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Developing predictive models for residual back pain after percutaneous vertebral augmentation treatment for osteoporotic thoracolumbar compression fractures based on machine learning technique

Hao Wu^{1†}, Chao Li^{3†}, Jiajun Song^{2†} and Jiaming Zhou^{2*}

Abstract

Background Machine learning (ML) has been widely applied to predict the outcomes of numerous diseases. The current study aimed to develop a prognostic prediction model using machine learning algorithms and identify risk factors associated with residual back pain in patients with osteoporotic vertebrae compression fracture (OVCF) following percutaneous vertebroplasty (PVP).

Methods A total of 863 OVCF patients who underwent PVP surgery were enrolled and analyzed. One month following surgery, a Visual Analog Scale (VAS) score of ≥ 4 was deemed to signify residual low back pain following the operation and patients were grouped into a residual pain group and pain-free group. The optimal feature set for both machine learning and statistical models was adjusted based on a 2000-resample bootstrap-based internal validation via an exhaustive search. The area under the curve (AUC), classification accuracy, sensitivity, and specificity of each model were then calculated to evaluate the predictive performance of each model.

Results In our current study, two main findings were observed: (1) Compared with statistical models, ML models exhibited superior predictive performance, with SVM demonstrating the highest prediction accuracy; (2) several variables were identified as the most predictive factors by both the machine learning and statistical models, including bone cement volume, number of fractured vertebrae, facet joint violation, paraspinal muscle degeneration, and intravertebral vacuum cleft.

Conclusion Overall, the study demonstrated that machine learning classifiers such as SVM can effectively predict residual back pain for patients with OVCF following PVP while identifying associated predictors in a multivariate manner.

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Keywords Visual analog scale, Machine learning, Percutaneous vertebroplasty, Residual back pain, Prognostic prediction, Osteoporotic vertebrae compression fracture

Introduction

Osteoporosis is a skeletal disorder characterized by bone weakening due to losing biomechanical properties [1]. Secondary to these changes, osteoporosis patients are prone to fractures resulting from minor trauma [2]. Osteoporotic vertebral compression fractures (OVCF) are prevalent among elderly individuals and have become one of the main complications of osteoporosis [3, 4]. OVCF is a prevalent etiology of thoracolumbar back pain, leading to diminished quality of life for affected individuals and presenting a burgeoning challenge in global health [5, 6]. Percutaneous vertebroplasty (PVP) emerges as a well-established and safe procedure for managing OVCFs [7]. Despite the relatively high success rates of pain relief following percutaneous vertebroplasty (PVP), which typically ranges from 78 to 95%, a notable proportion of patients continue to experience persistent back pain, with incidence rates varying between 1.8% and 15.6% [8]. Various factors, including bone mineral density, postoperative infection, adjacent vertebrae refracture, nerve damage resulting from bone cement leakage, and rib fractures, are associated with the persistence of postoperative back pain [7, 9, 10]. Identifying risk factors before surgery can help spine surgeons predict postoperative pain in patients undergoing PVP, allowing for better decision-making and personalized rehabilitation plans for those at high risk [11, 12]. Hence, to explore this matter, researchers have developed predictive models utilizing clinical risk factors to predict the probability of post-treatment back pain manifestation in these patients.

The development of machine learning technology has facilitated the development of machine learning-based clinical prediction models for the medical field [13–15]. While machine learning has been extensively utilized in medical diagnostics and imaging, its utilization in epidemiological datasets for the prediction of diverse health outcomes is a recent advancement. In a recent review conducted by Khan et al., machine learning is examined within the framework of spine disease [16, 17]. The review emphasizes the numerous benefits of utilizing machine learning, particularly its ability to effectively manage extensive datasets and identify complex, nonlinear associations between potential predictors and observational results. Nevertheless, these studies have inherent limitations. One such limitation is that prior research has primarily relied on weight or feature importance metrics to evaluate the impact of individual factors on predictive models [15]. While these methods offer some insight into the significance of factors for prognostic prediction, heuristic search algorithms, specifically designed to

identify the most effective feature subset, have the potential to pinpoint a set of features that optimize predictive performance.

The primary aims of this research endeavor are twofold: firstly, to conduct a comparative analysis of the predictive efficacy of machine learning techniques, and secondly, to employ heuristic search algorithms to pinpoint critical factors linked to the onset of functional decline. The creation and refinement of such algorithms could furnish healthcare practitioners with a valuable instrument for the identification and treatment of individuals susceptible to neurological deterioration after surgical interventions.

