univariate analysis (**Table 2**) revealed significant differences in bone mineral density, bone cement volume, postoperative vertebral height recovery rate, number of fractured vertebrae, presence of concomitant lumbar fascia injury, bone cement distribution, cement leakage, 25-(OH)D_3 levels, BGP, PTH, and EAQ scores between the residual low back pain group and the non-residual low back pain group ($P < 0.05$).

Table 1. Comparison of baseline characteristics between the two groups

Baseline data	Modeling cohort (n = 524)	Validation cohort (n = 225)	t/χ^2	*P*
Sex				
Male	216 (41.22)	98 (43.56)	0.352	0.553
Female	308 (58.78)	127 (56.44)		
Age (years, $\bar{x} \pm s$)	62.21±9.73	62.83±11.26	0.762	0.447
Course of the disease (d, $\bar{x} \pm s$)	6.02±2.55	6.26±2.73	1.159	0.248
BMI (kg/m^2, $\bar{x} \pm s$)	22.43±2.64	22.17±3.10	1.171	0.242
History of Smoking [n (%)]				
Yes	151 (28.82)	68 (30.22)	0.150	0.698
No	373 (71.18)	157 (69.78)		
History of Alcohol Consumption [n (%)]				
Yes	105 (20.04)	49 (21.78)	0.292	0.589
No	419 (79.96)	176 (78.22)		
Educational background				
Junior high school or below	312 (59.54)	139 (61.78)	0.328	0.567
High school or higher	212 (40.46)	86 (38.22)		
Hypertension [n (%)]				
Yes	180 (34.56)	83 (36.89)	0.445	0.505
No	344 (65.44)	142 (63.11)		
Diabetes [n (%)]				
Yes	134 (22.57)	62 (27.56)	0.320	0.571
No	390 (77.43)	163 (72.44)		
Hyperlipidemia [n (%)]				
Yes	128 (24.57)	59 (26.22)	0.271	0.603
No	396 (75.43)	166 (73.78)		
COPD [n (%)]				
Yes	82 (15.65)	31 (13.78)	0.430	0.512
No	442 (84.35)	194 (86.22)		
Surgical approach				
PKP	399 (76.15)	162 (72.00)	1.439	0.230
PVP	125 (23.85)	63 (28.00)		
Bone density (T-score) ($\bar{x} \pm s$)	-2.34±0.41	-2.44±0.39	3.105	0.002
Volume of bone cement injected (ml, $\bar{x} \pm s$)	3.19±0.43	3.23±0.55	1.070	0.285
Duration of surgery (min, $\bar{x} \pm s$)	52.61±13.77	54.58±27.40	1.307	0.192
Postoperative restoration rate of vertebral body height (%, $\bar{x} \pm s$)	42.18±5.03	43.73±8.10	3.180	0.001
Number of fractured vertebrae				
1	261 (49.81)	106 (47.11)	0.459	0.493
≥ 2	263 (50.19)	119 (52.89)		
Surgical Puncture Approach				
Unilateral	212 (40.46)	104 (46.22)	2.144	0.143
Bilateral	312 (59.54)	121 (53.78)		
Combined with lumbar and dorsal fascia injury [n (%)]				
Yes	180 (34.35)	73 (32.44)	0.256	0.613
No	344 (65.65)	152 (67.56)		
The distribution of bone cement				
Not covered the fracture line	124 (23.66)	58 (25.77)	0.382	0.536
Covered the fracture line	400 (76.34)	167 (74.23)		
Bone cement leakage				
Yes	168 (32.06)	67 (29.78)	0.381	0.537
No	356 (67.94)	158 (70.22)		

Level of 25-(OH)D_3 (μg/L, $\bar{x} \pm s$)	13.90±1.95	14.52±2.18	3.848	0.000
BGP (ng/ml, $\bar{x} \pm s$)	14.10±2.02	14.58±1.97	3.003	0.002
PTH (ng/ml, $\bar{x} \pm s$)	8.66±0.79	8.97±1.02	4.494	0.000
WBC (10^9/L, $\bar{x} \pm s$)	6.39±1.39	6.54±1.52	1.316	0.189
Alb (g/L, $\bar{x} \pm s$)	50.25±6.83	51.12±12.35	1.233	0.218
EAQ Score (point, $\bar{x} \pm s$)	32.97±3.88	35.62±5.48	7.520	0.000

