Article

A Prediction Model for Surgical Decision-Making in Rotator Cuff Tears Using Anatomical and Functional Factors

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AIM: This study aims to develop a clinical prediction model that integrates anatomical characteristics, functional status, and relevant clinical factors to guide surgical decision-making for rotator cuff tears.
METHODS: This retrospective study included patients with rotator cuff tears treated at Peking University International Hospital between March 2019 and February 2022. A total of 337 patients meeting the predefined inclusion criteria were selected and divided into a surgical group (n = 100) and a non-surgical group (n = 237) based on whether they underwent surgical or non-surgical treatment. By systematically reviewing electronic medical records, we collected demographic information, clinical characteristics (affected shoulder, history of shoulder trauma, and duration of symptoms), Neer classification, Neer impingement test results, and Jobe test results. Based on magnetic resonance imaging data, professional physicians evaluated acromion morphology classification and measured the acromion–humeral distance. Quantitative evaluation of shoulder function was performed using the modified Constant-Murley Score, with individual component scores systematically recorded to enable a detailed functional assessment. Statistical analysis was completed using R software. Specifically, baseline characteristics of the two patient groups were compared and analyzed. A backward stepwise selection method was subsequently used in the multivariate logistic regression analysis to identify independent predictors related to surgical decisions and construct a prediction model that estimates the probability of surgical intervention for patients with rotator cuff tears. The model's performance was comprehensively evaluated across three dimensions: discrimination ability, calibration, and clinical utility.
RESULTS: There were significant differences between the two groups in terms of age, shape of the acromion, positive rate of the Jobe sign, Neer classification, and functional score ($p < 0.05$). Multivariate logistic regression analysis demonstrated that age (odds ratio [OR] = 1.070), tear depth (OR = 4.414), types II and III acromion (OR = 8.138 and 11.209), and increased abduction angle (OR = 1.800) were independent predictors of surgical intervention. In contrast, external rotation (OR = 0.566), increased internal rotation angle (OR = 0.696), and Neer classification (OR = 0.297) were negative predictors (all $p < 0.05$). The constructed nomogram prediction model based on these predictors displayed excellent discrimination (area under the curve = 0.934, sensitivity = 0.890, specificity = 0.840) and calibration (Hosmer-Lemeshow test, $p = 0.9977$). Furthermore, the decision curve analysis confirmed its clinical utility.
CONCLUSIONS: This study developed a prediction model based on a nomogram, utilizing selected anatomical, functional, and clinical factors to assess the probability of surgical treatment for patients with rotator cuff tears. Internal validation demonstrated the model's good discriminatory ability and acceptable calibration. These findings suggest the model may aid in risk stratification and treatment selection; however, external validation and prospective impact studies are required before routine clinical implementation.

Keywords: rotator cuff tears; prediction model; surgical indications; acromion morphology; risk stratification

Introduction

Rotator cuff tears are common shoulder disorders. Variability in pathology and presentation challenges surgical decision-making and leads to persistent disagreement over indications [1,2]. The incidence of rotator cuff tears increases with age, significantly affecting patients' quality of life. Treatment options involve a tradeoff between conservative treatment and surgical intervention. Existing guidelines mostly rely on anatomical parameters, such as tear size and acromion morphology, and demographic factors, such as the patient's age. However, the accuracy of these factors as independent predictive indicators is limited, and they cannot fully support personalized treatment [3].

Recently, functional biomechanical indicators, such as abduction and external rotation range of motion, have been used to assess tear severity and the risk of conservative treatment failure. Nevertheless, effective tools for integrating these functional indicators with anatomical features are still lacking [2,4]. Currently, research on predictive mod-

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els mostly focuses on a single dimension and fails to comprehensively quantify surgical requirements. Moreover, it lacks a clear modeling validation process [2].

This study aims to construct a predictive model integrating anatomical and functional factors. We developed this model using retrospective data and conducted an internal validation to assess its discrimination, calibration, and clinical utility. The findings may aid in risk stratification and treatment selection for patients with rotator cuff tears.

Methods

Study Population

This study retrospectively enrolled 337 patients from Peking University International Hospital between March 2019 and February 2022. The patients were divided into a surgical group (SG) (n = 100) and a non-surgical group (N-SG) (n = 237) based on their treatment methods. The patient screening process is illustrated in Fig. 1.

Data on the patient's sex, age, affected shoulder, shoulder trauma situation, symptom duration, Neer sign [5], Neer grade [6], and Jobe sign [7] were collected from medical records and analyzed.

The Neer sign [6] is mainly used to diagnose subacromial impingement syndrome. The examiner stood behind the patient, stabilized the scapula with one hand, and maintained the shoulder joint in internal rotation with the other hand. The thumb of the affected arm was positioned downward. The affected shoulder was then flexed above the head. If pain was elicited, the test was deemed positive, indicating that the structures under the acromion are compressed and that a rotator cuff injury may be present.

The Jobe sign [8], also known as the empty can test, is commonly used to assess supraspinatus muscle function. During the examination, the patient is instructed to elevate the shoulder joint to 90° within the scapular plane (approximately 30° anterior to the coronal plane) while maintaining internal rotation with the thumb pointing downward. The examiner then applies downward resistance as the patient attempts to maintain the elevated position. If pain or weakness occurs during this maneuver, it is considered positive, indicating a supraspinatus-related pathology.

Regarding the severity assessment, Neer grade [7], also known as the rotator cuff injury classification, is as follows: Grade 0: No signal of rotator cuff injury is detected on the MRI; Grade 1 (mild): Edema and congestion in the rotator cuff tendons, which may indicate a mild tear. Abnormal signals in tendons can be observed using magnetic resonance imaging (MRI); Grade 2 (moderate): Partial tear of the rotator cuff tendons (not penetrating the entire tendon layer) accompanied by thinning and fibrosis of the tendon; Grade 3 (severe): Complete tear of the rotator cuff, with complete disruption of the tendon. Based on the Ellman classification of rotator cuff tear depth: Grade 0: There is tendon degeneration, edema, etc., but no tear; Grade 1: The tear depth is less than 3 mm; Grade 2: The tear depth is between 3 and 6 mm; Grade 3: The tear depth is greater than 6 mm or exceeds 50% of the full thickness of the tendon [9].

Classification of Acromion Type

The types of acromions were classified based on MRI-observed morphology using a previously established classification system. This system classifies acromion types into three categories: Type I (flat type), Type II (arc-shaped type), and Type III (hook-shaped type) (Fig. 2) [8]. Differences in acromion morphology are associated with mechanical impacts and rotator cuff lesions, highlighting the significance of this classification. Two experienced musculoskeletal radiologists independently reviewed the MRI images to ensure the reliability of the assessment. Disagreements in classification were resolved through consensus discussions.