Materials and methods

Inclusion of patients

Clinical data from patients diagnosed with osteoporotic vertebral compression fractures (OVCF) who underwent percutaneous vertebroplasty (PVP) treatment were retrospectively analyzed at department of orthopedics in Tianjin Bodi Hospital from January 2016 to January 2023. Inclusion criteria encompassed a confirmed diagnosis of OVCF, receipt of PVP treatment, availability of comprehensive clinical data, and a minimum follow-up duration of one year. The exclusion criteria encompassed fractures involving the posterior column of the vertebral body with fragment intrusion into the spinal canal, new fractures of the vertebral body following surgery, active infections of the lumbar spine or adjacent regions, postoperative vertebral body infections, the existence of spinal malignant tumors, and severe cardiac or pulmonary dysfunction that would preclude the patient from undergoing surgery. Among the cohort of 863 patients, 398 were identified as male and 465 as female. After the surgical procedure, patients were monitored at different time points, during which Visual Analog Scale (VAS) scores were documented. The presence of moderate to severe residual back pain was characterized by a VAS score equal to or exceeding 4. One month after surgery, a Visual Analog Scale (VAS) score of ≥ 4 was deemed to signify residual low back pain following the operation [18]. Patients were divided into two groups based on their VAS scores: those experiencing postoperative residual back pain (RP Group, VAS ≥ 4 points, Group A in Table 1) and those content with the postoperative result (NP Group, VAS < 4 points, Group B in Table 1). This research was carried out with the approval of the hospital's ethics committee, and all participants provided written informed consent.

Table 1 The main demographic variables between the two groups of patients

Characteristics	Group A (n = 134)	Group B (n = 729)	P value
Age, years	75.3 ± 8.2	77.3 ± 7.8	0.006*
Sex, n (%)			0.83
male	67 (50)	372 (51)	
female	67 (50)	357 (49)	
BMI, kg/m ²			0.50
≤ 27	60 (44)	349 (48)	
>27	74 (56)	380 (52)	
Smoking			<0.001*
Yes	46 (35)	377 (52)	
No	88 (65)	352 (48)	
Drinking			0.51
Yes	66 (49)	337 (46)	
No	68 (51)	392 (54)	
Heart disease			0.16
Yes	32 (24)	136 (19)	
No	102 (76)	593 (81)	
Hypertension			0.99
Yes	45 (34)	245 (34)	
No	89 (66)	484 (66)	
Diabetes			0.008*
Yes	47 (36)	177 (25)	
No	87 (64)	552 (75)	

BMI: Body Mass Index
*The difference possessing statistical significance
*P<0.05

Study variables

Before the surgical procedure, data on age, gender, body mass index (BMI), smoking status, alcohol consumption, history of heart disease, hypertension, and diabetes were collected. The study involved an analysis of operation-related variables, imaging findings, and clinical outcomes, including pre-operative Visual Analog Scale scores, post-operative VAS scores, pre-operative bone mineral density, fracture segment, number of fractured vertebrae, duration of the operation, occurrence of cement leakage, changes in posterior fascia signal on MRI, volume of injected cement, rate of cement diffusion, pre-operative Oswestry Disability Index, surgical approach, facet joint violation, presence of depression, degree of local kyphosis correction, and restoration of anterior vertebral height. These variables were compared between groups, t-tests were performed for continuous variables and chi-squared tests were performed for categorical variables.

Imaging and clinical evaluation

Patients underwent post-operative follow-up at regular intervals of 1 week, 2 weeks, 1 month, 3 months, and 1 year at the outpatient clinic. The severity of low back pain was assessed using the Visual Analog Scale (VAS), ranging from 0 (no pain) to 10 (most severe pain). Patients

selected a number from a scale of 11 options, representing their pain level on a scale of 0 to 10 points.

Several related clinical measures were retrospectively selected based on previous studies [18–20]. These variables were considered as pre-and postoperative factors that may affect back pain relief in patients underwent PVP surgery. The kyphosis angle of the fractured vertebral body was evaluated by drawing lines along the upper and lower margins of the affected vertebra on lateral X-ray images. This angle, determined by the intersection of these lines, quantified kyphosis, with the difference between preoperative and postoperative values, indicating the extent of corrective intervention. To evaluate vertebral body compression, particularly anterior and central compression of the fractured vertebral body, lateral X-rays were used for measurements. The average height of the posterior edge of adjacent vertebral bodies above and below the fractured vertebral body was estimated as the height of the posterior edge of the fractured vertebral body. Subsequently, the anterior and central heights of the fractured vertebral body were measured, and the ratio of these heights to the estimated height of the posterior edge served as an index for compression severity. In cases of low back fascia injury, MRI T2-weighted and fat-suppressed images depicted a prolonged region of heightened signal intensity consistent with low back fascia injury, along with tenderness in the corresponding area. Facet joint violation, resulting from needle penetration through the facet joint surface or complete perforation of the joint cavity during vertebroplasty, was evaluated through postoperative CT scans of cemented vertebral bodies on the first day following the procedure. The cement diffusion volume rate refers to the proportion of injected bone cement volume to the volume of the vertebral body. An appropriate diffusion volume ratio of bone cement, such as 0.2, has been shown to effectively alleviate fracture pain and reduce the risk of cement leakage.

Data analyses

In our study, we adhered to the Transparent Reporting of Multivariable Prediction Models for Individual Prognosis or Diagnosis (TRIPOD) checklist and followed guidelines for machine learning (ML) predictive models. Data preprocessing involved excluding patients with missing follow-up VAS scores, resulting in a total of 763 patients. Subsequently, we applied a recursive feature selection technique using lasso regression on the training dataset to identify the optimal predictors for the modeling process. Categorical predictors were transformed into dummy variables, and continuous variables were standardized through centering and scaling.