Note: COPD: Chronic obstructive pulmonary disease. PKP: Percutaneous kyphoplasty. PVP: percutaneous vertebroplasty. 25-(OH)D_3: 25-hydroxyvitamin D_3. BGP: osteocalcin. PTH: Parathyroid Hormone. WBC: White Blood Cell. Alb: Albumin. EAQ: Exercise Activity Questionnaire score.

Table 2. Comparison of baseline characteristics between groups with and without residual low back pain in the modeling group

Baseline data	Residual lower back pain group (n = 108)	Non-residual low back pain group (n = 416)	t/χ^2	*P*
Sex				
Male	46 (42.59)	170 (40.87)	0.106	0.745
Female	62 (57.41)	246 (59.13)		
Age (years, $\bar{x} \pm s$)	62.30±10.21	62.19±11.28	0.092	0.927
Course of Disease (d, $\bar{x} \pm s$)	6.22±2.79	5.97±2.36	0.943	0.346
BMI (kg/m^2, $\bar{x} \pm s$)	22.64±2.20	22.38±2.76	0.907	0.365
History of Smoking [n (%)]				
Yes	34 (31.48)	117 (28.13)	0.471	0.493
No	74 (68.52)	299 (71.87)		
History of Alcohol Consumption [n (%)]				
Yes	24 (22.22)	81 (19.47)	0.405	0.525
No	84 (77.78)	335 (80.53)		
Educational background				
Junior high school or below	65 (60.19)	247 (59.38)	0.023	0.878
High school or higher	43 (39.81)	169 (40.62)		
Hypertension [n (%)]				
Yes	39 (36.11)	141 (33.89)	0.187	0.666
No	69 (63.89)	275 (66.11)		
Diabetes [n (%)]				
Yes	27 (25.00)	107 (25.72)	0.013	0.909
No	81 (75.00)	312 (74.28)		
Hyperlipidemia [n (%)]				
Yes	25 (23.15)	103 (24.76)	0.121	0.728
No	83 (76.85)	313 (75.24)		
COPD [n (%)]				
Yes	16 (14.81)	66 (15.87)	0.072	0.789
No	92 (85.19)	350 (84.13)		
Surgical approach				
PKP	84 (77.78)	315 (75.72)	0.199	0.655
PVP	24 (22.22)	101 (24.28)		
Bone density (T-score) ($\bar{x} \pm s$)	-2.85±0.61	-2.21±0.57	10.245	0.000
Volume of bone cement injected (ml, $\bar{x} \pm s$)	3.20±0.43	3.19±0.41	0.224	0.823
Duration of surgery (min, $\bar{x} \pm s$)	54.29±13.86	52.18±14.10	1.391	0.165
Postoperative restoration rate of vertebral body height (%, $\bar{x} \pm s$)	38.54±5.23	43.12±8.85	5.148	0.000
Number of fractured vertebrae				
one	30 (27.78)	231 (55.53)	26.413	0.000
≥ two	78 (72.22)	185 (44.47)		

Surgical Puncture Approach				
Unilateral	41 (37.96)	171 (41.11)	0.352	0.553
Bilateral	67 (62.04)	245 (58.89)		
Combined with lumbar and dorsal fascia injury [n (%)]				
Yes	65 (60.19)	115 (27.64)	40.260	0.000
No	43 (39.81)	301 (72.36)		
The distribution of bone cement				
Not covered the fracture line	46 (42.59)	78 (18.75)	26.982	0.000
Covered the fracture line	62 (57.41)	338 (81.25)		
Bone cement leakage				
Yes	56 (51.85)	112 (26.92)	24.462	0.000
No	52 (48.25)	304 (73.08)		
Level of 25-(OH)D_3 (μg/L, $\bar{x} \pm s$)	11.72±1.33	14.46±1.81	14.729	0.000
BGP (ng/ml, $\bar{x} \pm s$)	13.19±1.96	14.33±1.28	7.302	0.000
PTH (ng/ml, $\bar{x} \pm s$)	9.91±0.92	8.34±1.19	12.754	0.000
WBC (10^9/L, $\bar{x} \pm s$)	6.41±1.29	6.38±1.37	0.205	0.838
Alb (g/L, $\bar{x} \pm s$)	49.75±5.44	50.38±7.09	0.860	0.390
EAQ Score (points, $\bar{x} \pm s$)	29.12±3.13	33.97±4.25	11.100	0.000