Measurement of AHD

MRI assessments were performed using 1.5 Tesla (T) MRI scanners (GE Signa HDxt, GE Medical Systems, LLC, Waukesha, WI, USA) equipped with a specialized shoulder coil. Acromio-humeral distance (AHD) was measured following the method described by Siow *et al*. [10]. A picture archiving and communication system (PACS) from the Radiology Department (GE PACS Workstation) was used. An average value was obtained from independent assessments by a rehabilitation physician specializing in shoulder surgery and an experienced musculoskeletal radiologist to ensure measurement reliability. AHD was measured in millimeters from coronal oblique T1-weighted images, focusing on the minimal distance between the subchondral bone plate of the humeral head and cortical margin of the acromion (Fig. 3). Rotator cuff tear severity was classified based on MRI findings by an experienced orthopedic surgeon: grade 1, superficial tear; grade 2, moderate tear (with tear thickness reaching 50%); grade 3, deep tear (with tear thickness >50% or approaching a full-thickness tear) (Fig. 3) [8].

In coronal oblique T1-weighted MRI (Fig. 3), the shortest distance between the cortical margin of the acromion and the subchondral bone surface of the humeral head was measured.

CMS Assessment

We employed the Constant-Murley Shoulder Score (CMS) as a comprehensive indicator to evaluate functional limitations in patients with shoulder disorders. CMS is a well-established, standardized tool that integrates objective measurements and patient self-reports to assess overall shoulder function [7]. It encompasses multiple areas, including pain (15 points), activities of daily living (20 points), range of motion (40 points), and strength (25 points), thereby offering a comprehensive reflection of a patient's functional ability [11].

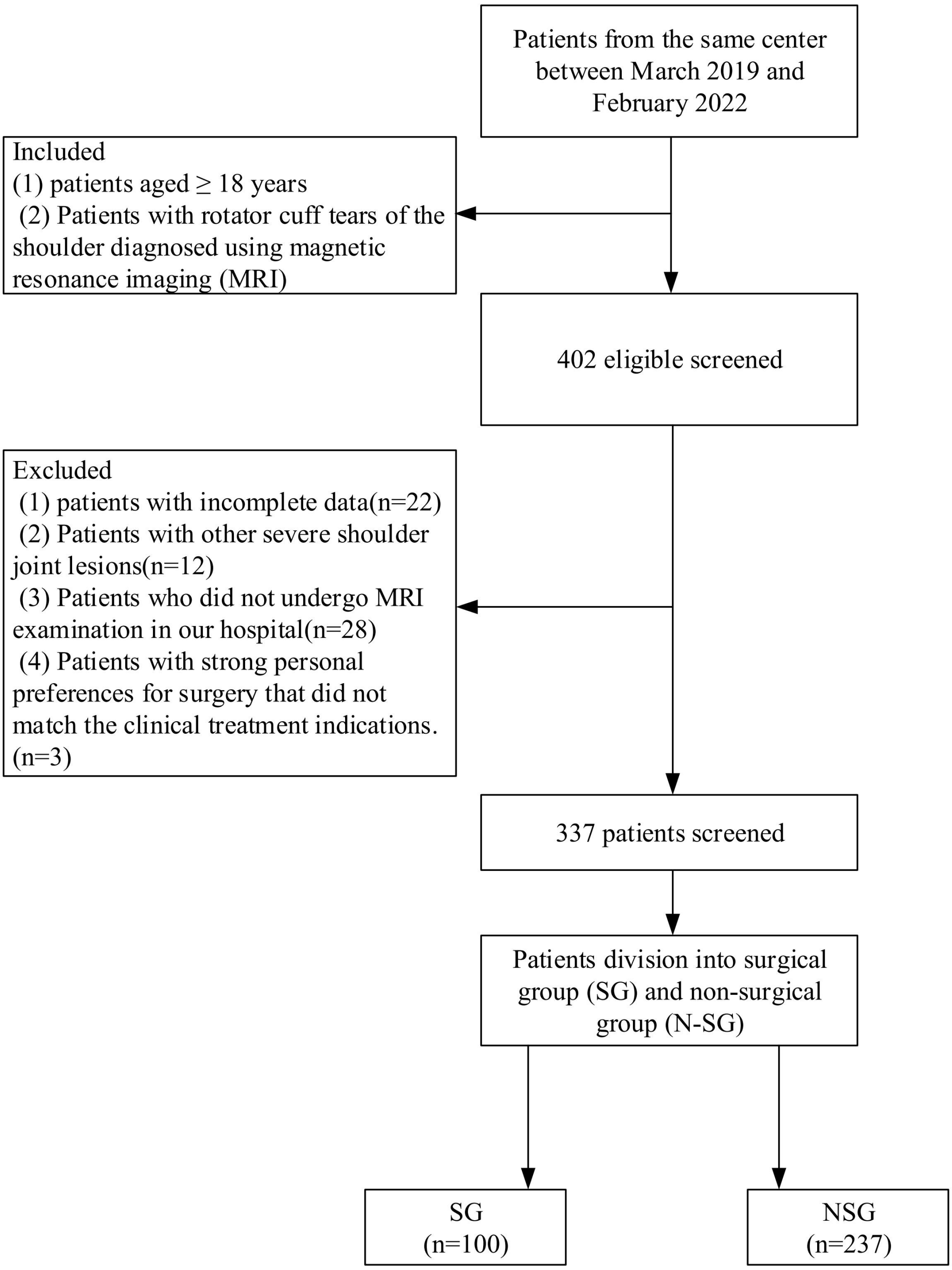

Fig. 1. Process of research subject selection.

Pain was categorized into four levels: no pain (15 points), mild pain (10 points), moderate pain (5 points), and severe pain (0 points). Activities of daily living were assessed in two domains: activity level (10 points) and pain-free range of motion to reach specific body positions (10 points). Activity level comprises three components: work limitations, leisure activity limitations, and sleep disturbance, each contributing to the overall score. Work and leisure limitations were classified into three grades: no limitation (4 points), moderate limitation (2 points), and severe limitation (0 points). Sleep disturbance was graded as follows: no disturbance (2 points), occasional disturbance (1 point), or frequent disturbance (0 points). The pain-free reaching position was evaluated across five anatomical landmarks: mid-back (2 points), xiphoid process (4 points), neck (6 points), head-neck junction (8 points), and above the head (10 points). Active range of motion assessment includes shoulder flexion, abduction, external rotation, and internal rotation, with each movement scoring up to 10 points. Flexion and abduction were graded on a six-point scale: 0–30°

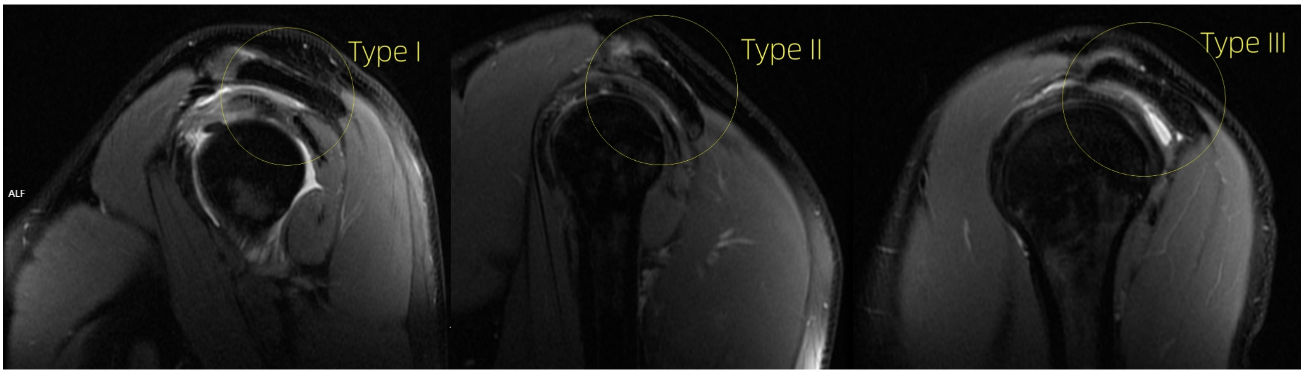

Fig. 2. Three typical acromion shapes were observed on magnetic resonance imaging (MRI).

