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Construction and Validation of a Prediction Model for Surgical Outcome in Degenerative Lumbar Scoliosis

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Abstract

Background： Degenerative lumbar scoliosis (DLS) is a complex spinal disorder that has attracted increasing attention in contemporary spine research and clinical practice. Predicting postoperative outcomes in patients with DLS remains challenging. This study aimed to identify independent predictors of postoperative outcomes and to develop and validate a prognostic model for patients with DLS.

Methods： This study included patients with DLS managed by posterior-only fusion surgery. Demographic, radiological and operating characteristics of patients were collected and organized from the hospital medical records. The surgical outcome was evaluated according to the Oswestry Disability Index (ODI), Physical Functioning (PF) and Mental Health (MH) in the Short Form- 36 (SF-36), complications and revision surgery. Satisfactory outcome (SO) was defined by ODI ≤ 22, PF and MH at or above normative values, no postoperative complications, and no revision surgery. Predictors of postoperative prognosis were identified through the least absolute shrinkage and selection operator (LASSO) regression analysis. The Shapley Additive Explanations (SHAP) method was applied to rank the importance of each variable. Four predictive models—Logistic Regression, KNearest Neighbors (KNN), Multi-layer Perceptron (MLP), Naive Bayes—were constructed using the training set and evaluated for performance, with validation conducted on the test set.

Results： In this retrospective case-control study, 233 patiens (mean age 61.4 years) were included. Ninety-nine patients (42.4%) patients achieved SO. LASSO regression identified six variable features, which, ranked in order of importance by SHAP analysis, were preoperative ODI, postoperative pelvic incidence minus lumbar lordosis (PI-LL), preoperative PF, preoperative Cobb angle, number of decompression segments, and postoperative LL. Among the four predictive models, the MLP model achieved the best performance, with an AUC of 0.869 in the training set and 0.851 in the test set. Clinical decision curve analysis indicated that the MLP model provides significant clinical utility. An MLP-based calculator was developed to support surgical prognostic assessment in patients with DLS.

Conclusion： Preoperative ODI, postoperative PI-LL, preoperative PF, preoperative Cobb angle, the number of decompression segments, and postoperative LL were defined as independent predictors of surgical prognosis in patients with DLS. The MLP-based models demonstrated robust performance, providing a valuable tool for prognosis prediction.

Key words: Lumbar scoliosis, Deformity correction, Surgery, Prognosis prediction, Machine learning, Quality of life.

Introduction

Degenerative lumbar scoliosis (DLS) is a complex spinal disorder and has become a prominent focus in contemporary spine research and clinical practice[1]. Its clinical presentation ranges from axial stiffness and back pain to progressive neurological impairment, substantially diminishing patients' quality of life[2]. Surgical intervention is typically considered for individuals with severe back and/or neurological symptoms[3]. Despite extensive investigation into diverse surgical strategies for DLS, the marked heterogeneity in clinical manifestations and structural deformities continues to complicate the evaluation of surgical outcomes.

Accurate prediction of surgical prognosis is essential for formulating appropriate operative strategies. Several studies have studied examined prognostic factors associated with surgical outcomes in patients with DLS[1, 4, 5]. Pre- and postoperative deformity parameters, as well as the magnitude of deformity correction are generally considered to be closely related to postoperative prognosis[4, 5]. However, despite the identification of many relevant variables, two major challenges remain unsolved. Firstly, there is no quantitative reference standard to guide surgeons in achieving maximum therapeutic benefit with minimal surgical morbidity. The optimal extent of deformity correction remains controversial. Some investigators argue that complete deformity correction is necessary to achieve satisfactory treatment outcomes[6-8], whereas others report that aggressive correction may increase surgical trauma and that modest, targeted correction may yield superior functional improvement[9]. Secondly, factors beyond deformity-related parameters, including age, sex, intraoperative blood loss, operative duration, number of fusion segments and extent of decompression may substantially influence the prognosis of DLS surgery, yet few studies have systematically evaluated their prognostic value. Consequently, accurate prediction of surgical outcomes in DLS

remain challenging. Developing an appropriate prognostic model can substantially improve the accuracy of predicting surgical outcomes and provide quantitative evidence to guide individualized treatment planning for patients with DLS.

Accordingly, this study aimed to investigate the outcomes of surgery in DLS, identify independent prognostic factors, and construct validated predictive models to assess the probability of achieving a satisfactory outcome (SO). The optimal model was subsequently selected based on performance metrics. To the best of our knowledge, this represents the first predictive model specifically designed to predict surgical outcomes in patients with DLS.