Note: COPD: Chronic obstructive pulmonary disease. PKP: Percutaneous kyphoplasty. PVP: percutaneous vertebroplasty. 25-(OH)D_3: 25-hydroxyvitamin D_3. BGP: osteocalcin. PTH: Parathyroid Hormone. WBC: White Blood Cell. Alb: Albumin. EAQ: Exercise Activity Questionnaire score.

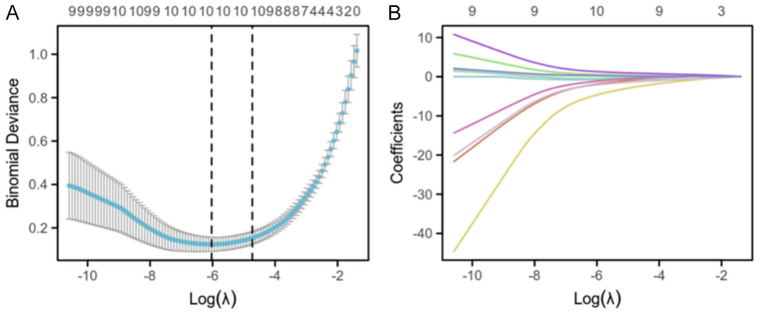

Figure 1. LASSO regression analysis. A: LASSO coefficient path plot; B: LASSO regression analysis with ten-fold cross-validation.

Multivariate logistic regression analysis

Based on LASSO regression with λ _ min.1se for variable selection, a total of 10 factors were identified: bone density, postoperative vertebral height recovery rate, number of fractured vertebrae, combined lumbar and dorsal fascia injury, bone cement distribution, bone cement leakage, serum 25(OH)D_3 level, BGP, PTH, and EAQ score (**Figure 1**). A subsequent multivariate logistic regression was conducted using the variables selected by the aforementioned LASSO regression. Regression analysis indicated that the number of fractured vertebrae, the distribution of bone cement, bone cement leakage, serum 25-(OH)D_3 level, combined lumbar and dorsal fascia injury, and the EAQ score were independently associated with postoperative residual low back pain ($P < 0.05$), identifying them as significant predictors (**Tables 3**, **4**).

Construction of a nomogram for persistent low back pain following PVP/PKP

Based on the independent predictors identified by LASSO-logistic regression, a nomogram was constructed to estimate the probability of persistent postoperative low back pain (**Figure 2**).

Model validation

The predictive performance of the nomogram was assessed using ROC curve analysis. In the modeling cohort, the area under the ROC curve (AUC) was 0.837 (95% CI: 0.792-0.882), with a sensitivity of 91.80% and specificity of 72.15% (**Figure 3A**). In the validation cohort, the AUC was 0.858 (95% CI: 0.803-0.914), with a sensitivity of 86.89% and specificity of 77.64% (**Figure 3B**). Calibration curve analysis was employed to analyze the agreement between predicted probabilities and observed outcomes. The C-index was 0.837 (95% CI: 0.719-0.883) in the modeling cohort (**Figure 3C**) and 0.858 (0.802-0.914) in the validation cohort (**Figure 3D**), indicating good calibration and discrimination of the model.