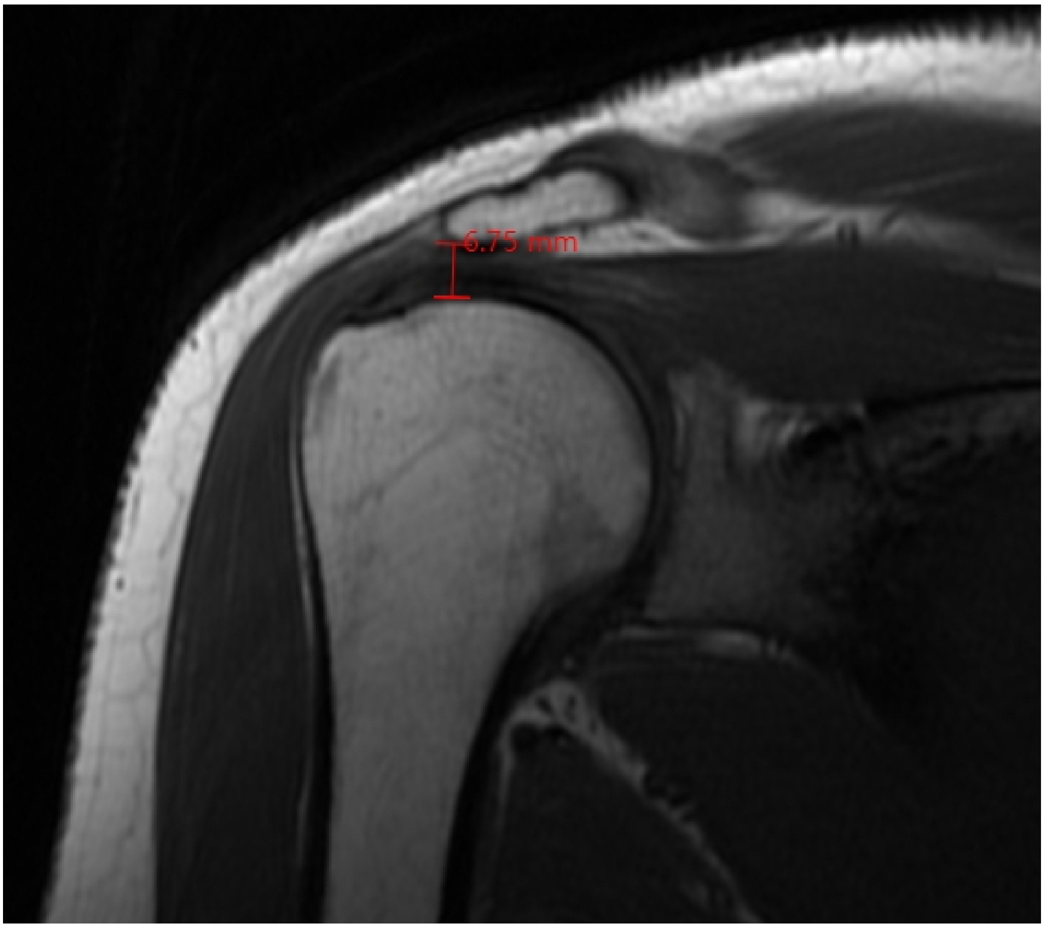

Fig. 3. Measurement of acromio-humeral distance (AHD) on coronal oblique MRI.

(0 points), 31–60° (2 points), 61–90° (4 points), 91–120° (6 points), 121–150° (8 points), and 151–180° (10 points). External rotation was scored on a scale of 2–10, in increments of 2, based on the highest achievable hand position relative to the head, with higher scores indicating better functional ability. Internal rotation was assessed by the highest reachable vertebral level or anatomical site, scored on a 6-point scale from 0 to 10, with higher values reflecting improved function. We performed a statistical analysis of individual item scores to determine the predictive value of each indicator. However, we encountered challenges with strength measurements due to difficulties maintaining the required 90-degree shoulder abduction, leading to variable outcomes. To ensure data reliability and consistency, we adopted a modified version of CMS, as described in the literature [10]. This modification excluded the strength component, yielding a maximum possible score of 75 points compared to the standard 100. The maximum possible score for the revised version of the CMS grading system is 75 points (excluding the original 25-point muscle strength assessment component). This adjustment reflects the absence of a strength domain, which usually adds 25

points to the total CMS. Previous studies have confirmed the efficacy of a modified CMS score based on clinical conditions [12–14].

Sample Size Calculation

As this was a retrospective study, we assessed the adequacy of our sample size using established criteria for developing a prediction model [15]. We followed the contemporary framework proposed by Riley *et al*. [15] to estimate the required sample size for the new binary prediction model. Eight candidate predictor variables were considered: six numeric variables and one three-level categorical variable (requiring two dummy variables). Since no previously published model provided a Cox-Snell R^2 for our specific population and outcome, we used the C-statistic along with the prevalence to calculate sample size with the 'pmsampsize' function in R package (version 4.3.1, R Foundation for Statistical Computing, Vienna, Austria).

Based on an anticipated C-statistic of 0.93 and a prevalence of 29.7% for the event of interest, a minimum of 321 participants was recommended to ensure model stability. Our final study (n = 337) exceeded this threshold, suggesting a sufficient sample size for a reliable model estimation.

Statistical Analysis

All statistical analyses were conducted using R software (version 4.3.1; R Foundation for Statistical Computing, Vienna, Austria). Normality of the data was evaluated using the Shapiro–Wilk test. Descriptive statistics are presented as the median interquartile range (IQR), which is suitable for non-normally distributed data. The χ^2 test was used for categorical data, and the Mann–Whitney U test was employed for non-normally distributed continuous variables. Multivariate logistic regression with backward stepwise selection was used to identify factors associated with the decision to undergo surgery and to develop a predictive model. The results were presented as odds ratios (ORs) with corresponding 95% confidence intervals (CIs). A nomogram was created using multivariate logistic regression to estimate the probability of surgical decision-making in rotator cuff tears. The model performance was evaluated in terms of discrimination, calibration, and clinical utility. Discrimination was quantified using the area under the curve (AUC). Internal validation was performed using bootstrap 1000 resampling and 10-fold cross-validation to improve reliability. Calibration was assessed using a calibration curve that plotted the observed probabilities against predicted probabilities. Clinical utility was assessed using decision curve analysis (DCA), which quantifies the net benefit across a range of threshold probabilities to evaluate the model's potential to inform clinical decision-making.