Patients and methods

Study design and study population

This retrospective case-control study evaluated patients with DLS who underwent surgery at *the Xijing Hospital of the Air Force Medical University* between January 2011 and October 2023. Inclusion criteria were: 1) aged 40 years or older; 2) radiographic diagnosis of DLS, defined as a coronal Cobb angle > 10°; 3) neurological impairment; 4) treatment with a posterior-only procedure for adult scoliosis; 5) a minimum follow-up of 2-years. Exclusion criteria were: 1) a history of spinal surgery, and 2) a history of spinal deformity during childhood or adolescence.

Surgical Procedure

All patients underwent posterior spinal decompression and instrumented fusion. Auxiliary surgery, including facetectomy, osteotomy and decompression by laminectomy and foraminotomy, was performed according to individual pathoanatomical characteristics.

Data collection

Demographic and operative variables (age, sex, comorbidities, operative duration, intraoperative blood loss, hospital stay, decompression segments, fusion segments and postoperative complications) were extracted from the hospital electronic medical records. Radiographic parameters were measured on standing spine radiographs preoperatively and postoperatively. Variables included the Cobb angle, lumbar lordosis (LL), and spinopelvic parameters including pelvic tilt (PT), pelvis incidence (PI) and sacral slope (SS). PI-LL was also calculated. Correction of angles was defined as the preoperative value minus the postoperative value. The correction of PI-LL was defined as the absolute value after the operation minus the absolute value before the operation. Therefore, a positive value indicated a postoperative increase, and a negative value indicated a decrease.

Surgical outcome was evaluated using Oswestry Disability Index (ODI) and the Short Form-36 (SF-36) Physical Functioning (PF) and Mental Health (MH) subscales, postoperative complications and revision surgery. The ODI questionnaire has been validated for use in Chinese[10]. Consistent with prior literature, ODI≤22 was considered as an acceptable symptom state[11]. The SF-36 questionnaire has been validated for a number of orthopedic conditions and surgeries[12, 13] and for use in Chinese[14]. Postoperative PF and MH subscale scores reaching the normative values of the general healthy population (**Supplementary table 1**) were considered satisfactory[13]. And SO required meeting all four criteria: 1) ODI ≤ 22; 2) PF and MH at or above normative values; 3) no postoperative complications; 4) no revision surgery.

To ensure reliability, three surgeons with over 20 years of experience in spine surgery independently evaluated all cases. Mean values were used for quantitative variables, and medians for ordinal variables.

Supplementary table 1 mean scores on dimensions of SF-36[11]

Age (years)	Physical functioning	Mental health
16-24	94	74
25-34	95	73
35-44	89	70
45-54	84	72
55-64	74	74
65-74	60	73

135

136 *Statistical Analysis*

137 Descriptive statistics were conducted to characterize the study populations.
138 Categorical variables were described as frequencies and percentages, and continuous
139 variables were presented as mean values with standard deviation (SD) or median with
140 interquartile range (IQR). Comparisons between patients achieving SO and those who
141 did not were performed using the Pearson χ^2 test for categorical variables and the
142 Kruskal-Wallis test for continuous variables. To identify prognostic factors, the Least
143 Absolute Shrinkage and Selection Operator (LASSO) regression was applied to select
144 variables associated with surgical outcomes of patients with DLS. The Shapley
145 Additive Explanations (SHAP) method was applied to rank the importance of each
146 variable. Four predictive models were developed: Logistic Regression, K-Nearest
147 Neighbors (KNN), Multi-layer Perceptron (MLP), and Naive Bayes.

148 Model performance was evaluated using the area under the receiver operating
149 characteristic curve (AUC) and decision curve analysis (DCA) to assess discriminative
150 ability and clinical utility, respectively. The optimal model was selected based on
151 comparative performance. A user-friendly prediction calculator was then constructed,
152 consisting of a parameter-input panel and a results-output model.

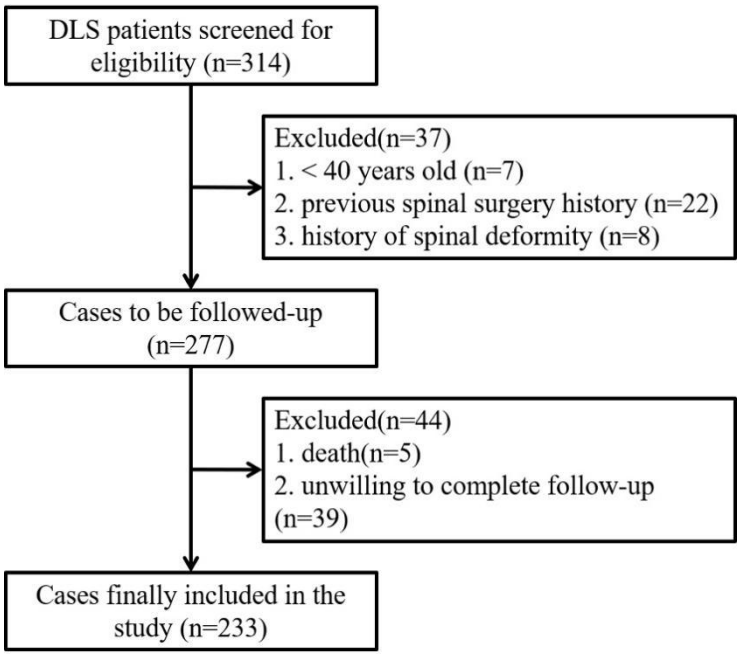
153 All statistical analyses were performed using SPSS 17.0 and R 4.0.4 with packages
154 ggplot2, rms, Rcpp, tidyverse, caret, leap, MASS, pROC, InformationValue, neuralnet,