In current study, 80% of the samples were allocated to the training set, and the remaining 20% were reserved for the testing set (External validation set).

Machine learning prediction

Several machine learning models were trained on the training set and 5-fold cross-validation was performed for internal validation for each machine learning model using default parameters to establish a baseline prediction performance for each model.

The machine learning models included logistic regression (LR), general linear model (GLM), linear discriminant analysis (LDA), partial least squares discriminant analysis (PLS-DA), Support Vector Machine (SVM) with a radial basis function (RBF) kernel, K-Nearest-Neighbor (KNN), naïve Bayes (NB), Random Forest (RF), Extreme Gradient Boost, Light Gradient Boosting Machine (LGBM) and CatBoost models. Model performance was assessed using various discrimination metrics, including the area under the receiver operating characteristic curve (ROC or AUC), accuracy, sensitivity, specificity and brier score. As some machine learning algorithms do not provide probabilities as output, similar to logistic regression models, Platt scaling was employed to transform the model's less interpretable output scores into more interpretable probabilities, facilitating the calibration assessment.

Following internal validation, the machine learning models were trained with training set and tested on the external validation set for obtaining the performances of each model respectively.

Identifying optimal feature-subset using exhaustive search

The sequential backward selection procedure began with the complete set of features, evaluating various models' performances by systematically removing individual features from the current pool of candidate features at each iteration. The feature whose removal resulted in the most significant improvement in classification accuracy

was excluded from the subsequent iteration. This iterative process continued until no further enhancement in classification accuracy was observed through feature exclusion. It's important to note that sequential backward selection may lead to a local optimum rather than a global optimal feature subset. To address this, an exhaustive search was conducted to systematically enumerate all potential models for classification. A 5-fold cross-validation technique was employed to evaluate the effectiveness of individual feature subsets within the training dataset. This involved dividing the training dataset into five distinct subsets, with four subsets used for model training iteratively, and the fifth subset reserved for internal validation purposes. This process was repeated until each subset had been utilized once as the validation set. The optimal feature subset was determined for each machine learning method using both sequential backward selection and exhaustive search techniques. The most discriminative feature subset was selected as the optimal subset by aggregating the preferences of all machine learning models, with features included in the optimal subset by three or more models. Following this, all machine learning models were trained on the training dataset using the optimal feature subset and subsequently evaluated on a validation dataset. Model performance on the training dataset was assessed.

Results

Baseline patients data

The baseline data is shown in Table 1. No significant differences in terms of age or sex were observed between the two groups. The postoperative VAS score were shown in Table 2.

Prediction performance

Based on LASSO regression, 12 features were selected for further analyses, including age, gender, BMI, Cobb angle, Bone cement volume, Number of fractured vertebrae, Posterior fascia signal changes on MRI, Cement diffusion volume rate, Facet joint violation, Paraspinal muscle degeneration, Depression, Intervertebral vacuum cleft. In our current study, machine learning models could classify two groups based on clinical measures selected by LASSO regression. The SVM model demonstrates the highest predictive performance with an AUC of 0.85. The predictive accuracy of the LGBM model is slightly inferior to it with an AUC of 0.83. Among all ML models, KNN exhibits the poorest predictive performance with an AUC of 0.72 (Fig. 1; Table 3).

Feature selection

Figure 2 illustrates the optimal feature subset selected by both the ML and statistical models via internal cross-validation. Following an exhaustive search, several variables

Table 2 Comparison of VAS scores between two groups of patients treated with PVP

Period	Group A (n = 122)	Group B (n = 641)	P value
Pre-VAS	7.6 ± 1.9	8.2 ± 1.3	<0.001**
Post-VAS			
At 1 day	5.8 ± 1.7	4.1 ± 1.2	<0.001**
At 1 week	5.2 ± 1.4	3.7 ± 1.1	<0.001**
At 2 weeks	4.7 ± 1.5	3.2 ± 0.8	<0.001**
At 1 month	3.8 ± 1.3	2.8 ± 1.0	<0.001**
At 3 month	3.0 ± 1.3	2.5 ± 1.2	<0.001**
At 1 year	2.3 ± 1.0	1.8 ± 0.7	<0.001**