Inter-Rater Reliability Analysis

The intraclass correlation coefficient (ICC) based on a two-way mixed-effects model were employed to assess inter-rater reliability, measuring the consistency of mean measurements (ICC [16,17]). Results demonstrated excellent consistency (ICC = 0.92, 95% CI: 0.85–0.96, p <0.001).

Results

Baseline Characteristics of the Study Population

The comparison of the baseline characteristics revealed significant differences between the two groups (Table 1). The patients in the SG group were older (median age: 60.00 years, interquartile range: 51.00–65.25), and the median age of those in the N-SG group was 48.00 years (interquartile range: 39.00–57.00); the difference was significant ($p < 0.001$). The prevalence of shoulder peak Types II (82.0% versus 65.8%, $p < 0.001$) and III (14.0% versus 8.4%, $p < 0.001$) was higher in the SG group, while Type I shoulder peak was more common in the N-SG group (25.7% versus 4.0%, $p < 0.001$). Furthermore, the positive rate of Jobe sign was higher in the SG group (81.0% versus 63.6%, $p = 0.001$). The distribution of Neer grades differed significantly between the two groups ($p < 0.001$). Functional scores, including hand pain-free range of motion, abduction angle, and tear depth grades, exhibited significant intergroup differences ($p < 0.001$). Specifically, functional limitations were more severe in the SG group (work limitation: median: 0.00, interquartile range: 0.00–2.00), whereas in the N-SG group, they were 2.00 (interquartile range: 2.00–2.00). However, variables such as gender ($p = 0.171$), dominant side ($p = 0.353$), and trauma history ($p = 0.509$) did not exhibit significant associations with group allocation.

Identification of Independent Predictors for Surgical Decision-Making

Multivariate logistic regression analysis was conducted to identify the independent predictors of surgical intervention (Table 2). Age (OR = 1.070, 95% CI: 1.035–1.106, $p < 0.001$) and tear depth grade (OR = 4.414, 95% CI: 2.726–7.146, $p < 0.001$) were significantly positively correlated with surgical risk. The shoulder blade type exhibited a significant impact on the results; Types II (OR = 8.138, 95% CI: 1.860–35.615, $p = 0.005$) and III (OR = 11.209, 95% CI: 1.637–76.743, $p = 0.014$) exhibited a higher surgical possibility compared to Type I. Functional movement parameters became key predictors: an increase in the external rotation angle (OR = 0.566, 95% CI: 0.397–0.807, $p = 0.002$) and an increase in the internal rotation angle (OR = 0.696, 95% CI: 0.509–0.953, $p = 0.024$) can reduce the surgical risk. However, an increase in the abduction angle (OR = 1.800, 95% CI: 1.204–2.692, $p = 0.004$) increased the likelihood of requiring surgery. The Neer grade was negatively correlated with surgical risk (OR = 0.297, 95% CI: 0.148–0.597, $p = 0.001$), with a lower grade indicating lower surgical risk.

To assess the potential multicollinearity among the independent variables included in the multivariable logistic regression model, we calculated the variance inflation factor (VIF) for each predictor. All VIF values were less than 10,

Table 1. Baseline characteristics of the study population.

Variable	Total (n=337)	SG (n = 100)	N-SG (n = 237)	Z/χ^2-value	p-value
Age, years (Median (IQR))	51.00 (41.00–62.00)	60.00 (51.00–65.25)	48.00 (39.00–57.00)	–6.323	<0.001
Sex				1.876	0.171
Male, n (%)	171 (50.7%)	45 (45.0%)	126 (53.2%)		
Female, n (%)	166 (49.3%)	55 (55.0%)	111 (46.8%)		
Side of dominance				0.862	0.353
Yes, n (%)	196 (58.2%)	62 (62.0%)	134 (56.5%)		
No, n (%)	141 (41.8%)	38 (38.0%)	103 (43.5%)		
Trauma				0.437	0.509
Yes, n (%)	127 (37.7%)	35 (35.0%)	92 (38.8%)		
No, n (%)	210 (62.3%)	65 (65.0%)	145 (61.2%)		
Duration of symptoms, months (Median (IQR))	3.00 (2.00–11.00)	4.00 (2.00–12.00)	3.00 (1.50–8.00)	–1.959	0.050
Types of acromions				21.992	<0.001
Type I	65 (19.3%)	4 (4.0%)	61 (25.7%)		
Type II	238 (70.6%)	82 (82.0%)	156 (65.8%)		
Type III	34 (10.1%)	14 (14.0%)	20 (8.4%)		
Neer's sign				0.476	0.490
Yes, n (%)	323 (95.8%)	97 (97.0%)	226 (95.4%)		
No, n (%)	14 (4.2%)	3 (3.0%)	11 (4.6%)		
Jobe's sign				10.229	0.001
Yes, n (%)	231 (68.5%)	81 (81.0%)	150 (63.6%)		
No, n (%)	106 (31.5%)	19 (19.0%)	87 (36.7%)		
AHD, mm (Median (IQR))	5.60 (4.80–6.20)	5.35 (4.68–6.10)	5.60 (4.90–6.30)	1.718	0.086
Neer grade				–6.011	<0.001
Grade 0	9 (2.7%)	0 (0%)	9 (3.8%)		
Grade 1	57 (16.9%)	11 (11.0%)	46 (19.4%)		
Grade 2	148 (43.9%)	26 (26.0%)	122 (51.5%)		
Grade 3	123 (36.5%)	63 (63.0%)	60 (25.3%)		
Constant-Murley Shoulder Score (Median (IQR))	30.00 (18.00–38.00)	18.00 (16.00–26.00)	34.00 (26.00–40.00)	8.509	<0.001
Pain score (0–15)	5.00 (0.00–5.00)	0.00 (0.00–5.00)	5.00 (0.00–5.00)	7.791	<0.001
Work restrictions	2.00 (0.00–2.00)	0.00 (0.00–2.00)	2.00 (2.00–2.00)	8.757	<0.001
Restrictions on recreational activities	2.00 (0.00–2.00)	0.00 (0.00–2.00)	2.00 (2.00–2.00)	8.265	<0.001
Sleep impact	1.00 (0.00–1.00)	0.00 (0.00–1.00)	1.00 (0.00–1.00)	7.780	<0.001
Hand pain-free movement reaching the destination position	6.00 (6.00–8.00)	6.00 (6.00–6.00)	6.00 (6.00–8.00)	5.037	<0.001
Abduction angle	4.00 (2.00–4.00)	4.00 (2.00–4.00)	4.00 (4.00–4.00)	3.842	<0.001
Flexion angle	4.00 (4.00–6.00)	4.00 (4.00–4.00)	6.00 (4.00–6.00)	6.300	<0.001
External rotation angle	4.00 (2.00–6.00)	2.00 (2.00–4.00)	4.00 (2.00–6.00)	7.855	<0.001
Internal rotation angle	4.00 (2.00–4.00)	2.00 (0.00–4.00)	4.00 (2.00–4.00)	8.261	<0.001
Tear depth grade				–9.091	<0.001
Grade 0	209 (62.0%)	34 (34.0%)	175 (73.8%)		
Grade 1	41 (12.2%)	0 (0%)	41 (17.3%)		
Grade 2	12 (3.6%)	1 (1.0%)	11 (4.6%)		
Grade 3	75 (22.3%)	65 (65.0%)	10 (4.2%)		

IQR, interquartile range; SG, surgical group; N-SG, non-surgical group.

indicating that multicollinearity was not a significant concern in our model.