shiny. Statistical significance was defined as $P < 0.05$. No multiplicity adjustment was performed for P values.

Results

Patient characteristics

A total of 314 DLS patients who underwent surgery were identified based on preoperative imaging and medical record in this study. Among them, 233 patients who met the inclusion criteria were enrolled (**Fig. 1**). The clinicopathologic characteristics of the patients were listed in **Table 1**. The symptoms of the included cases mainly included low back pain, lower limb pain, leg numbness and neurogenic claudication. Most of the cases (212 cases) underwent grade 1 or 2 osteotomy, such as Smith-Petersen osteotomy and Ponte osteotomy. Eleven patients underwent grade 3 or higher osteotomy, including pedicle subtraction osteotomy and vertebral column resection. The median follow-up period was 4.5 years (range: 2-10 years). All patients' quality of life were improved at last follow-up. Postoperative complications occurred in 27 cases, most of which were degeneration of adjacent segments (**Supplementary table 2**). No patient received revision. According to the standard set by this research, SO was ultimately achieved in 99 (42.4%) patients.



172

173 **Fig. 1** Patient disposition flowchart.

174

Table 1 Patient Characteristics

Characteristics	SO (n=99)	USO (n=134)	P
Age (y, mean ± S.D.)	60.4 ± 8.5	62.2 ± 7.8	0.099
Sex (%)			0.307
Male (%)	25(25.3)	21 (31.3)	
Female (%)	74 (74.7)	46 (68.7)	
Surgical blood loss [ml, median (IQR)]	800 (300-1200)	800 (400-1600)	0.41
Operation time [min, median (IQR)]	305 (210-370)	320 (220-415)	0.18
No. of fused segments [median (IQR)]	5 (3-6)	5 (3-7)	0.25
No. of decompression segments [median (IQR)]	2 (2-3)	3 (2-4)	<0.001*
Underlying diseases (%)	28 (28.3)	36 (26.9)	0.81
Cobb angle (°, mean ± S.D.)			
Preoperative	20.3 ± 9.9	18.9 ± 6.7	0.23
Postoperative	9.1 ± 7.3	9.3 ± 5.8	0.78
Correction	11.2 ± 8.4	9.6 ± 7.5	0.13
LL (°, mean ± S.D.)			
Preoperative	37.3 ± 17.1	33.2 ± 15.0	0.06
Postoperative	42.6 ± 11.6	38.4 ± 11.6	0.01*
Correction	-5.3 ± 11.6	-5.2 ± 11.7	0.93
PI (°, mean ± S.D.)			
Preoperative	48.6 ± 10.2	49.4 ± 11.2	0.56
Postoperative	48.3 ± 10.2	49.2 ± 10.8	0.55

Correction	-0.3 ± 1.1	-0.3 ± 1.9	0.99
PT (°, mean ± S.D.)			
Preoperative	17.6 ± 9.0	22.0 ± 10.2	0.001*
Postoperative	15.1 ± 7.5	18.4 ± 8.8	0.002*
Correction	2.3 ± 6.2	3.3 ± 8.2	0.26
SS (°, mean ± S.D.)			
Preoperative	31.0 ± 10.2	27.4 ± 10.7	0.01*
Postoperative	33.2 ± 10.0	30.7 ± 8.0	0.04*
Correction	2.3 ± 6.2	3.3 ± 8.2	0.26
PI-LL (°, mean ± S.D.)			
Preoperative	12.5 ± 12.6	17.5 ± 12.0	0.002*
Postoperative	7.2 ± 7.5	11.8 ± 9.2	<0.001*
Correction	5.3 ± 11.3	5.6 ± 10.8	0.80
Preoperative ODI [median (IQR)]	53 (50-60)	60 (57-67)	<0.001*
Preoperative SF-36/ physical function [median (IQR)]	40 (30-55)	25 (10-35)	<0.001*
Preoperative SF-36/ mental health [median (IQR)]	48 (44-60)	48 (44-52)	0.005*

Abbreviations: SO: Satisfactory outcome; USO: Unsatisfactory outcome; S.D., Standard deviation; IQR, Interquartile Range; LL: lumbar lordosis; PI: pelvic incidence; PT: pelvic tilt; SS: sacral slope; PI-LL: Pelvic incidence minus lumbar lordosis; ODI: Owestry Disability Index; SF-36: Short Form 36; PF: physical function, MH: mental health. * indicates P<0.05.