VAS: Visual Analog Scale

*The difference possessing statistical significance

*P<0.05, **P=0.000

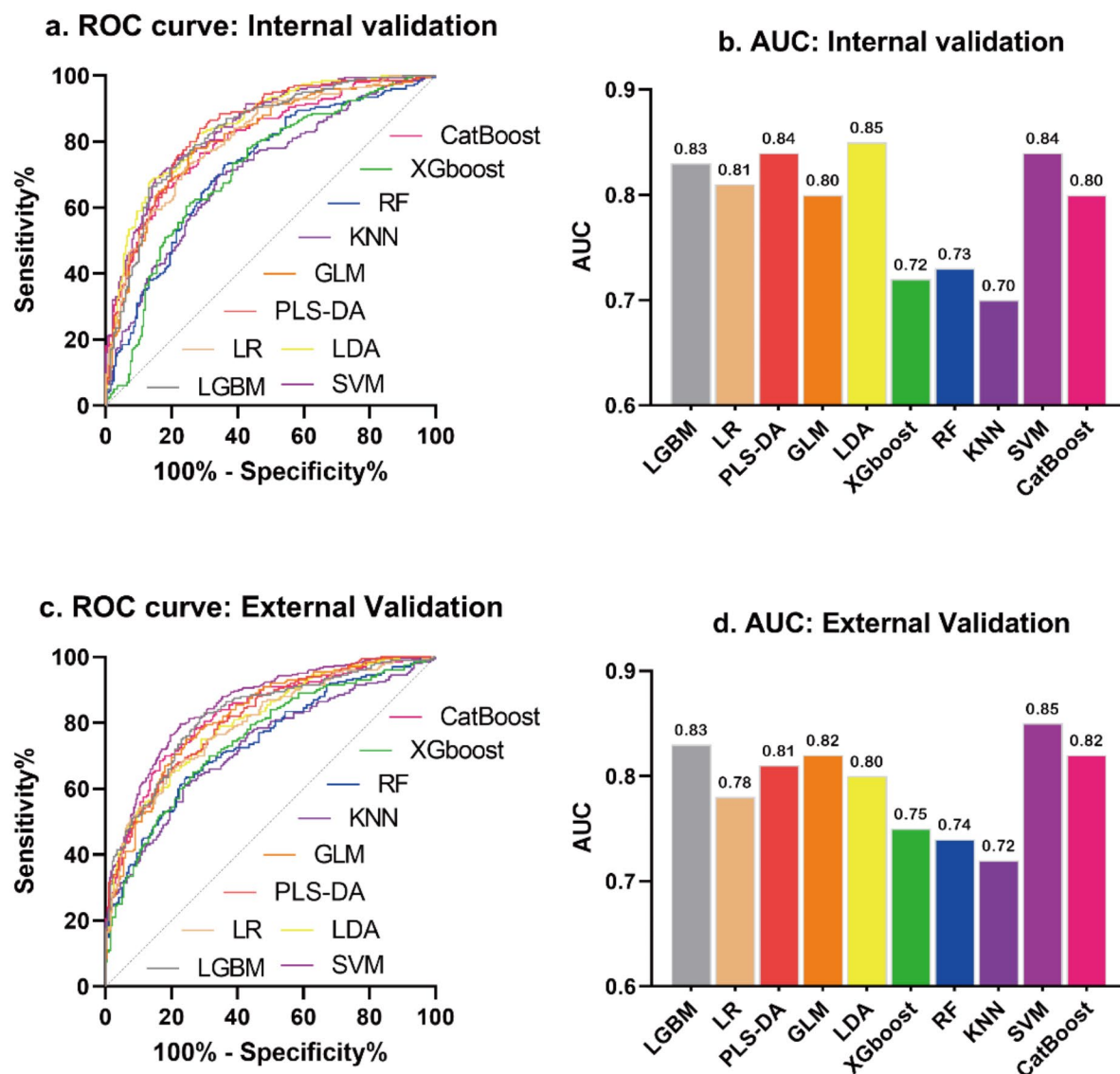


Fig. 1 The baseline prediction performances for machine learning models. Panel **a**: The ROC curves for machine learning models (ML) during internal validation. Panel **b**: the area under the curve of ML models during internal validation. Panel **c**: ROC curves for ML models during external validation. Panel **d**: AUC of ML models during external validation

were repeatedly selected into the optimal subset by various models. The Number of fractured vertebrae and intravertebral vacuum cleft were selected with most of the models (10 votes) while paraspinal muscle degeneration (9 votes), and bone cement volume (9 votes) were also repeatedly selected. We then utilized all ML models to train with the optimal feature subset on the training data and tested it on the external validation data. The SVM model demonstrates the highest predictive performance with an AUC of 0.88. The predictive accuracy of the LGBM and PLS-DA model is slightly inferior to it

with an AUC of 0.86. Among all ML models, RF exhibits the poorest predictive performance with an AUC of 0.80 (Fig. 3; Table 4).

Discussion

In our current study, two main findings were observed: (1) ML models could classify patients with postoperative pain, with SVM demonstrating the highest prediction accuracy; (2) several variables were identified as the most predictive factors by the machine learning models including bone cement volume, number of fractured vertebrae,

Table 3 Comparison of the AUCs, accuracies, sensitivities, and specificities of baseline prediction performance for machine learning models

Model	AUC	Accuracy (%)	Sensitivity (%)	Specificity (%)	Brier Score
SVM	0.85	83.6	81.6	87.6	0.13
XGboost	0.75	71.2	78.1	68.9	0.24
RF	0.74	69.8	82.3	78.1	0.26
KNN	0.73	70.7	73.2	76.7	0.22
pls-DA	0.82	81.5	80.3	78.7	0.14
GLMnet	0.83	86.3	81.2	85.7	0.17
LDA	0.80	78.7	88.7	82.3	0.16
LR	0.78	76.5	78.9	88.6	0.16
LGBM	0.83	83.2	82.3	78.5	0.15
CatBoost	0.82	84.5	83.4	82.3	0.18

GLM-net, a generalized linear model with elastic net regularization; KNN, k-nearest neighbours; LDA, linear discriminant analysis; LR, logistic regression.; PLS-DA, partial least squares discriminant analysis; RF, randomforest; SVM, Support Vector Machine; XGBoost, extreme gradient boosting, LGBM, Light Gradient Boosting Machine

facet joint violation, paraspinal muscle degeneration, and intravertebral vacuum cleft.