Table 3. Assignment table

Factor	Assignment
Bone density	Actual value
Postoperative vertebral height recovery rate	Actual value
Number of fractured vertebrae	Number of fractured vertebrae: 1 = 0; ≥ 2 = 1
Combined with lumbar and dorsal fascia injury	No = 0; Yes = 1
Bone cement distribution	Covered fracture line = 0; Not covered fracture line = 1
Bone cement leakage	No = 0; Yes = 1
Level of 25-(OH)D_3	Actual value
BGP	Actual value
PTH	Actual value
EAQ Score	Actual value

Note: 25-(OH)D_3: 25-hydroxyvitamin D_3. BGP: osteocalcin. PTH: Parathyroid Hormone. EAQ: Exercise Activity Questionnaire score.

Table 4. Multivariate logistic regression analysis of rich factors for postoperative residual lower back pain

Key factor	b	S.E.	Chi-square value	*P*	OR	95% CI for OR	
Number of fractured vertebrae	1.488	0.536	7.707	0.006	4.428	1.549	12.661
Postoperative vertebral height recovery rate	-1.572	0.581	7.321	0.007	0.208	0.066	0.648
Bone cement leakage	1.513	0.612	6.112	0.013	4.540	1.368	15.067
Level of 25-(OH) D_3	-1.621	0.687	5.567	0.018	0.198	0.051	0.760
Combined with lumbar and dorsal fascia injury	1.686	0.722	5.453	0.020	5.398	1.311	22.223
EAQ Score	-1.579	0.681	5.376	0.020	0.206	0.054	0.783

Note: 25-(OH)D_3: 25-hydroxyvitamin D_3. EAQ: Exercise Activity Questionnaire score.

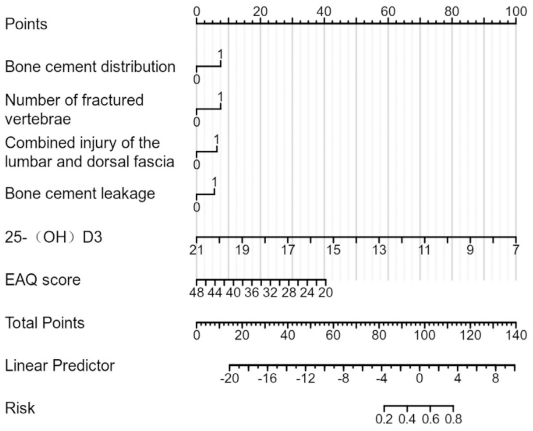

Figure 2. Nomogram model.

Discussion

PKP and PVP are a highly effective, minimally invasive techniques for the treatment of OVCFs, providing rapid relief and facilitating restoration of vertebral body height. However, some patients continue to experience varying degrees of lower back pain after surgery, commonly referred to as “residual lower back pain”. The reported incidence of residual low back pain ranges from approximately 10% to 40%, which can impede early postoperative recovery and reduce long-term quality of life [10, 11]. While controversy persists regarding the risk factors for residual low back pain following PKP/PVP, clinically practical predictive tools remained scarce.

In this study, six independent risk factors were identified using LASSO-logistic regression: number of fractured vertebrae, bone cement distribution, bone cement leakage, serum 25-(OH)D_3 levels, combined lumbar and dorsal fascia injury, and EAQ score. Based on these factors, a predictive nomogram was constructed, demonstrating strong discriminatory ability (AUC of 0.837 in training set and 0.858 in validation set) and good calibration, as indicated by C-statistics of 0.837 and 0.858, respectively, in internal validation. These findings offer a quantitative tool for the early clinical identifica-