Supplementary table 2 Postoperative Complications

Complications	No. of cases
Urinary tract infection	2
Superficial infection	2
leakage of cerebrospinal fluid	3
pulmonary infection	1
Transient neurologic deficit	2
Adjacent segment disease	17

Selection of variables

We initially performed a correlation analysis among the variables, revealing significant correlations (Fig. 2a). To reduce multicollinearity, we applied LASSO regression for feature selection (Fig. 2(b and c)). Six predictive variables were selected, including “number of decompression segments,” “preoperative Cobb,” “postoperative LL,” “postoperative PI-LL,” “preoperative ODI,” and “preoperative PF.” Coefficients for each selected variable are shown in Fig. 2(d).

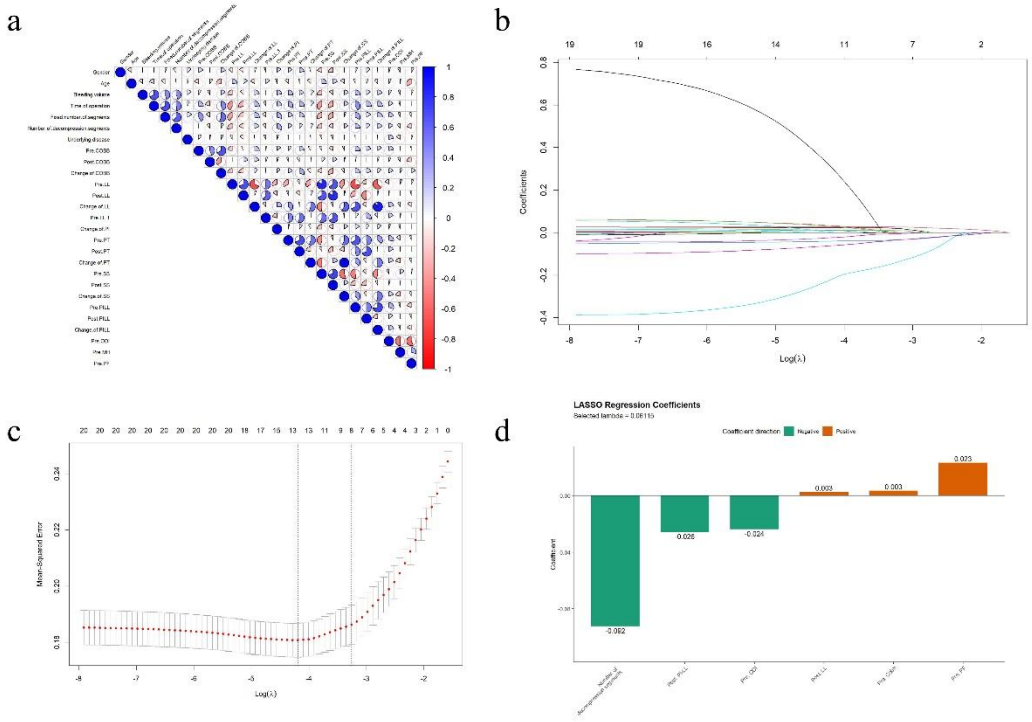


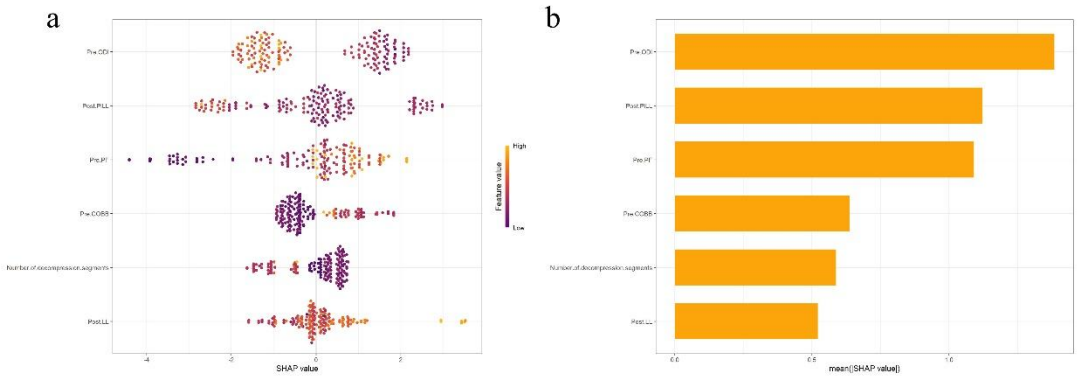
Fig. 2 Process of Selecting Variables through LASSO Regression. (a) Correlation heatmap of continuous variables, with larger pie segments indicating stronger correlations. (b) LASSO coefficient profiles of the 27 variables. The coefficient profile plot was produced against the log (λ) sequence. The best penalty coefficient lambda was selected using a tenfold cross-validation and minimization criterion. (c) By verifying the optimal parameter (λ) in the LASSO model, the binomial deviance curve was plotted versus log (λ) and dotted vertical lines were drawn. 6 variables with nonzero coefficients were selected by lambda.se. (d) Coefficients for Variables with Nonzero