Percutaneous vertebroplasty (PVP) surgery is widely acknowledged as an effective minimally invasive

approach for managing osteoporotic vertebral compression fractures (OVCFs), offering swift pain relief, early enhancement of mobility, and improved quality of life for patients [21–23]. Beall et al. (2018) [24] observed that residual back pain emerged as a prevalent adverse event within the initial 30 days following percutaneous vertebroplasty (PVP), with 4.9% of patients experiencing persistent back pain even after a year of follow-up. The enduring presence of residual back pain substantially diminishes patient satisfaction with the surgical procedure and their overall quality of life. Several studies have investigated the occurrence of residual back pain following percutaneous vertebroplasty (PVP) [25, 26]. In a retrospective analysis by Barr et al., 38 patients with 70 vertebrae treated with PVP experienced varying degrees of pain relief, with 63% reporting significant relief, 32% reporting moderate relief, and 5% reporting inadequate relief [27]. Dohm et al. conducted a comparative analysis of PVP and percutaneous kyphoplasty for the treatment of osteoporotic vertebral compression fractures, focusing on postoperative adverse events [28]. The study identified procedural pain and back pain as the most prevalent adverse events at the 30-day postoperative mark. Our

Optimal Feature subset selected by ML models

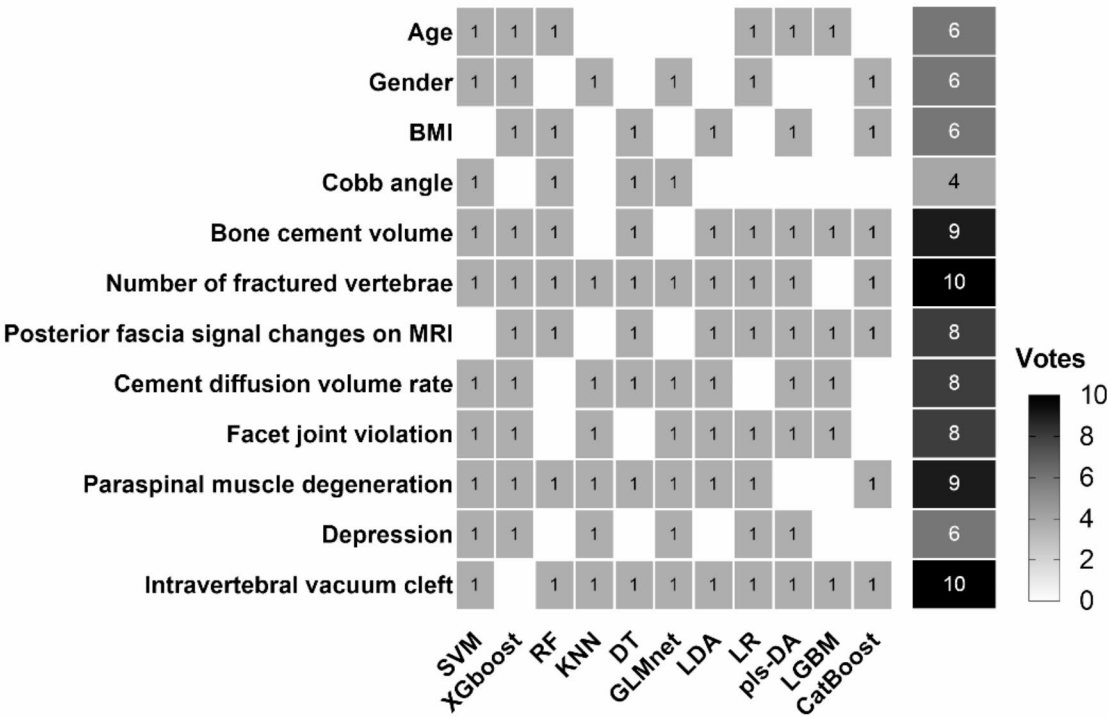


Fig. 2 The optimal feature subset selected by both machine learning models and statistical models. The heatmap illustrated the votes of each feature by all models