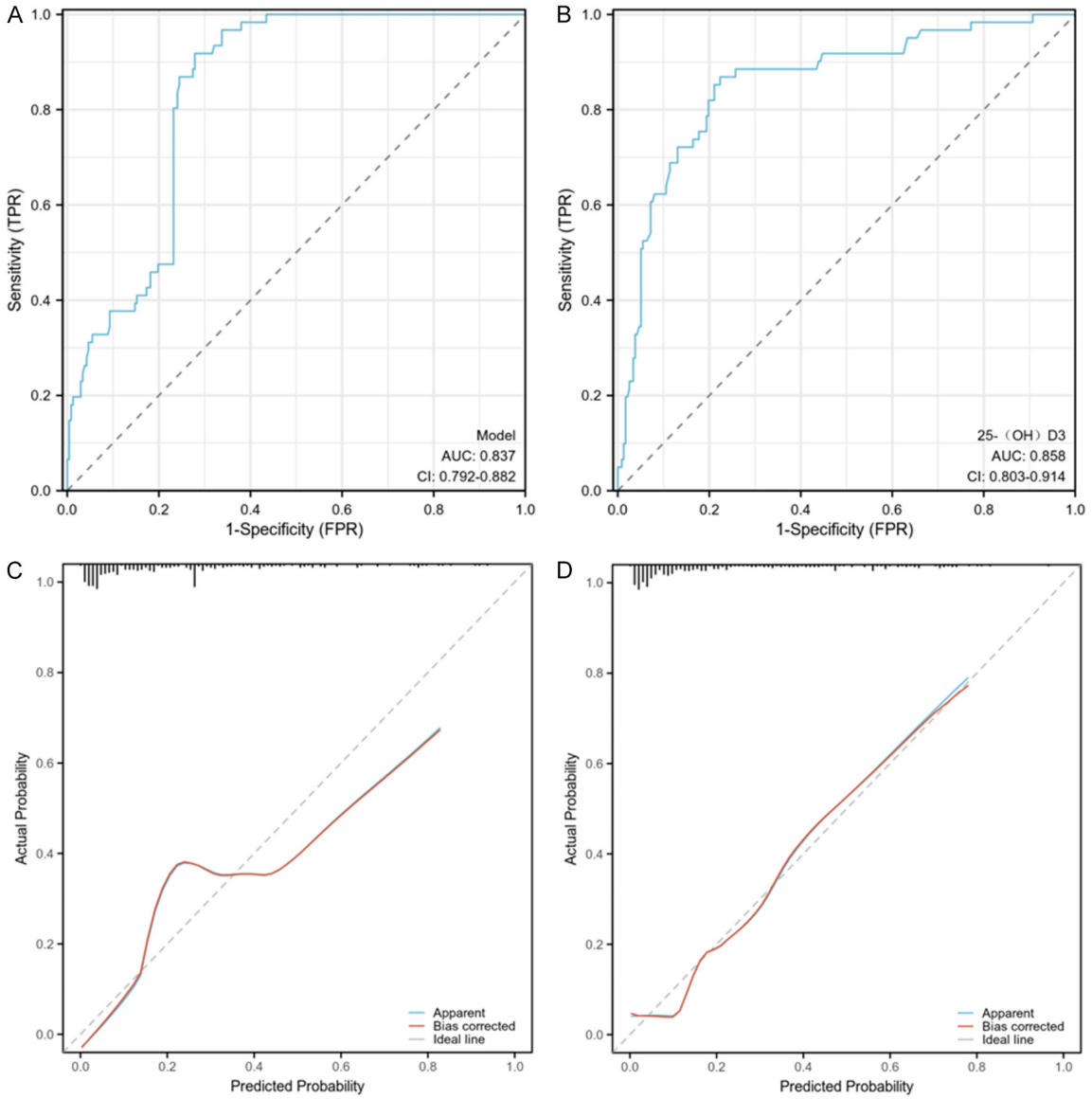

Figure 3. Model verification. A: ROC curve for the nomogram in the modeling cohort; B: ROC curve for the nomogram in the validation cohort; C: Calibration curve for the nomogram in the modeling cohort; D: Calibration curve for the nomogram in the validation cohort.

tion of high-risk patients and for the development of tailored intervention strategies.

Among these six independent predictors, the number of fractured vertebrae is a readily quantifiable and clinically accessible indicator. Multilevel vertebral fractures reflect a more extensive skeletal involvement, characterized by greater cumulative bone loss and increased biomechanical instability [12]. While PKP or PVP effectively stabilizes the targeted vertebra, it may redistribute mechanical stress to adjacent non-instrumented segments and neighboring intervertebral joints, potentially causing facet joint dysfunction, paraspinal muscle hyperactivity, and subsequent persistent postoperative low back pain [13, 14]. Moreover, multilevel vertebral fractures are strongly associated with more advanced osteoporosis, serving as a robust clinical marker of systemic bone fragility and independently predicting poorer functional outcomes, consistent with prior reports [15].