198 Coefficients Selected by Lambda.min.

199

200 *Shapley Additive Explanations* (*SHAP) analysis and interpretation*

201 As shown in Figure 3(a), the SHAP visualization ranks the six most important risk
202 factors associated with postoperative outcomes in patients with DLS. The most
203 influential factors in ranking order were preoperative ODI, postoperative PI-LL,
204 preoperative PF, preoperative Cobb angle, number of decompression segments, and
205 postoperative LL (Figure 3b).



206

207 **Fig. 3** SHAP Interpretation of the Model. **(a).** SHAP values for all samples and features,
208 with each row representing a feature and the *x*-axis indicating the SHAP value. Yellow
209 dots denote higher feature values, while purple dots indicate lower feature values. **(b).**
210 Ranking of variable importance based on mean SHAP values. The most influential
211 factors in ranking order were preoperative ODI, postoperative PI-LL, preoperative PF,
212 preoperative Cobb angle, number of decompression segments, and postoperative LL.

213

214 *Model construction and validation*

215 All subjects were randomly divided into training and test sets at a ratio of 7:3.
216 Based on the six variables selected by LASSO regression, four machine learning
217 algorithms—Logistic Regression, KNN, MLP, and Naive Bayes—were used to

construct and validate predictive models in the training set.

The MLP model demonstrated strong predictive performance in both the training and test sets, with AUCs of 0.869 (95% CI 0.818–0.921) and 0.851 (95% CI 0.764–0.938), respectively (**see** Figure 4). A comprehensive performance summary for each model is presented in Table 2. DCA curves showed that, across threshold probabilities ranging from 0.00 to 0.80, all six models yielded positive net benefits for predicting SO in patients undergoing DLS surgery in both the training and validation cohorts. The MLP model provided the highest net benefit across most threshold ranges, suggesting good clinical utility (Fig. 5).