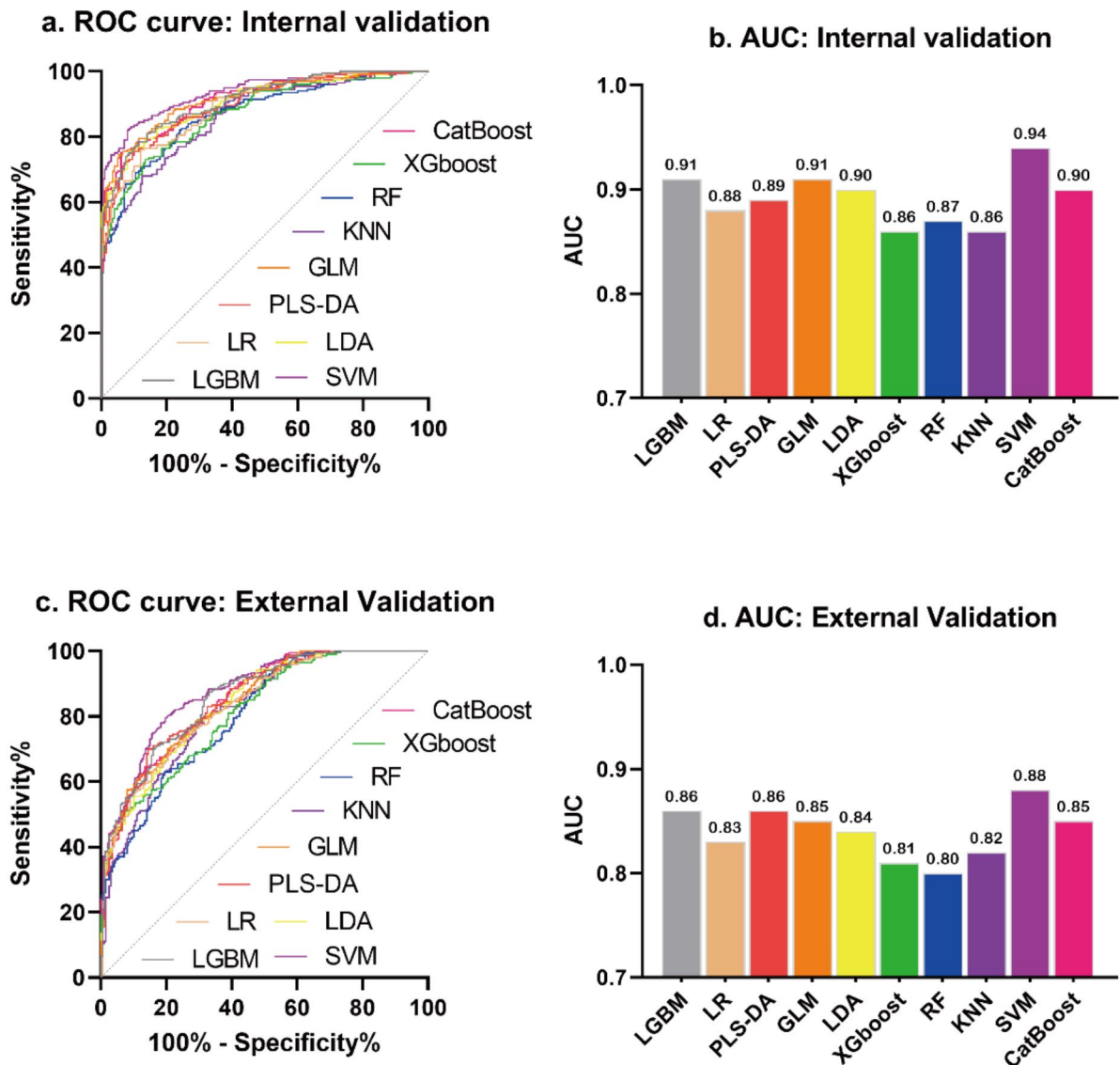


Fig. 3 The prediction performances of optimal feature subset for machine learning models. Panel **a**: The ROC curves for machine learning models (ML) during internal validation. Panel **b**: the area under the curve of ML models during internal validation. Panel **c**: ROC curves for ML models during external validation. Panel **d**: AUC of ML models during external validation

current study found a 13.81% occurrence of residual back pain 30 days following PVP, consistent with existing literature. We chose a one-month postoperative observation period to minimize potential confounding variables related to residual back pain resulting from differences in follow-up durations. In the past decades, researchers have focused on developing clinical prediction models to identify OVCF patients with postoperative back pain preoperatively, utilizing methods like linear regression and general linear models [18, 19, 29]. However, with the advancement of machine learning (ML) technology,

numerous studies have investigated the efficacy of ML models in predicting outcomes. Recognizing the advantages of ML approaches, such as their ability to handle nonlinear data and their robustness, researchers have found that ML models showed promising potential in predicting surgical outcomes related to the medical field [30–33]. In our current study, we systematically compared the predictive performance of ML models and found that ML models could identify patients with postoperative pain based on perioperative evaluations. Our findings were also consistent with previous research

Table 4 Comparison of the AUCs, accuracies, sensitivities, and specificities of prediction performance of optimal feature-subset for machine learning models

Model	AUC	Accuracy (%)	Sensitivity (%)	Specificity (%)	Brier Score
SVM	0.88	91.5	82.3	87.3	0.10
XGboost	0.81	83.2	77.9	81.2	0.18
RF	0.80	76.7	78.8	80.1	0.20
KNN	0.82	79.8	83.5	77.7	0.17
pls-DA	0.86	80.6	82.3	80.2	0.12
GLMnet	0.85	81.5	81.8	83.2	0.13
LDA	0.84	80.6	85.7	79.2	0.12
LR	0.83	82.5	81.2	80.7	0.14
LGBM	0.86	88.7	84.3	81.5	0.12
CatBoost	0.85	83.6	81.5	88.2	0.13

GLM-net, a generalized linear model with elastic net regularization; KNN, k-nearest neighbours; LDA, linear discriminant analysis; LR, logistic regression.; PLS-DA, partial least squares discriminant analysis; RF, randomforest; SVM, Support Vector Machine; XGBoost, extreme gradient boosting, LGBM, Light Gradient Boosting Machine

indicating the superiority of the SVM model over other prediction models for forecasting the outcome of OVCF patients. Recognizing the SVM model’s ability to handle complex nonlinear relationships between features, Khan et al. similarly discovered that the SVM model was the top-performing ML model in predicting surgical outcomes in patients with degenerative cervical myelopathy [34].