Studies have demonstrated that inadequate distribution of bone cement (e.g., fail to cover

the fracture line) is a significant predictor of persistent postoperative low back pain. The presence of a fracture line indicates structural discontinuity and micromotion within the vertebral body. If bone cement fails to adequately bridge and stabilize the fracture interface, the fracture ends may move during patient activity or weight-bearing, stimulating nociceptive nerve endings within the vertebra and resulting in persistent pain [16, 17]. These findings highlight the importance of ensuring that bone cement is evenly distributed within the vertebrae and completely covers the fracture site during surgery [18]. Bone cement leakage may also contribute to persistent low back pain. This effect is likely mediated by mechanical irritation of the paraspinal soft tissues, leading to a localized inflammatory cascade that sustains nociceptive signaling and delay symptom resolution [19, 20].

In addition, low serum 25-(OH)D_3 levels represent a major risk factor contributing to persistent lower back pain. Physiologically, Vitamin D not only regulates calcium and phosphorus metabolism and bone mineralization but also plays roles in muscle function, suppression of inflammatory responses, and modulation of pain perception [21, 22]. Severely low 25-(OH)D_3 levels can impair calcium and phosphorus deposition and interfere with callus formation at fracture sites, thereby delaying fracture healing and increasing the risk of persistent low back pain following PKP/PVP [23, 24]. Consistent with previous reports [25], low serum 25-(OH)D_3 levels may impair calcium absorption, decrease bone density, and elevate the risk of back pain.

The paravertebral fascia is a crucial load-bearing structure in the posterior spine. Damage to this fascia may lead to local hematoma, scar adhesions, and abnormal pressure within the fascial cavity, ultimately causing chronic low back pain [26-28]. PKP/PVP surgery primarily addresses the structural repair of vertebrae, while soft tissue injuries are often overlooked. In some cases, if these issues are not properly addressed or do not recover sufficiently, postoperative pain may be difficult to alleviate through conventional treatment [29, 30].

Furthermore, EAQ score was incorporated into the predictive model to reflect patients' emotional status and anxiety, highlighting the significance of the biopsychosocial model in managing patients with OVCF [31, 32]. A high EAQ score generally indicates heightened pain sensitive and elevated expectations for surgical outcomes, predisposing patients to postoperative catastrophic thinking and precipitating a vicious cycle of "pain-anxiety-pain" [33-35]. Therefore, preoperative psychological assessments of patients should be emphasized. For those exhibiting obvious symptoms of anxiety or depression, a combination of psychological interventions and medication is recommended to improve their postoperative condition.

In this study, the nomogram achieved AUC values of 0.837 and 0.858 in the modeling and validation cohorts, respectively. The corresponding C-indices were 0.837 and 0.858, indicating good discrimination and calibration performance. These findings suggest that integrating multidimensional factors-including bony architecture, soft tissue status, nutritional profile, and psychological factors-enhances the predictive accuracy for residual low back pain following PKP/PVP, thereby enabling early identification of high-risk patients and facilitating the formulation of personalized intervention plans. Although this study attempted to include an adequate sample size, potential selection bias cannot be completely excluded due to its retrospective and single-center design. In addition, variations in surgical techniques among surgeons may influence bone cement distribution and leakage patterns. Therefore, prospective, multicenter studies are warranted to validate the generalizability and robustness of this model.

Conclusion

Residual lower back pain post-PKP/PVP results from the interaction of multiple factors, rather than by a single technical or biological determinant. This study developed and validated a nomogram model incorporating six predictive factors: number of fractured vertebrae, distribution of cement-uncovered fracture lines, cement leakage, 25-(OH)D_3 level, concomitant lumbar fascia injury, and EAQ score. The model demonstrated good predictive performance in internal validation, providing a practical tool for perioperative risk stratification and individualized patient management.

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Disclosure of conflict of interest

None.

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