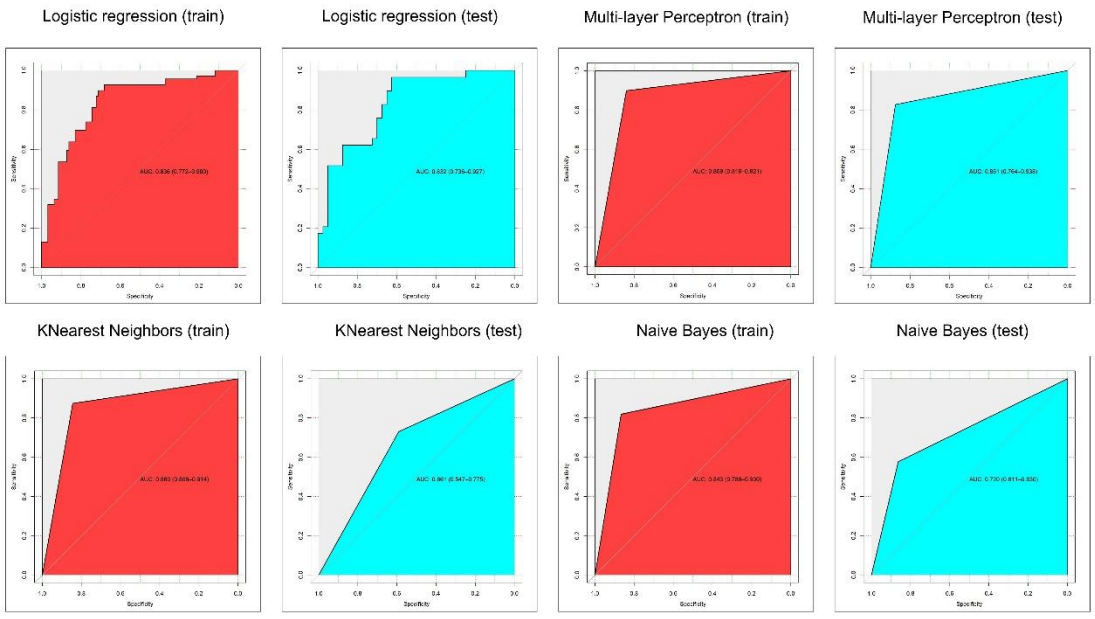


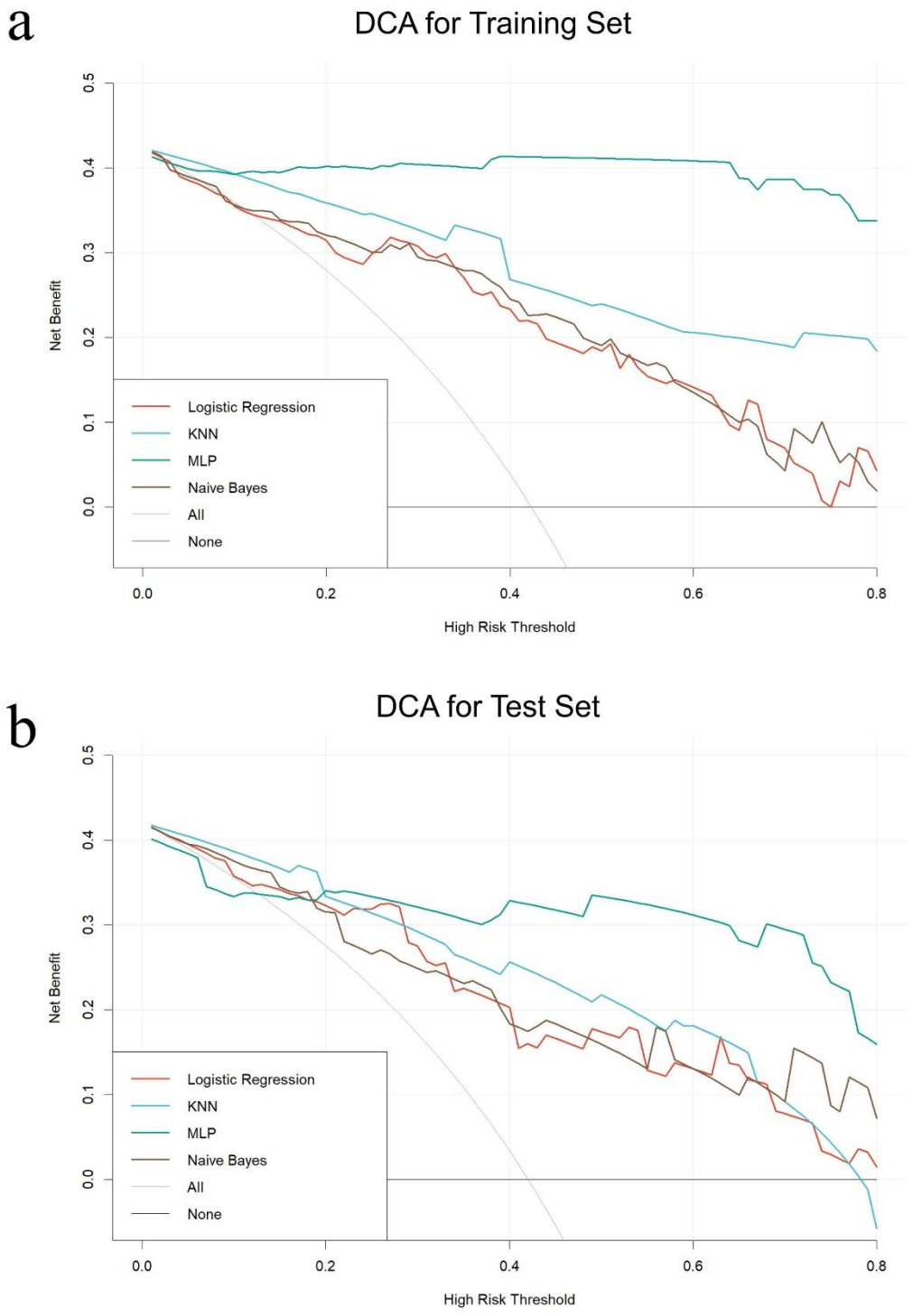
Fig.4 ROC Curves for Four Machine Learning Models. Pink represents the training set, and light green represents the test set. The MLP model demonstrated strong predictive performance in both the training and test sets, with AUCs of 0.869 (95% CI 0.818–0.921) and 0.851 (95% CI 0.764–0.938), respectively.