Furthermore, to identify risk factors for postoperative pain in patients with OVCF, our current study performed an exhaustive search to identify an optimal feature subset. We identified a set of variables including bone cement volume, number of fractured vertebrae, facet joint violation, paraspinal muscle degeneration, and intravertebral vacuum cleft. In our study, all patients were prescribed long-term, standard anti-osteoporosis medication post-surgery. Many people with osteoporotic vertebral compression fractures (OVCF) experience either ongoing or sporadic fractures affecting multiple spinal segments. The collapse of several vertebral bodies can disrupt the overall alignment of the spine. To compensate for this imbalance, patients may adopt pelvic retroversion and lumbar lordosis, but these non-physiological adjustments often strain the back muscles, leading to lower back pain. Jones et al. conducted a multiple linear regression analysis on various factors, including the Pain Disability Questionnaire (PDQ), and found that patients with single-segment fractures tended to experience better postoperative pain relief [35]. Consistent with these findings, our study revealed that patients with multi-segment osteoporotic vertebral compression fractures (OVCFs) had higher postoperative Visual Analog Scale (VAS) scores compared to those with single-segment OVCFs. Additionally, our analysis indicated that having more than two fractured vertebrae was

significantly associated with an increased risk of postoperative residual back pain. In patients with osteoporotic vertebral compression fractures (OVCF), injuries to the lower back fascia are frequently observed [36]. Recent studies have suggested that thoracolumbar back fascia injury could contribute to ongoing back pain following percutaneous vertebroplasty [37, 38]. A prospective study by Yan et al. reported a high incidence of low back fascia injury, with rates reaching 42.1% [39]. Besides low back pain resulting from cancellous bone edema in the vertebral body, edema of the lower back fascia may also contribute to persistent low back pain post-percutaneous vertebroplasty. The use of bone cement can reduce micro-movements in the fractured trabecular bone through interface fixation, aiding in pain relief within the fractured vertebral body. However, postoperative back pain caused by soft tissue injuries, such as lumbar back fascia injury, is often overlooked. Yang et al. found that preoperative lumbar back fascia injury significantly affects pain relief following percutaneous vertebroplasty (PVP), with an odds ratio (OR) of 3.8 [29]. They also suggested that the intense pain experienced by OVCF patients before surgery may lead to the underestimation of pain resulting from lumbar back fascia injury. Surgery effectively reduces pain associated with the fracture, making pain from lower back fascia injury more apparent. Our research also identified lumbar back fascia injury as a significant risk factor for persistent back pain following PVP. As the edema in the lower back fascia resolves, initial postoperative residual low back pain gradually decreases. The notable difference in Visual Analog Scale (VAS) scores observed between the two groups post-surgery (1 month) may be explained by this phenomenon. Additionally, Guo et al. suggested that magnetic resonance imaging (MRI) may not accurately detect thoracolumbar back fascial damage [40], highlighting the need for further research on the correlation between thoracolumbar back fascial injury and persistent back pain following vertebroplasty. In recent years, there has been a surge in literature investigating the impact of bone cement distribution on the effectiveness of percutaneous vertebroplasty (PVP). Consistently, research has shown that better bone cement distribution correlates with greater improvements in both short-term and long-term Visual Analog Scale (VAS) scores [41, 42]. Some researchers have suggested a relationship between the amount of bone cement injected and the size of the vertebral body, defining the ratio of injected bone cement volume to vertebral body volume as the bone cement diffusion volume ratio [43]. Studies have demonstrated that a bone cement diffusion volume ratio of 0.2 is optimal for achieving effective pain relief and reducing the risk of bone cement leakage in fracture treatment [44]. Additionally, studies by Liu et al. and Li et al. have