Jobe sign (p = 0.645), pain score (p = 0.311), and other restrictive measures, including restrictions on recreational activities and sleep impact, were excluded from the final prediction model.

Establishment of Nomogram

A nomogram (Fig. 4) was developed based on the results of multivariable logistic regression analysis to estimate the probability of surgical intervention. Independent predictors incorporated into the model included age, Neer grade, tear depth grade, shoulder abduction angle, internal rotation angle, external rotation angle, and acromial morphol-

Table 2. Logistic regression analysis of risk factors for surgical decision making in rotator cuff tears.

Variable	OR (95% CI)	Wald Chi-Square	*p*-value	B-value	Standard error (SE)
Age	1.070 (1.035–1.106)	16.144	<0.001	0.068	0.017
Acromial type					
Type I	1				
Type II	8.138 (1.860–35.615)	7.749	0.005	2.097	0.753
Type III	11.209 (1.637–76.743)	6.063	0.014	2.417	0.981
Jobe's sign	0.791 (0.292–2.144)	0.212	0.645	–0.234	0.509
Neer grade	0.297 (0.148–0.597)	11.614	0.001	–1.214	0.356
Pain score	0.900 (0.735–1.103)	1.027	0.311	–0.105	0.104
Work restrictions	0.568 (0.085–3.774)	0.343	0.558	–0.566	0.966
Restrictions on recreational activities	1.384 (0.207–9.247)	0.112	0.738	0.325	0.969
Sleep impact	1.315 (0.445–3.888)	0.245	0.621	0.274	0.553
Hand pain-free movement reaching the destination position	1.187 (0.776–1.815)	0.625	0.429	0.171	0.217
Abduction angle	1.800 (1.204–2.692)	8.196	0.004	0.588	0.205
Flexion angle	0.770 (0.535–1.109)	1.970	0.160	–0.261	0.186
External rotation angle	0.566 (0.397–0.807)	9.927	0.002	–0.569	0.181
Internal rotation angle	0.696 (0.509–0.953)	5.123	0.024	–0.362	0.160
Tear depth grade	4.414 (2.726–7.146)	36.46	<0.001	1.485	0.246

OR, odds ratio; CI, confidence interval.

ogy (types I–III). Each predictor was assigned a point value proportional to its regression coefficient (log odds ratio). The total score, calculated by summing the points for all variables, corresponded to the predicted probability of surgical intervention.

Model Performance Metrics

The predictive model demonstrated good discrimination and calibration for surgical decision-making in rotator cuff tears. Receiver operating characteristic (ROC) curves (Fig. 5A) analysis demonstrated the model's excellent predictive capability, with an AUC of 0.934 (95% CI: 0.907–0.961). The cutoff value of the ROC curve was 0.274, with a sensitivity of 0.890 and specificity of 0.840. Moreover, the bootstrap-corrected C-index was 0.922 (95% CI: 0.908–0.964), and the AUCs from 10-fold cross-validation (Fig. 5B) were greater than 0.8, indicating good discriminatory ability.

Calibration Verification

The calibration curves (Fig. 6A,B) revealed a close alignment between the predicted and actual occurrence rates. A good fit of our model was revealed by the Hosmer-Lemeshow goodness-of-fit test (χ^2 = 1.0748, p = 0.9977). The bootstrapping-corrected Brier score was 0.1003, E_max was 0.0365, and the unreliability index was 0.0074, confirming good calibration. Furthermore, the calibration slope was 0.8858, and the intercept was –0.0559, indicating minimal systematic bias and acceptable calibration.

Clinical Utility Assessment

The decision curve analysis (Fig. 7A,B) revealed a superior net benefit of the model compared to "treat-all" and "treat-none" strategies across a wide range of clinically relevant threshold values. This model maintained a positive net benefit even at low intervention thresholds, supporting its utility in clinical decision making.

Discussion

This study systematically analyzed the baseline characteristics and specific functional motion parameters, such as shoulder abduction, external rotation, and internal rotation angles, in patients with rotator cuff tears to develop a predictive model for surgical intervention. This model demonstrated strong discriminative ability and excellent calibration, offering both clinical insight into decision-making factors and a practical tool for guiding treatment strategies.

We identified age, acromial morphology types II and III, tear depth, and specific functional motion parameters, including shoulder abduction, external rotation, and internal rotation angles, as independent predictors of surgical intervention. Age and tear depth displayed a significant positive association with the need for surgical intervention, consistent with prior findings [18]. With advancing age, progressive degeneration of rotator cuff tissues and diminished healing potential are likely to contribute to increased surgical indications. Similarly, deeper tears, particularly full-thickness lesions, are typically associated with greater functional impairment, thereby increasing the likelihood of surgical intervention. Furthermore, Types II and III acromial morphologies were significantly associated with higher surgical probability. This association may be due to narrow-