Table 2 Performance of four models

	AUC (95%CI)	F1	Accuracy	Sensitivity	Specificity
Logistic regression (training)	0.836(0.772-0.900)	0.711	0.760	0.727	0.784
Logistic regression (test)	0.832(0.736-0.927)	0.679	0.754	0.750	0.756
MLP (training)	0.870(0.818-0.921)	0.849	0.865	0.805	0.918
MLP (test)	0.851(0.764-0.935)	0.828	0.855	0.827	0.875
KNN (training)	0.860(0.806-0.914)	0.846	0.858	0.818	0.894
KNN (test)	0.661(0.547-0.775)	0.603	0.643	0.513	0.788
Naïve Bayes (training)	0.843(0.786-0.900)	0.825	0.846	0.831	0.857
Naïve Bayes (test)	0.720(0.611-0.830)	0.638	0.757	0.714	0.776

Abbreviations: MLP: Multi-layer Perceptron; KNN: K-Nearest Neighbors.

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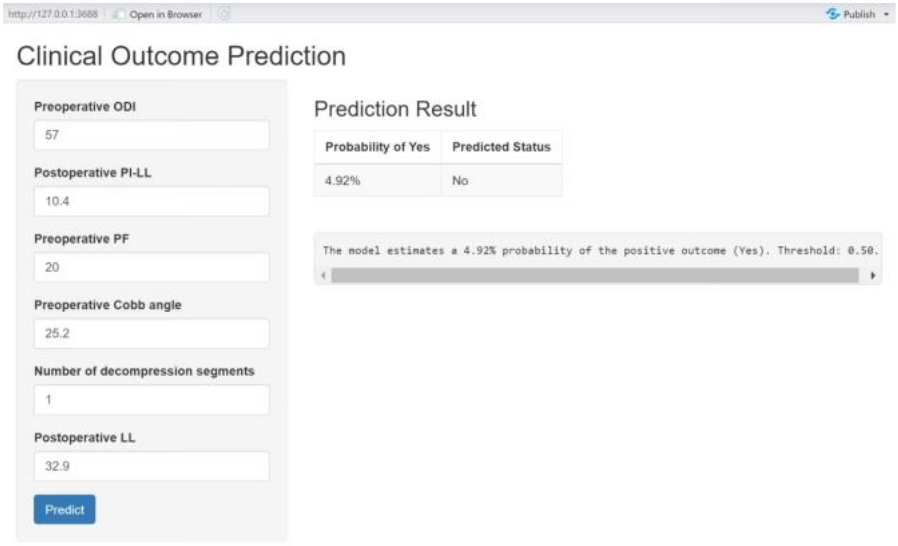
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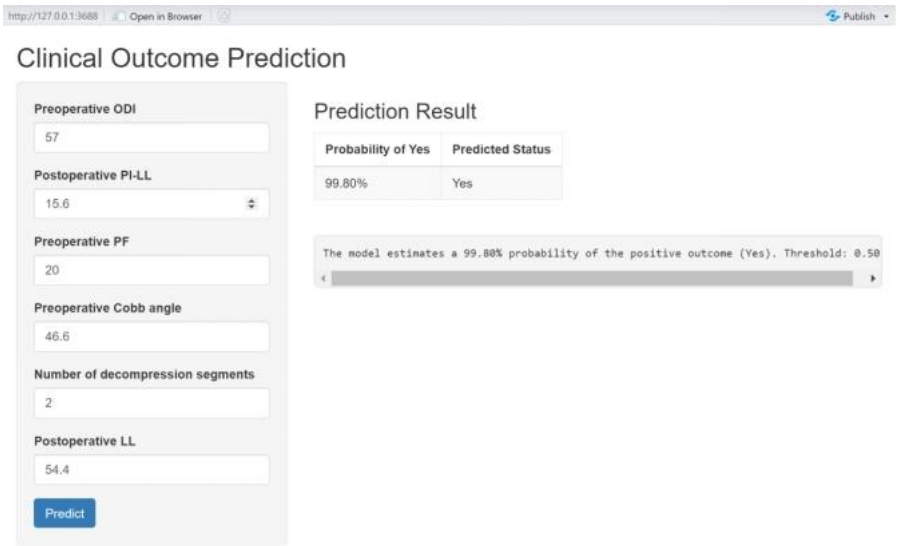
234 **Fig. 5** Decision Curves for Four Machine Learning Models: **(a)** Training Set, **(b)**

235 Testing Set.

236

To facilitate the prediction of surgical outcomes in patients with DLS, we further developed a calculator based on the optimal predictive model to estimate the probability of achieving an SO. The calculator consists of an input panel for entering model parameters and an output panel that displays individualized prediction results (**Supplementary Fig. 1**).





Supplementary Fig. 1 MLP-Based Calculator for Predicting Surgical Outcomes

in Patients with Degenerative Lumbar Scoliosis.