indicated that injecting bone cement clumps bilaterally into the vertebral body results in superior pain relief and less residual back pain post-surgery compared to independent clumps[45, 46]. Li et al.'s correlation analysis found that independent bone cement morphology is a significant risk factor for residual back pain, with an odds ratio of 2.23. The ongoing back pain attributed to inadequate bone cement distribution stems from continued stimulation of trabecular bone in the uncovered middle region, causing discomfort and minor nerve activation. Our study revealed that the RP Group had a cement diffusion volume rate below 0.2, and subsequent exhaustive search analysis identified a cement diffusion volume rate as a crucial risk factor for persistent back pain following percutaneous vertebroplasty (PVP) treatment[18, 47]. Currently, there is limited research on facet joint violation and its link to enduring back pain following percutaneous vertebroplasty (PVP). Pain stemming from facet violation during PVP may be due to nerve stimulation within the joint capsule and articular surface, as well as spinal segment destabilization caused by facet joint injury. Li et al. conducted thoracolumbar computed tomography scans after percutaneous kyphoplasty, revealing that approximately 15% of patients had puncture needle channels penetrating the facet joint. Patients with facet invasion exhibited significantly higher Visual Analog Scale (VAS) and Oswestry Disability Index (ODI) scores within one-month post-surgery compared to the control group. Yan et al. observed significant pain at the puncture site one month after surgery in seven patients, suggesting a potential association with facet joint invasion [40]. However, this pain was relieved following local block treatment. Our study also identified facet joint violation as a risk factor for persistent back pain following percutaneous vertebroplasty (PVP). Currently, there is a lack of research exploring the connection between depression and persistent back pain after percutaneous vertebroplasty (PVP). Multiple studies have indicated a significant negative relationship between concurrent depression and the improvement of postoperative pain and functional recovery [48–51]. Additionally, the use of antidepressants before surgery has shown to be beneficial in enhancing postoperative pain relief and functional recovery. Our study supports these findings, suggesting that depression, unlike other comorbidities such as hypertension, diabetes, or chronic obstructive pulmonary disease, is a risk factor for suboptimal pain relief after PVP. Furthermore, implementing systematic and standardized rehabilitation protocols for osteoporotic vertebral compression fracture (OVCF) patients undergoing percutaneous vertebroplasty (PVP) has demonstrated benefits in enhancing bone mineral density, reducing postoperative residual back pain, and lowering the risk of refracture. In our study, all patients received

long-term regular anti-osteoporosis medication post-surgery. Nonsteroidal anti-inflammatory drugs (NSAIDs) were administered to individuals experiencing mild to moderate residual back pain post-surgery if they were unable to tolerate it [52, 53]. Early and appropriate exercises targeting the lower back muscles can help improve muscle strength and alleviate discomfort [54]. Additionally, for patients with osteoporotic vertebral compression fractures (OVCF) who present with depression, preoperative standardized antidepressant therapy may facilitate postoperative pain relief and promote early engagement in daily activities [55, 56]. Hence, it is imperative to establish systematic and standardized rehabilitation interventions for patients with osteoporotic vertebral compression fractures following percutaneous vertebroplasty.

The clinical significance of our current study is twofold: (1) Utilizing a prediction model, surgeons would be able to identify patients who are at a higher risk of experiencing postoperative pain. Such timely detection could guide healthcare providers in providing personalized treatment strategies that are aligned with each patient's unique risk factors. An accurate predictive model would also equip surgeons with the knowledge to engage in comprehensive discussions with patients regarding their prognosis and potential health risks; (2) By applying exhaustive search and voting strategy, risk factors were selected by all ML models. By leveraging different models, each with its unique strengths and weaknesses, we can reduce the risk of overfitting to a particular model's biases. This leads to more robust and generalizable models. Multiple models can also provide a more comprehensive view of feature importance. Some features might be significant in one model but not in another, indicating their relevance across different perspectives and contexts.

This study is constrained by various limitations in its examination of the risk factors associated with residual back pain after PVP: (1) The study's sample size was limited and sourced from a singular institution; (2) Furthermore, instances of rib fractures, infections, new fractures, and significant bone cement leakage, as reported in prior research, were not observed; (3) Consequently, a large-scale, multicenter investigation is necessary to offer a more thorough insight into the pertinent risk factors; (4) The duration of our follow-up period was relatively brief. It is imperative to conduct long-term, multi-period follow-up studies to validate and strengthen the conclusions drawn from our research; (5) In our current study, we collected clinical measures which were associated with pain relief in patients underwent PVP, however, this does not mean that all risk factors associated with postoperative pain have been included in this study, which is also one of the limitations of this research. Future studies with larger samples are needed to include more

comprehensive clinical and imaging indicators for building predictive models and identifying risk factors.

Abbreviations

ML	Machine Learning
OVCF	Osteoporotic Vertebral Compression Fracture
PVP	Percutaneous Vertebroplasty
VAS	Visual Analog Scale
SVM	Support Vector Machines
AUC	Area Under The Curve
BMI	Body Mass Index
TRIPOD	Transparent Reporting of Multivariable Prediction Models for Individual Prognosis or Diagnosis
LR	Logistic regression
GLM	General linear model
LDA	Linear discriminant analysis
PLS	DA-Partial least squares discriminant analysis
RBF	Radial basis function
KNN	K-Nearest-Neighbor
NB	Naïve Bayes
RF	Random Forest
DT	Decision Tree
ROC	Receiver operating characteristic curve
PDQ	Pain Disability Questionnaire
OR	Odds ratio
MRI	Magnetic resonance imaging
ODI	Oswestry Disability Index
NSAIDS	Nonsteroidal anti-inflammatory drugs

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Author contributions

WH designed the study and wrote the manuscript. LC and SJJ participated in the collection of data and data statistics. ZJM revised the manuscript. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Board of the local medical center. Written informed consent was obtained from each participant prior each procedure.

Consent for publication

The authors affirm that human research participants provided informed consent for publication of the images in all Figures.

Competing interests

The authors declare no competing interests.

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