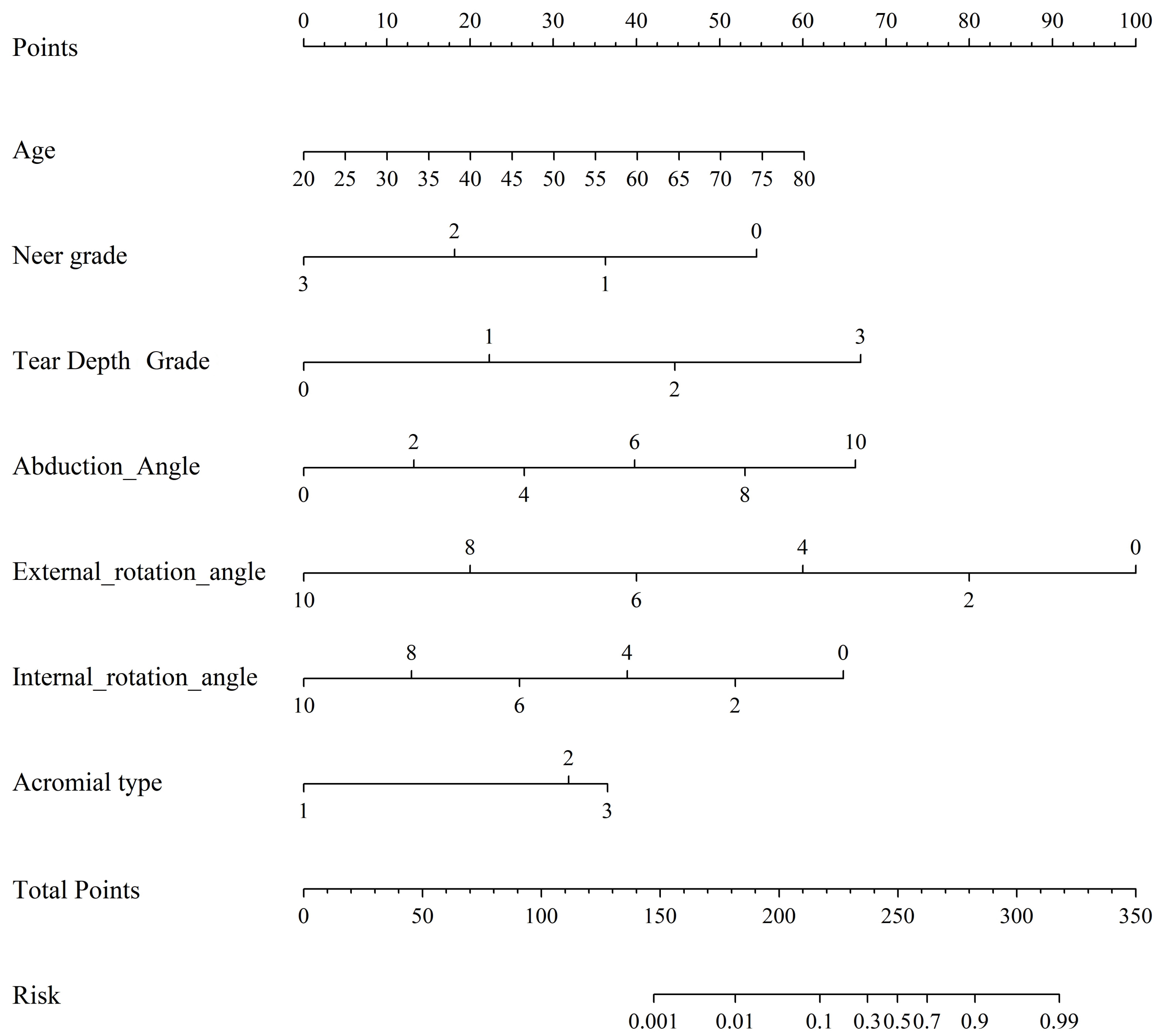

Fig. 4. Nomogram for predicting the probability of surgical intervention.

ing of the subacromial space and chronic mechanical impingement. These findings support the established theory that these anatomical variants predispose individuals to mechanical wear and tendon injury [3].

After adjusting for other variables, higher Neer grades were associated with a lower likelihood of surgical intervention (OR < 1). Although this finding may initially appear counterintuitive, it likely reflects the multifactorial nature of surgical decision-making—where the determination of surgical indications depends not only on radiographic severity but also on the comprehensive consideration of individual patient factors and overall functional status.

Among functional parameters, an increased abduction angle was positively associated with surgical necessity, whereas reduced external and internal rotation angles were linked to higher surgical indications. The positive correlation between preserved abduction and surgical indication is apparently paradoxical but biologically plausible. It suggests that patients maintaining good abduction may not have milder disease; rather, they may have more complex or extensive tears, such as massive or irreparable rotator cuff tears that allow for compensatory “pseudo-mobility”. Cadaveric studies support this phenomenon, demonstrating that even complete tears of the posterosuperior rotator cuff (PSRC) can preserve passive abduction under unloaded conditions [19,20]. However, these findings are limited by their inability to reflect active and dynamic shoulder functions in living patients, underscoring the importance of further clinical validation.

As rotator cuff pathology progresses over time, patients often develop compensatory mechanisms to maintain shoulder elevation, such as excessive activation of the trapezius and serratus anterior. In such cases, a preserved abduction angle may mask the underlying supraspinatus dysfunction

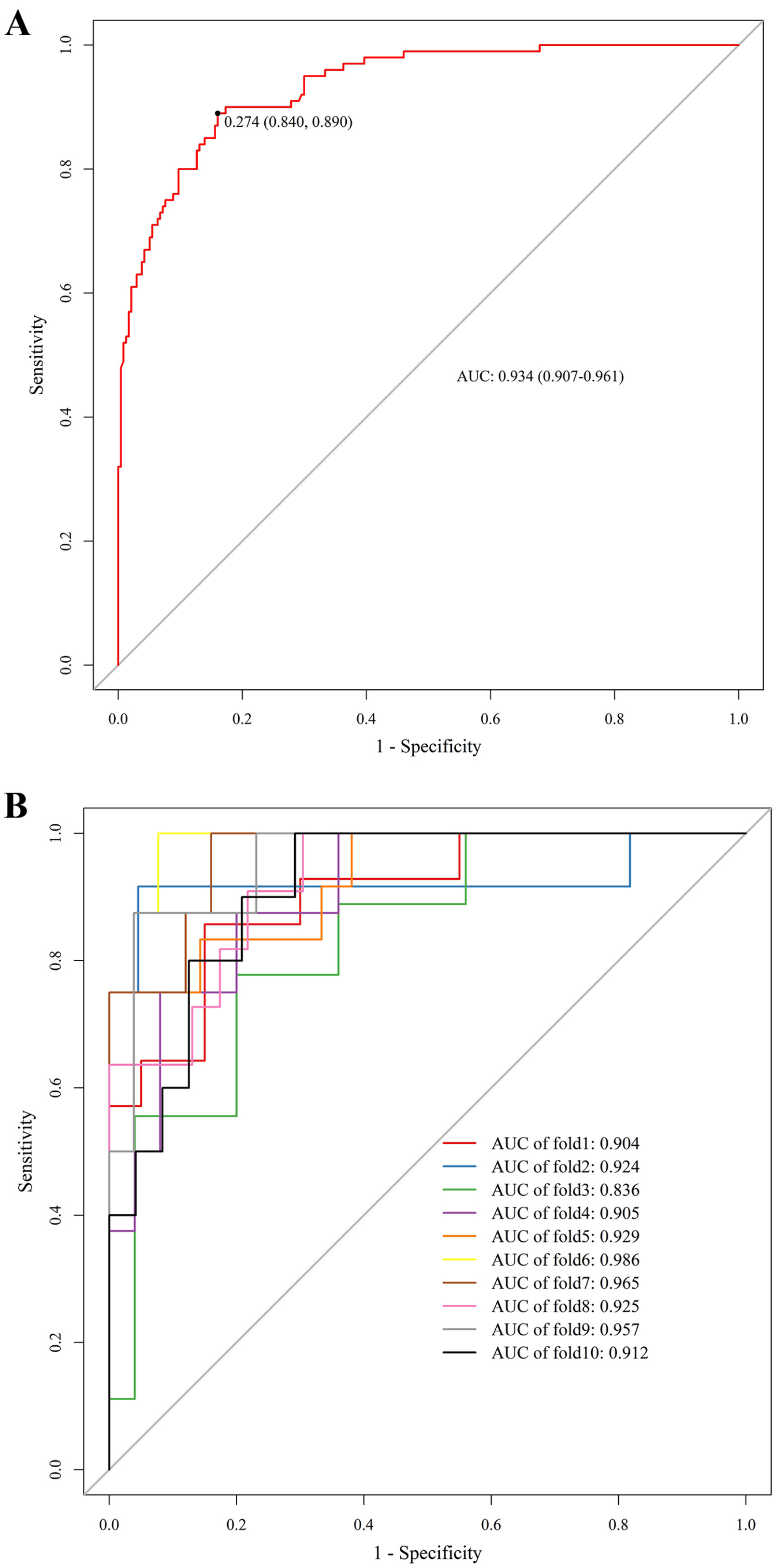

Fig. 5. Predictive performance of the comprehensive risk prediction model for rotator cuff injury surgery (A) and 10-fold cross-validation results (B). (A) The ROC curve depicts the diagnostic performance of the comprehensive risk prediction model for rotator cuff injury surgery. (B) ROC curves for each fold in the 10-fold cross-validation of the comprehensive risk prediction model for rotator cuff injury surgery. AUC, area under the curve; ROC, receiver operating characteristic.