Discussion

The incidence of both DLS and the number of related surgical procedures continue to rise as the elderly population grows[3, 15]. Because of age-related physiological vulnerability and the complexity of DLS pathology, postoperative recovery and long-term outcomes remain difficult to anticipate. A reliable predictive model is therefore essential for supporting clinical decision-making and improving patient counseling.

In this study, SO was defined using postoperative ODI score, SF-36 PF and MH scores, complication status, and revision surgery. Based on these criteria, we retrospectively analyzed the clinical and radiographic characteristics of patients with DLS. LASSO regression identified six independent risk factors: preoperative ODI, postoperative PI-LL, preoperative PF, preoperative Cobb angle, number of decompression segments, and postoperative LL, which were selected to construct four predictive models. Model validation demonstrated that MLP exhibited the most robust discriminative power and clinical utility. An MLP-based calculator was subsequently developed to estimate individualized probabilities of achieving SO in patients with DLS, providing clinicians with an accessible tool for outcome prediction.

The six predictors identified in this study are consistent with previously reported prognostic factors in DLS surgery[6, 16-18]. A greater number of decompressed segments reflects more extensive surgical trauma, increased risk of spinal cord or nerve root injury and longer operative duration[18], all of which may compromise postoperative recovery. Preoperative ODI and PF also emerged as important predictors, aligning with the intuitive observation that patients with better baseline function and lower disability are more likely to achieve favorable postoperative outcomes.

The Cobb Angle remains a fundamental measure of coronal deformity in DLS[17]

and has been correlated with quality of life of patients with scoliosis[8, 19]. This study has reached a similar conclusion that the Cobb angle is associated with the surgical outcome of DLS patients. More importantly, the nomogram revealed that the Cobb angle exerted a weaker influence on postoperative quality of life compared with the sagittal balance parameter PI-LL. Sagittal alignment has increasingly been recognized as a major determinant of disability in adult spinal deformity, and has been shown to have a tremendous impact on health[20]. PI-LL, an important indicator of sagittal spinal balance, has been shown to guide perioperative planning and predict postoperative function. Prior studies highlighted PI–LL as a critical target for deformity correction and a potential contributor to adjacent segment disease when excessively elevated[6, 16, 21]. Research. from our group and others further showed that patients with high PI-LL may benefit from larger corrective adjustments[22, 23]. Despite extensive investigation, the optimal PI-LL target remains debated, with evidence indicating that that optimal alignment varied by ethnicity[9], preoperative PI[24] and age[25]. In our cohort, postoperative PI-LL was the second most influential predictor of surgical outcomes in patients with DLS, surpassed only by preoperative ODI.

Among our machine learning models, the MLP model demonstrated high predictive accuracy in both the training and test sets. The resulting MLP-based calculator enables surgeons to incorporate objective, data-driven prognostic information into preoperative planning rather than relying solely on individual experience. This tool may enhance risk stratification, improve patient counseling, and support personalized surgical strategies. This study has several limitations. Firstly, variables used to predict the surgical outcome were limited to those available in the institutional medical records database, unmeasured factors may influence prognosis and reduce model robustness. Secondly, postoperative recovery time was not analyzed

because patients often could not recall the precise timing of functional improvement, making reliable documentation difficult. Future prospective follow-up will allow more accurate temporal modeling. Thirdly, the sample size was relatively small, expanding the dataset will strengthen model training and improve generalizability.

Conclusions

Preoperative ODI, postoperative PI-LL, preoperative PF, preoperative Cobb angle, number of decompression segments, and postoperative LL were identified as independent predictors of surgical prognosis in patients with DLS. The MLP-based predictive model demonstrated strong predictive performance and offers a practical tool for identifying high-risk individuals and guiding surgical decision-making.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate

This study was conducted in accordance with the principles of the Declaration of Helsinki, it was approved by the Institutional Review Board of Xijing Hospital (ethics approval No. KY20201017-C-1) on October 8, 2020. The requirement for informed

consent was waived by the Institutional Review Board of Xijing Hospital. All participants were aged 40 years or older; therefore, no minors were enrolled, and parental or legal guardian consent was not required.

Consent for publication

Not applicable.

Conflict of interest

The authors declare that they have no financial or other conflicts of interest in relation to this study and its publication.

Author contribution

Hao Bai, Jing Wang, and Kaili Hao drafted the manuscript, analyzed the data, and prepared the figures. Xiong Zhao, Zhensheng Ma, Tianqing Li, Yang Zhang, and Tianchen Ma collected and measured the data. Wei Lei, Zixiang Wu, and Fengyafei designed the study and revised the manuscript. All authors reviewed the manuscript.

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