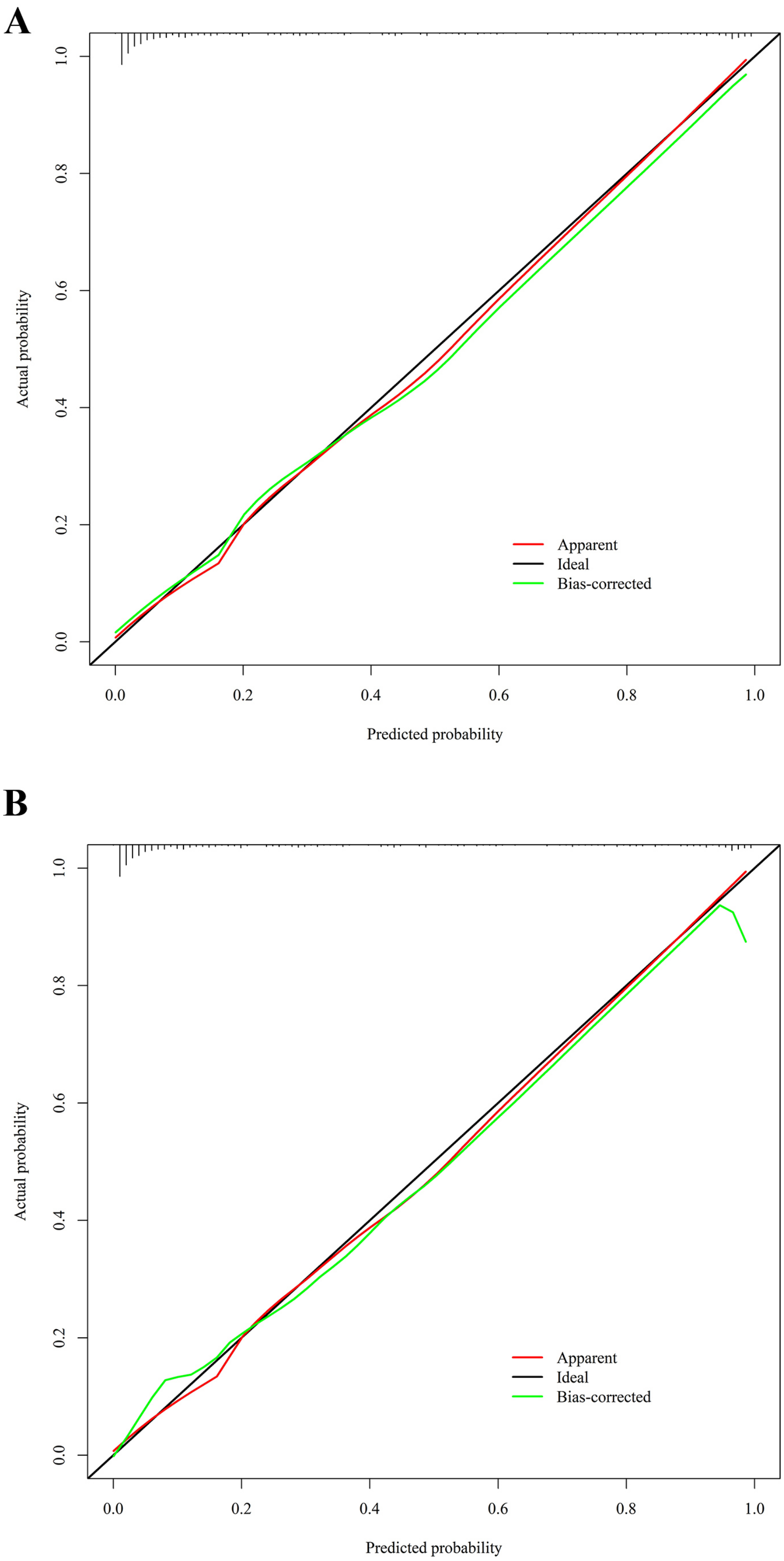

Fig. 6. Calibration curve of the prediction model for surgical intervention in rotator cuff tears. (A) Performance calibration curve of the prediction model for surgical intervention in rotator cuff tears using the bootstrap method. (B) Performance calibration curve of the prediction model for surgical intervention in rotator cuff tears using a 10-fold cross-validation method.

or advanced tendon degeneration. Thus, a relatively preserved abduction angle should not be interpreted as evidence of intact rotator cuff function; instead, it may serve as a red flag for a significant structural compromise.

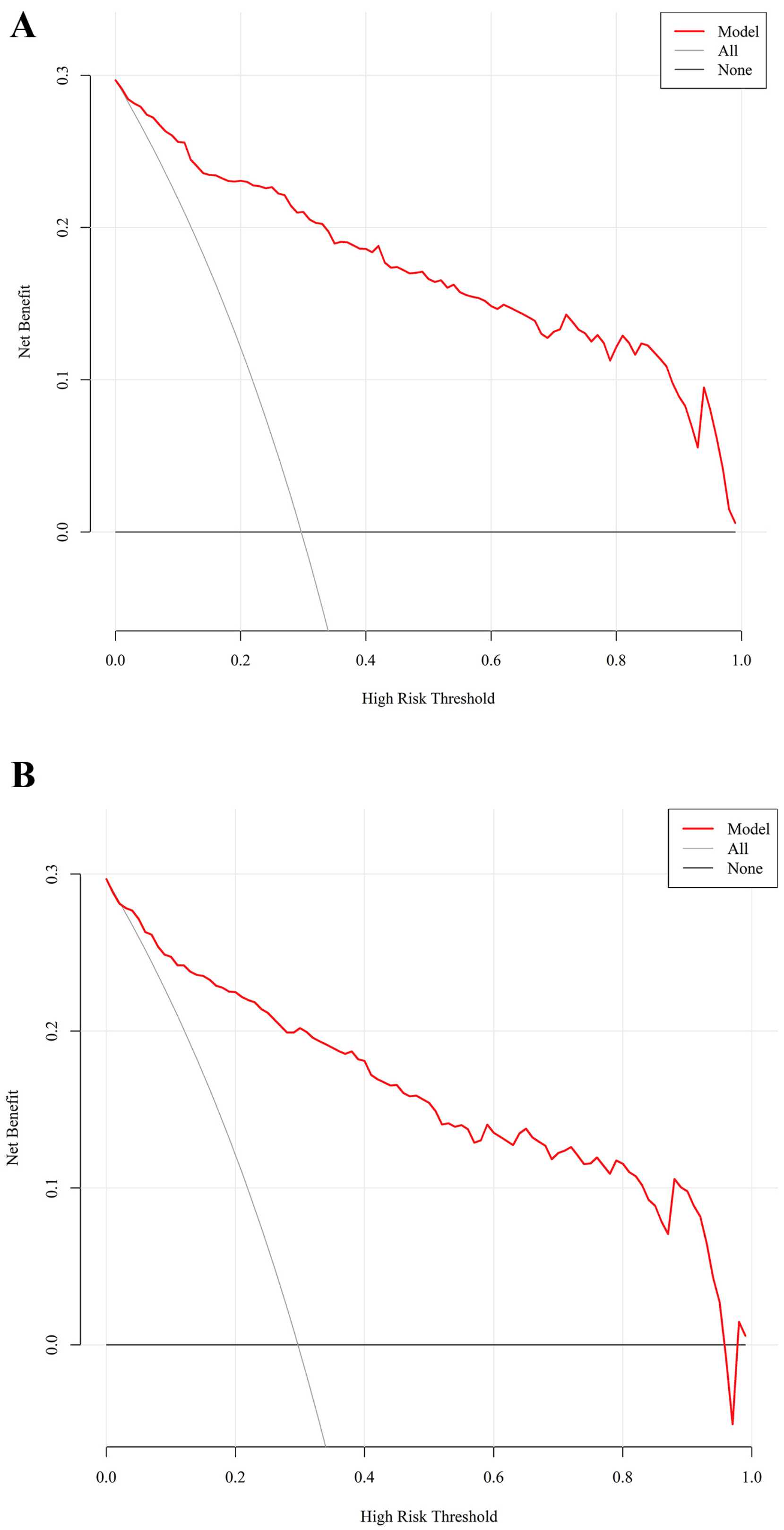

Fig. 7. Decision curve analysis of the prediction model for surgical intervention in rotator cuff tears. (A) Bootstrap validation. (B) 10-fold cross-validation.

In contrast, some patients exhibit severely restricted active abduction despite minimal structural damage, often due to pain inhibition rather than mechanical deficiency [21]. These individuals may benefit from surgery primarily for pain relief. Conversely, those with large, retracted tears frequently experience superior humeral head migration and loss of glenohumeral stability [18,22–24]. However, they reported less pain and retained a near-normal active motion through muscular compensation. For this group, surgical goals shift from pain control to restoring joint biomechanics and preventing arthropathy [22,24].

Impaired external and internal rotations were consistently associated with elevated surgical risk, consistent with well-established pathophysiological principles. Limited external rotation typically reflects infraspinatus and teres minor dysfunction [25], while restricted internal rotation often indicates subscapularis involvement [26]. Additionally, loss of internal rotation may stem from secondary capsular contracture, as observed in adhesive capsulitis ("frozen shoulder") [27]. These observations reinforce the importance of rotational strength and range of motion as key indicators of rotator cuff integrity and prognostic value, consistent with existing literature [28,29]. Here, "force couples" refer to balanced muscle groups that stabilize the shoulder during movement.

This apparently contradictory finding, with better shoulder abduction and worse rotation, indicates greater surgical risk and reflects substantial patient heterogeneity. There may be two different phenotypes: (1) the "stiff and painful" phenotype, characterized by significant limitation of movement but relatively intact tendon structure, in which non-surgical treatment may be sufficient; (2) the "weakness with pseudo-function" phenotype, manifested as seemingly good abduction ability but insufficient rotation ability, indicating that the force couple has been disrupted and the structure is severely damaged, resulting in a higher risk of disease progression and requiring earlier consideration of surgical treatment. This distinction emphasizes the importance of comprehensive assessment of shoulder function, considering multiple movement parameters rather than relying solely on isolated indicators such as abduction [29].

The predictive model developed in this study incorporates key clinical and functional parameters, including patient age, acromial morphology, tear depth, and shoulder range of motion, specifically abduction, external rotation, and internal rotation angles. It demonstrated excellent discriminative performance in distinguishing patients requiring surgical intervention from those suitable for nonoperative management (AUC = 0.934). Calibration plots and the Hosmer-Lemeshow test indicated strong agreement between predicted probabilities and observed outcomes, supporting the reliability of the model in real-world clinical settings. Furthermore, ROC curve analysis revealed that the model could effectively identify surgical candidates with high sensitivity (0.890) and specificity (0.840) at an optimal cutoff value of 0.274, underscoring its potential for precise risk stratification.

The clinical value of our nomogram lies in its ability to translate the complex interactions between patient age, tear characteristics, acromion morphology, and functional status into an individualized visual risk score [2]. This facilitates shared decision-making by objectively identifying two key cohorts: one, low-risk patients (with partial tears, Type I acromion, and preserved motion) who can be managed conservatively, avoiding unnecessary surgery [30], and two high-risk patients (with full-thickness tears, hooked acromion, and functional loss) for whom surgery is strongly indicated, preventing delays that could lead to irreversible muscle degeneration [5,31]. The decision curve analysis confirms that using this model provides a superior net benefit across a wide range of clinical thresholds, optimizing outcomes by reducing both overtreatment and undertreatment [32].

This study has several limitations. The retrospective design of this study may introduce selection bias, as patients with more severe symptoms are more likely to be offered surgery and choose it, which could potentially inflate the model's apparent performance. Future prospective multicenter validation studies are essential to confirm its generalizability, particularly in specific subpopulations, such as athletes. Moreover, the reliability of specific functional movement assessments in primary care settings requires further investigation. Finally, incorporating quantitative imaging biomarkers of muscle quality (fat infiltration) could further enhance the precision of the model.

Conclusions

The predictive model developed in this study effectively identified surgical candidates among patients with rotator cuff tears. Key predictors included age, acromial morphology, tear depth, and shoulder-specific functional motion parameters. The model demonstrates strong discriminative performance and good calibration, offering objective and reliable support for clinical decision-making and enabling more personalized treatment planning to improve patient outcomes. Widespread clinical implementation will require further validation through multicenter prospective studies and long-term follow-ups.

Availability of Data and Materials

The data used and analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contributions

NX and CL contributed to the conception and design of the study. NX and FX contributed to data acquisition. CL and FX participated in measuring and collating the AHD data. NX, FX, and CL were involved in the analysis and interpretation of the data, as well as drafting the manuscript. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study obtained ethics approval from the Institutional Review Committee of the Ethics Committee of Peking University International Hospital (Ethics review number: 2023-KY-0001-02) and conducted in accordance with the Declaration of Helsinki. Application for informed consent was waived for this study by the Institutional Review Committee of the Ethics Committee of the Peking University International Hospital.

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Conflict of Interest

The authors declare no conflict of interest.

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